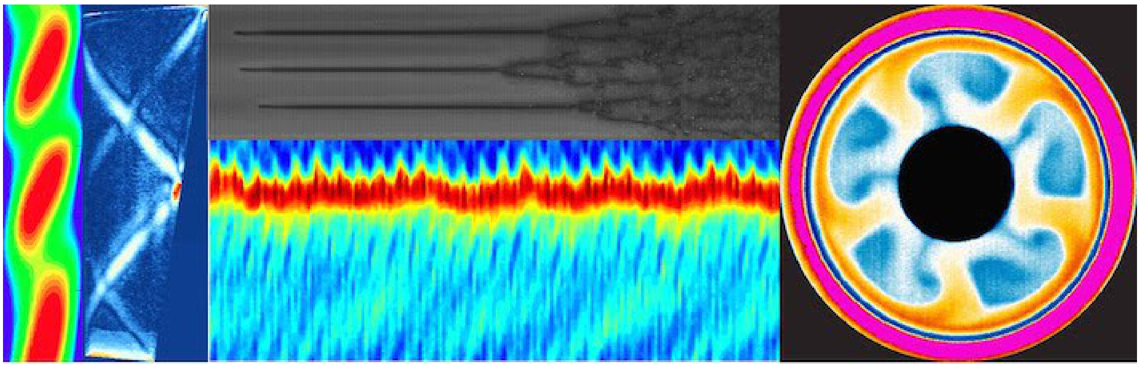
# LIA-ISTROF workshop 2019

Instabilities and Turbulence in Stratified Rotational Flows
Cottbus, $19^{th}$-$20^{th}$ June 2019



Brandenburg University of Technology Cottbus-Senftenberg
Department of Aerodynamics and Fluid Mechanics

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# Workshop topics and schedule

The workshop is addressed to students and researchers working in the field of instability and transition to turbulence in rotating and stratified flows in order to exchange the latests developments of theoretical, experimental, and numerical tools.

The applications of these flows in thermal science, geophysics and astrophysics will be discussed. The main topics covered by the workshop are: instabilities, turbulent flows, rotating flows, convection, magnetohydrodynamics, viscoelastic flows, etc.

The topics are subdivided in four main sessions during the workshop: TEHD (Thermo-electro-hydrodynamic), Atmoflow, Taylor-Couette, and waves. Some talks with topics of interest and related, but not belonging to the main sessions will be given in a fifth session called "miscellaneous".

# Workshop Schedule

Talks: 15'+5' discussion

| TIME | 19th | TIME | 20th |
|---|---|---|---|
| 9:00 AM | WELCOME | 9:00 AM | Lemoult-misc |
| 9:30 AM | Le Gal- waves | 9:20 AM | Crumeyrolle-misc |
| 9:50 AM | Rodda-waves | 9:40 AM | Mouzaoui-misc |
| 10:10 AM | Brunet-waves | 10:00 AM | Talioua-TC |
| 10:30 AM | Xu-waves | 10:20 AM | Merbold-TC |
| 10:50 AM | COFFEE BREAK | 10:40 AM | COFFEE BREAK |
| 11:20 AM | Meletti-waves | 11:10 AM | Prigent-TC |
| 11:40 AM | Harlander-waves | 11:30 AM | Singh-TC |
| 12:00 PM | Labarbe/Kirillov-waves | 11:50 AM | CONCLUSIONS |
| 12:20 PM | LUNCH | 12:20 PM | LUNCH |
| 1:50 PM | Szabo-misc | | |
| 2:10 PM | Mutabazi-TEHD | | |
| 2:30 PM | Meyer-TEHD | | |
| 2:50 PM | Barry-TEHD | | |
| 3:10 PM | Yoshikawa-TEHD | | |
| 3:30 PM | COFFEE BREAK | | |
| 3:50 PM | Feudel-misc | | |
| 4:10 PM | Zaussinger-atmoflow | | |
| 4:30 PM | Travnikov-atmoflow | | |
| 4:50 PM | Haun-atmoflow | | |
| 5:10 PM | Tilgner-misc | | |
| 6:00 PM | LAB-TOUR/SCIENTIFIC COMMITEE | | |
| 7:00 PM | DINNER | | |

# Contents

# Waves

# Resonances of Internal Gravity Waves in Stratified Shear Flows

P. Le Gal⋆, G.Facchini⋆, J. Chen⋆, S. Le Dizès⋆, M. Le Bar⋆, B. Favier⋆, U. Harlander†, I. Borcia† & W. Meng‡

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Plane Couette or Plane Poiseuille flows are the simplest parallel shear flows. In the non stratified case, Plane Couette flow is known to be linearly stable whereas Plane Poiseuille flow is linearly unstable for Reynolds numbers larger than 5572 [1]. We will present here a new instability mechanism that affects both of these flows when they are stably stratified in density along the vertical direction, i.e. orthogonal to the horizontal shear. Stratified shear flows are ubiquitous in nature and in a geophysical context, we may think to water flows in submarine canyons, to winds in deep valleys, to currents along sea shores or to laminar flows in rivers or canals where density stratification can be due to temperature or salinity gradients. Our study is based on two sets of laboratory experiments with salt stratified water flows, on linear stability analyses and on direct numerical simulations. It follows recent investigations of instabilities in stratified rotating or non rotating shear flows: the stratorotational instability [2], [3], the stratified boundary layer instability [4] where it was shown that these instabilities belong to a class of instabilities caused by the resonant interaction of Doppler shifted internal gravity waves. Our laboratory experiments based on visualizations and PIV measurements, show in both cases and above a given threshold that depends on the Reynolds and Froude numbers, the appearance of braided wave patterns. The non linear saturation of the instability leads to a meandering in the horizontal plane arranged in layers stacked along the vertical direction [5]. Comparison with theoretical predictions for the instability threshold and the critical wavenumbers calculated by linear analysis is excellent. Moreover, direct numerical simulations permit to complete the description of this instability that can be interpreted as a resonant interaction of boundary trapped waves [6].

[1]S. Orszag, *Accurate solution of the Orr-Sommerfeld stability equation*, Journal of Fluid Mechanics, **50(4)**, 689-703, 1971.

[2]M. Le Bars & P. Le Gal, *Experimental analysis of the stratorotational instability in a cylindrical Couette flow*, Physical Review Letters **99**, 064502, 2007.

[3]G. Rüdiger, T. Seelig, M. Schultz, M. Gellert, Ch. Egbers & U. Harlander, *The stratorotational instability of Taylor-Couette flows with moderate Reynolds numbers*, Geophysical & Astrophysical Fluid Dynamics,**111**, 429-447, 2017.

[4]J. Chen, Y. Bai, & S. Le Dizès, *Instability of a boundary layer flow on a vertical wall in a stably stratified fluid*, Journal of Fluid Mechanics **795**, 262-277, 2016.

[5]D. Lucas, C.P. Caulfield, R. R. Kerswell, *Layer formation and relaminarisation in plane Couette flow with spanwise stratification*, arXiv:1808.01178, 2019.

[6]G. Facchini, B. Favier, P. Le Gal, M. Wang, M. Le Bars, *The linear instability of the stratified plane Couette flow*, Journal of Fluid Mechanics, **853**, 205-234, 2018.

# Differentially heated rotating annulus experiments to study gravity wave emission from jets and fronts

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Significant internal gravity wave (IGW) activity has been frequently observed in the vicinity of jet/front systems in the atmosphere. Although many studies have established the importance of these non-orographic sources, the mechanisms responsible for spontaneous wave emissions is still not fully understood. The complexity of the three-dimensional flow pattern and distribution of the sources over large areas point towards the need of laboratory experiments and idealised numerical simulations to help with the correct interpretation of the fundamental dynamical processes in a simplified, but yet realistic flow. In this study, we emphasise that the differentially heated rotating annulus experiment, classically showing an aspect ratio of about one, is not a particularly favourable set-up to investigate atmosphere-like emission of gravity waves from baroclinic jets due to an unrealistic ratio between the buoyancy frequency $N$ and the Coriolis parameter $f$. The latter is much larger than one for the atmosphere but smaller than one for the classical annulus. Hence, we present an overview of modified versions of the classic baroclinic experiment, with a more realistic $N/f$, as a better choice for the study of IGWs. The first modified experiment is a thermohaline version in which a juxtaposition of convective and motionless stratified layers can be created by introducing a vertical salt stratification. This new experimental setup, coined "barostrat instability", allows studying the exchange of momentum and energy between the layers, especially by the propagation of IGWs. Moreover, in contrast to the classical tank without salt stratification, we have layers with $N/f > 1$. A ratio larger than unity implies that the IGW propagation in the experiment is expected to be qualitatively similar to the atmospheric case. Interestingly, we found local IGW packets along the jets in the surface and bottom layers where the local Rossby number is larger than 1, suggesting spontaneous imbalance as generating mechanism [1], and not boundary layer instability. The second experiment is a newly built rotating annulus, supported by numerical simulations [2]. This one is much wider with a small fluid depth compared to the classical set-up and has a larger temperature difference between the inner and outer cylinder walls, which is more atmosphere-like since it shows an $N/f > 1$ even without the vertical salt stratification. The conditions for gravity wave emission in this new configuration and the gravity wave signal are examined in detail.

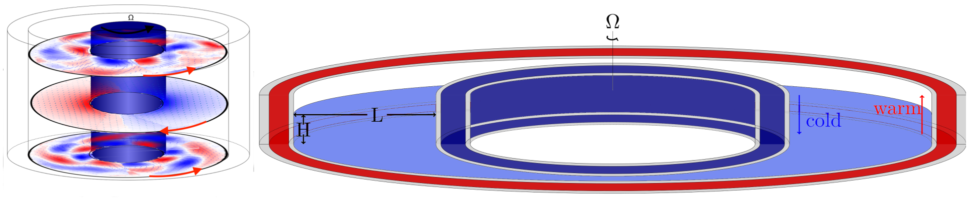


Figure 1: Sketch of the two experiments: barostrat on the left and atmosphere-like tank (with $H = 6$ cm and $L = 35$ cm) on the right.

[1]C. Rodda, I. Borcia, P. Le Gal, M. Vincze and U. Harlander, *Baroclinic, Kelvin and inertia-gravity waves in the barostrat instability experiment*, Geophysical and Astrophysical Fluid Dynamics, pages 1-32, 2018.

[2]S. Hien, J. Rolland, S. Borchert, L. Schoon, C. Zlicke, and U. Achatz, *Spontaneous gravity wave emission in the differentially heated rotating annulus experiment*, J. Fluid Mech., 838: 5?41, 2018.

# Linear and nonlinear regimes of an inertial wave attractor

M. Brunet & P-P. Cortet

Fluids submitted to a global rotation enable the propagation of a specific class of internal waves, called inertial waves, as a result of the restoring action of the Coriolis force. In closed domains, with walls not systematically vertical or horizontal, inertial waves at a given frequency converge, in certain geometry dependant ranges of frequencies, towards a limit cycle called wave attractor. These attractors appear as a consequence of the peculiar reflection laws of inertial waves whose dispersion relation sets their propagation angle with respect to the horizontal to a constant value dependant of the wave frequency. We present an experimental analysis of the linear and non-linear regimes of an attractor of inertial waves in a trapezoidal cavity under rotation. We show that the attractor is subjected to a triadic resonance instability which tranfers the attractor energy towards subharmonic waves. This instability of the attractor leads to a reduction of its velocity amplitude and to an increase of its wavelength in agreement with recent observations from numerical simulations in rotating fluids and experiments in stratified fluids. Varying the rotation rate and the forcing amplitude and wavelength, we identify the scaling laws followed by the attractor amplitude and wavelength in the linear and non-linear regimes. We show that the non-linear scaling laws can be well described by replacing the fluid viscosity in the linear attractor model by a turbulent viscosity accounting for the effective energy dissipation that the instability creates for the attractor. The identification of these scaling laws could help extrapolating attractor theory to geo/astrophysically relevant situations in which strong non-linear effects are expected.

# Inertial mode interactions in a rotating tilted cylindrical annulus with free surface

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Rotating fluids frequently show nonlinear wave interactions and turbulence. This is true in particular for non-uniformly rotating systems. One example of such a non-uniform rotating object is the Earth. Due to its fast rotation it is not exactly spherical. As a result of the interaction with the Sun and Moon the non-spherical Earth cannot rotate uniformly but shows precession and libration. This has consequences for the fluid enclosed in the outer Earth core. Due to the forcing it might become turbulent, one of the key factors in the present theories explaining the generation of the geomagnetic field. In the present research we show experimental results from a system that is simpler than classical precession experiments but form which very similar wave interactions and a collapse to turbulence can be found. This system consists of a rotating annulus that rotates about its symmetry axis slightly tilted with respect to the gravity vector. In contrast to classical precession experiments, the annulus has a free upper surface. Due to the tilt with respect to gravity a forced Kelvin mode is excited even without precession. In analogy to the more classical precession experiments we also find a resonant collapse when the forcing frequency corresponds with a resonant frequency of the rotating tank and try to connect our data to a low-order dynamical system that describes the main features of the nonlinear interaction in precession experiments. Moreover, we find a Kelvin wave forced geostrophic mode and free Kelvin modes that show triadic interactions. The triad is stable over a range of Ekman number, but the frequency of the triadic modes changes. This behavior has been observed in other rotating flows and can, at least partly, be explained by Doppler shift.

# Latest comparisons of experimental results and high performance non-linear numerical simulation on stratified rotational instabilities

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Understanding the mechanisms that can result in an outward transport of angular momentum is a central problem regarding astrophysical objects formation, particularly in the theory of accretion discs [1]. Among other candidates, the Strato Rotational Instability (SRI) has attracted attention in recent years as a possible instability leading to turbulent motion in these systems. The SRI is a purely hydrodynamic instability consisting of a classical Taylor-Couette (TC) system with stable density stratification due to, for example, salinity or a vertical temperature gradient.

Many information about the SRI can be obtained from numerical simulations and particularly designed laboratory experiments of axially-stratified TC setups, as the one in the BTU laboratory.

For obtaining a stable density stratification along the cylinder axis, the bottom lid of the setup is cooled, and its top part is heated, establishing axial linear temperature profiles varying between 3K and 5K. The inner and outer cylinders on the experimental setup rotate independently, with different angular velocities. The experimental results presented were obtained at different values of rotation ratio of $\mu = \Omega_{out}/\Omega_{in}$, where $\Omega$ is the angular velocity of the cylinder, and for different Reynolds numbers. More details about the experimental setup can be found in [2].

The experimental velocity profiles are obtained using *Particle Image Velocimetry* (PIV), with the camera co-rotating with the outer cylinder. The PIV measurements absolute error is of less than 2%, and all experiments were repeated at least 2 times at different days, so that the result's reproducibility could be guaranteed.

High performance parallel numerical simulations using the same configuration as the BTU experiment have been developed at the M2P2 laboratory at the Aix-Marseille University (AMU), and at the LAMPS laboratory at the University of Perpignan. The code solves the non-linear Navier-Stokes equations under the Boussinesq approximation. Details of the numerical scheme and the parallelization can be found in [3] and [4]. Latest comparisons of the experimental results with numerical simulations did show good agreements when compared qualitatively and quantitatively, regarding velocity profiles, and the analysis of the SRI frequencies in Fourier space.

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[1]Philip J Armitage. Cambridge University Press, 2010.

[2]T Seelig, U Harlander, & M Gellert. Geophysical & Astrophysical Fluid Dynamics, 112(4):239–264, 2018.

[3]S. Abide, M. S. Binous, & B. Zeghmati. International Journal of Computational Fluid Dynamics, 31(4-5):214–229, 2017.

[4]S. Abide, S. Viazzo, I. Raspo, & A. Randriamampianina. Computers & Fluids, 174:300–310, 2018.

# Stewartson layer instability in a wide-gap spherical Couette experiment: Rossby number dependence

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We give a brief overview on our recent work on inertial modes and wave attractors in spherical shell experiments. Further, we give a qualitative explanation, when the flow is dominated by wave attractors and when inertial modes can be expected. The largest part of our contribution will be devoted to the striking fact that the onset of instabilities strongly depend on the sign of the Rossby number. Hence we focus on the difference between cases where the Rossby number $Ro = (\Omega_i - \Omega_o)/\Omega_o > 0$ and cases with $Ro < 0$, where $\Omega_i$ and $\Omega_o$ are the inner and outer sphere angular velocities. The basic state in both situations is an axisymmetric shear flow with a Stewartson layer situated on the tangent cylinder. The tangent cylinder is given by a cylinder that touches the equator of the inner sphere with an axis parallel to the axis of rotation. The experimental results presented fully confirm earlier numerical results obtained by Hollerbach [1] showing that for $Ro > 0$ a progression to higher azimuthal wavenumbers $m$ can be seen as the rotation rate $\Omega_0$ increases, but $Ro < 0$ gives $m = 1$ over a large range of rotation rates. It is further found that in the former case the modes have spiral structures radiating away from Stewartson layer towards the outer shell whereas for $Ro < 0$ the modes are trapped in the vicinity of the Stewartson layer. Further, the mean flow excited by inertial mode self interaction and its correlation with the mode's amplitudes is investigated. The scaling of the critical $Ro$ with Ekman number $E = \nu/(\Omega_o d^2)$, where $\nu$ is kinematic viscosity and $d$ the gap width, is well within the bounds that have been established in a number of experimental studies using cylindrical geometry and numerical studies using spherical cavities. However, the present work is the first that *experimentally* examines Stewartson layer instabilities as a function of the sign of $Ro$ for the true spherical shell geometry.

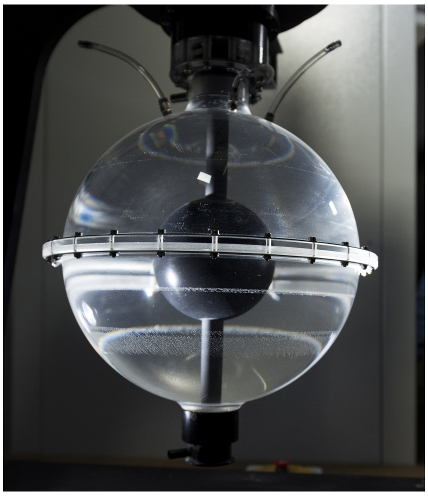

Figure 2: Experimental setup. Radius of the inner and outer sphere is 40mm and 120mm. Both spheres can rotate independently. Libration can be superposed on the rotation of both spheres.

[1] *J. Fluid Mech.*, vol. 492, 2003, pp. 289-302

# Instability windows of Chandrasekhar-Friedman-Schutz instability

J. Labarbe⋆ & O. Kirillov⋆

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Rotating, self-gravitating mass of incompressible ideal fluid possesses an axially symmetric equilibrium configuration known as the Maclaurin spheroid. Fluid viscosity causes dissipation-induced instability of this equilibrium [1], [2]. Chandrasekhar [3] discovered that radiation reaction force due to emission of gravitational waves could lead to a radiative instability of the Maclaurin spheroids. In the presence of both viscosity and resistivity the ratio of these two dissipative forces plays a crucial role [4], determining the instability window for the Chandrasekhar-Friedman-Schutz (CFS) instability. The CFS instability is commonly accepted nowadays as one of the main triggers of gravitational radiation from single neutron stars that is the next goal for the existing (LIGO, Virgo) and planned (LISA) detectors of gravitational waves [5], [6]. Perturbation theory for eigenvalues in combination with numerical methods was proposed for calculation of instability windows of the CFS instability already in [3], [4], [7]. We are extending this approach to the multiple-parameter case by adopting the methodology of [8], [9] to get better approximations and to put the CFS to the general context of the dissipation-induced instability theory.

[1]Chandrasekhar, S.: On stars, their evolution and their stability. Science 226(4674), 497–505 (1984)

[2]Roberts, R. H., Stewartson, K.: On the stability of a Maclaurin spheroid of small viscosity. Astrophys. J. 137, 777–790 (1963)

[3]Chandrasekhar, S.: Solutions of two problems in the theory of gravitational radiation. Phys. Rev. Lett. 24(11), 611–615 (1970)

[4]Lindblom, L., Detweiler, S. L.: On the secular instabilities of the Maclaurin spheroids. Astrophys. J. 211, 565–567 (1977)

[5]Ho, W. C. G.: Gravitational waves from neutron stars and asteroseismology. Phil. Trans. R. Soc. A 376, 20170285 (2018)

[6]Schutz B. F.: Gravitational-wave astronomy: delivering on the promises. Phil. Trans. R. Soc. A 376, 20170279 (2018)

[7]Schutz, B. F.: Perturbations and stability of rotating stars-III. Perturbation theory for eigenvalues. Mon. Not. R. astr. Soc. 190, 21–31 (1980)

[8]Kirillov, O. N., Verhulst, F.: Paradoxes of dissipation-induced instability or who opened Whitney's umbrella? Z. angew. Math. Mech. 90, 462–488 (2010)

[9]Kirillov, O. N.: Singular diffusionless limits of double-diffusive instabilities in magneto-hydrodynamics. Proc. R. Soc. A 473(2205), 20170344 (2017)

# TEHD

# Thermal convection induced by centrifugal and dielectrophoretic buoyancies in cylindrical annular cavities: a general review of recent results

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Generation of thermal convection in small systems is a key issue for the development of more efficient and long-term devices. In particular, this is important to evacuate heat from confined systems, where mechanical systems such as fans have no place. Thermoelectric convection represents a plausible way to achieve heat transfer in microdevices. Application of an alternating electric tension to a dielectric liquid subjected to a temperature gradient creates a body force density called dielectrophoretic force $\mathbf{F}_{DEP}$. This force comes from the inhomogeneity of the electric permittivity $\epsilon$ due to the temperature gradient. It contains a non-conservative part which plays the role of a buoyancy (with an effective gravity $\mathbf{g_e}$) that can induce thermoelectric convection in a dielectric fluid. We performed a stability analysis of the flow of a fluid of viscosity $\nu$ and thermal diffusivity $\kappa$ and thermal expansion coefficient $\alpha$, confined in a cylindrical annular cavities of width d, subject to a radial temperature gradient and to an alternating electric voltage to determine the critical parameters of the convective flow in the cavity [1], [2]. In annular cavity, thermoelectric convection appears in form of supercritical stationary helical modes [1] [2]. Thermoelectric convection is very suitable in microgravity conditions but it may also be implemented in terrestrial environment to improve the heat transfer by keeping a fixed temperature difference. In such situations, the flow is governed by three dimensionless control parameters : the Prandtl number $Pr = \nu/\kappa$ which defines the diffusive properties of the working fluid, the Rayleigh number $Ra = (\alpha\Delta T g d^3)/\nu\kappa$ and the electric Rayleigh number $L = (\alpha\Delta T g_e d^3)/\nu\kappa$. For a fixed value of $Pr$, we have determined the critical value of $Ra$ at which the convection sets in a fluid for an applied voltage (i.e. for a given value of $L$). This lead to the construction of a state diagram spanned by $(L, Ra)$ for each value of $Pr$ in which the electric modes are separated from hydrodynamic or thermal modes [3]. DNS have been performed for electric modes in order to compute heat transfer coefficient (Nusselt number) as function of electric voltage [3]. It was also shown that solid-body rotation of the annulus modifies the nature of critical modes of thermoelectric convection. The conference will make a general and synthetic overview of these recent results, few of them will be compared with experiments by BTU team.

**Acknowledgement:** The project is supported by the CNES and CNRS LIA 1092-ISTROF.

[1]H. Yoshikawa, O. Crumeyrolle & I. Mutabazi, Phys. Fluids 25, 024106 (2013).
[2]V. Travnikov, O. Crumeyrolle & I. Mutabazi, Phys. Fluids 27, 054103 (2015).
[3]A. Meyer, Ph.D. Dissertation, Normandie Université, Le Havre 2017
[4]C. Kang and I. Mutabazi, J. Appl. Phys. 125 (2019).

# Thermo-electro-hydrodynamic instability of a dielectric fluid in a vertical cylindrical annulus: Earth's gravity and weightless conditions

Antoine Meyer*, Torsten Seelig*, Philipp Gerstner†, Changwoo Kang‡, Martin Meier*, Marcel Jongmanns*, Martin Baumann †, Innocent Mutabazi ‡, Vincent Heuveline † & Christoph Egbers*

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When an electric field is applied to a dielectric fluid with a permittivity inhomogeneity, it undergoes the dielectrophoretic (DEP) force which can be seen as a buoyancy force resulting from an artificial electric gravity. In this study, the fluid is confined in a vertical cylindrical annulus with a hot inner surface and a cold outer one that produces the radial permittivity gradient. A high alternative electric potential is applied between the two cylinders. The resulting radial DEP force is able to destabilize the flow, leading to counter-rotating convection cells.

Under Earth's gravity conditions, a linear stability analysis showed that different modes can be observed depending on the dimensionless electric potential $V_E$. For low $V_E$, oscillatory toroidal vortices are originated by the Archimedean buoyancy. For large $V_E$, the DEP force is the main destabilizing mechanism and induces stationary helical modes. And for moderate $V_E$, the radial and axial buoyancies contribute together to generate stationary columnar vortices. Numerical and experimental investigation of this problem with an aspect ratio of 20 confirmed the existence of the columnar structure, but the toroidal vortices have never been observed due to the stabilizing effect of the base flow.

In microgravity condition, the theoretical and numerical analysis of the DEP force showed that the instability takes the form of stationary helical modes when the electric Rayleigh number $L$, based on the electric gravity, is larger than a value close to that of the classical Rayleigh-Bénard problem ($L \approx 1708$). In order to get experimental data in microgravity conditions, experiments have been performed during parabolic flight campaigns. The 22s of microgravity are too short to obtain a fully established unstable flow, but it has been possible to detect the growth of perturbations which allowed us to build a stability diagram, to characterize the geometry of the flow, and to compare the growth rates of perturbations between Earth's gravity and weightless environment.

# Linear stability analysis of thermoelectric convection in a vertical rectangular cavity with a horizontal temperature gradient and a high frequency voltage

E. B. Barry*, C. Kang*, H. N. Yoshikawa † & I. Mutabazi *

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Application of a high-frequency electric field to a dielectric liquid subjected to a temperature gradient creates a body force density called dielectrophoretic force $\mathbf{F}_{DEP}$. This force comes from the inhomogeneity of the electric permittivity $\epsilon$ due to the temperature gradient. This force contains a non-conservative part which can be assimilated to a buoyancy, with an effective gravity $\mathbf{g_e}$. The later represents the gradient of the electric energy stored in the capacitor. We performed a stability analysis of the flow of a fluid of viscosity $\nu$ and thermal diffusivity $\kappa$ and thermal expansion coefficient $\alpha$, confined in a vertical rectangular cavity of width $d$, subject to a horizontal temperature gradient and to an alternating electric voltage to determine the critical parameters of the convective flow in the cavity. The flow is governed by three dimensionless control parameters: the Prandtl number $Pr = \nu/\kappa$ which defines the diffusive properties of the working fluid, the Rayleigh number $Ra = (\alpha\Delta T g d^3)/\nu\kappa$ and the electric Rayleigh number $L = (\alpha\Delta T g_e d^3)/\nu\kappa$. For a fixed value of $Pr$, we have determined the critical value of $Ra$ at which the convection sets in a fluid for an applied voltage (i.e. for a given value of $L$). This lead to the construction of a state diagram spanned by $(L, Ra)$ for each value of $Pr$. For $Pr < 12.45$ and with small voltage $L < L_c$, the critical mode appears in form of transverse stationary rolls with a finite wave number of almost the width size d. This mode is called hydrodynamic mode [1]. For $Pr > 12.45$ and a large electric voltage $(L > L_c)$, the critical modes appears in form of oscillatory transverse modes with a small wavenumber. This mode is called thermal mode [1]. For large electric voltage $L > L_c$ which is independent of $Pr$, the critical mode appears in form of longitudinal steady convective rolls. This mode, whose threshold parameters $Lc = 2128.6$ and $q_c = 3.22$ are independent of $Pr$, is called electric mode [2], [3]. The present results have been obtained from the investigation of the flow stability against 3 perturbations and they are more precise than those obtained in previous studies [2], [3] performed with 2D perturbations. The understanding of the heat transfer in such flow configurations is very useful for the design of heat exchangers for microfluidic devices and for aeronautic and astronautic devices for orbital systems.

**Acknowledgement:** The project is supported by the CNES and the Region Normandie.

[1]A. Bahloul, I. Mutabazi & A. Ambari, Eur.Phys. J. AP 9, 253(2000).
[2]M. Tadie Fogaing, Ph.D. Dissertation, Université Le Havre Normandie, 2014
[3]M. Takashima & H. Hamabata, J. Phys. Soc. Jap. 53(5), 1728 (1984).

# Dielectric-heating-induced thermal convectio in isothermal parallel plane capacitors.

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The convective flow induced by an alternating electric field in an isothermal layer of dielectric fluid is investigated by the linear stability theory (Fig. 1). The flow is driven by an thermo-electrohydrodynamic (TEHD) force resulting from the coupling of an electrohydrodynamic effect with dielectric heating and/or by the thermal Archimedean buoyancy force. Under the assumption of high frequency electric fields, a theoretical model is developed to describe the averaged flow dynamics over an oscillation period of applied electric field. Critical condition for the driving forces to overcome stabilizing diffusion effects is determined for different fluid layers of different properties in both microgravity and Earth's gravity environments. The condition is independent of the Prandtl number and critical modes are stationary. Different from the TEHD instability in perfect dielectric fluids, the instability thresholds are sensitive to the frequency of electric field. On the ground, the instability also depends on the dimensionless thickness $H = (\alpha g d^3/e'\nu\kappa)^1/3$, where $\alpha$ is the coefficient of thermal expansion, $g$ is the gravitational acceleration, $e'$ is the coefficient of thermal decrease of permittivity, $\nu$ is the kinematic viscosity and $\kappa$ is the thermal diffusivity. At low $H$, the instability is driven by the TEHD force, as in microgravity environments, and the critical mode consists of four convection cells per wavelength (Fig. 2). The thermal Archimedean buoyancy force is, in contrast, dominant at high $H$ and the critical eigenfunctions are composed of a pair of convection cells per wavelength. We discuss obtained results in the light of the analogy of the TEHD force to the thermal Archimedean buoyancy force.

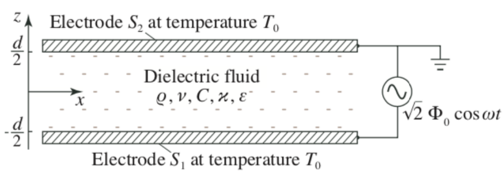


Figure 3: Schematic illustration of a parallel plane capacitor.

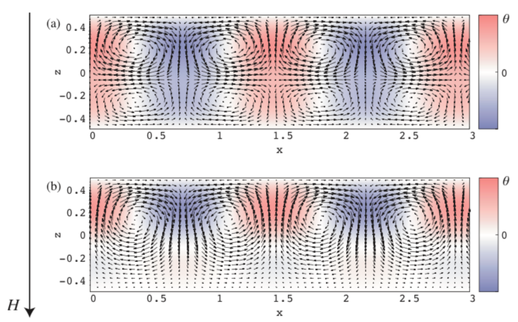


Figure 4: Critical eigenfunctions for different values of thickness $H$. (a) $H = 10$ and (b) $H = 400$.

# AtmoFlow

# GeoFlow I and GeoFlow II: A review

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Thermal driven convection in spherical geometry is of main interest in geo- and astrophysical research. To capture certain aspects of convective processes we investigate the micro-gravity experiment GeoFlow, located on the ISS.

This unique experimental setup consists of a bottom heated and top cooled spherical gap, filled with the silicon oil M5 or 1-Nonanol. The GeoFlow experiment on the ISS is the first spherical gap experiment which investigates the process of convection and internal heating under long-time micro-gravity conditions on the ISS. The radial force field, based on dielectrophorese, simulates a 'lab planet'. The volumetric heating source in the GeoFlow experiment is based on dielectric heating, which is strongly couple to the electric field. Consequently, the governing equations to describe the fluid flow are extended by the Maxwell equations. However, rotation and varying temperature gradients can be applied, to spread the experimental parameter space. Since the ISS requirements makes it impossible to use tracer particles, the flow structures are captured by interferometry, whose outcome is analyzed by a ground based adapted image processing technique. The main focus of the mission is the investigation of flow structures at the convective onset, the transition from laminar to turbulent flows and the influence of rotation on convection. We present a review of the GeoFlow mission and highlight the main outcomes form over 1 Mio experimental images. Additionally, we are presenting latest results concerning internal heating and its impact on rotating convection.

# Dielectrical heating effect on the convective flow in the spherical gap

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Convective driven flow induced by the radial force field in the spherical gap has been investigated numerically. The buoyancy force is caused due to the dielectrophretic effect. Furthermore, the influence of the dielectrical heating has been taken into account. The buoyancy force in the Navier-Stokes equation and the source term in the energy equation are coupled via the imposed electrical field according to $V_{rms}^2 r^{-5}$ and $V_{rms}^2 r^{-4}$, respectively, where We consider two kinds of the convective flow in the nonrotating case. The first one corresponds to the case when $\Delta T = T - T_{out} = 0$, i.e. the convective flow occurs only due to the dielectrical heating. After that we consider the case in which the inner surface is warmer than the outer one $\Delta T > 0$. In both cases the basic flow is $U_0 = 0$ and the temperature is radial dependent function $T_0(r)$. Stability analysis has been performed in frames of the linear theory. We calculated the critical Rayleigh number, i.e. critical voltage as function of the radius ratio $\eta = R_1/R_2$. If the spherical gap rotates with the angular velocity $\Omega$, the two-dimensional steady flow occurs because of the centrifugal force. Stability analysis shows that this flow becomes unstable with respect to the three-dimensional oscillated perturbations, i.e. the azimuthal critical wave number $m_c > 0$. We calculate the critical Rayleigh numbers and critical frequencies as function on the Taylor number. Analysis of the three-dimensional flows shows that whereas the instability in the case without rotation is subcritical, the instability becomes supercritical if the system rotates. The analysis of the amplitudes is performed.

# Technical requirements and realization of the AtmoFlow experiment.

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The main objective of the AtmoFlow experiment is the investigation of convective flows in the spherical gap geometry. Gaining fundamental knowledge on the origin and behavior of flow phenomena such as global cells and planetary waves is interesting not only from a meteorological perspective. The thermal and kinematic boundary conditions of AtmoFlow are adjusted to be closer to the complexity of atmospheres, than former experiments. Namely, the fluid cell is heated at the equator and cooled at the polar regions. Additionally, there is a volumetric heat source which can be used to investigate climate relevant topics. The boundaries are capable of independent rotation, resulting in various geo- and astrophysical scenarios. In total, 720 different experimental points are planned. Hereby, the parameter spaces is spanned by the Rayleigh-Roberts number of up to 3.5e05 and the Rossby number between $-3.59$ and 3.59. Many simplified types of planetary atmospheres and their corresponding flow regimes are within this parameter space. For example, zonal flows on Jupiter, Neptune, Uranus or baroclinic jet stream on Earth. We present the technical realization of the idea of such an experiment and preliminary numerical results of selected regimes, which are compared to actual planetary flow structures.

# Taylot-Couette

# Statistical analysis in the turbulent counter-rotating Taylor-Couette flow

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We report experimental results on the transition to turbulence in the Taylor-Couette flow, the flow produced between independently rotating coaxial cylinders. Once the geometry and the nature of the fluid are fixed, the flow is governed by two control parameters, the outer and the inner Reynolds numbers $Re_0$ and $Re_i$ associated to the rotation of the outer and the inner cylinders respectively. The variation of these parameters produces a large variety of regimes, which have been described by Coles [1] and Andereck et al. [2]. In this work, we are interested in the study of the turbulent regime observed in the counter rotating case identified as "featureless turbulence" in the diagram of Andereck et al. [2]. In our previous study [3], we have identified three other turbulent regimes after the "featureless turbulence" indicating the presence of large coherent structures in this turbulent flow for higher $Re_i$. For our series of measurements, we fixed the outer Reynolds number $Re_0 = -4368$ and varied the inner one from the laminar to the turbulent regime. The reliability of our measurements is validated comparing with other previous studies [1], [2], [4], [5], [6]. At $Re_i = 2496$, we found the turbulent regime identified as "featureless" characterized by small scales. In contrast, for higher $Re_i$ large structures appear in the flow. For $3000 < Re_i < 4000$, the space-time diagrams indicate the occurrence of disordered turbulent vortices. These turbulent vortices are well organized in time and space while they become wavy for $4000 < Re_i < 10000$. With a further increase of $Re_i$, the turbulent vortices become stationary [3]. The objective of this work is to realize a statistical analysis of this turbulent flow with and without coherent turbulent structures in the flow. The results are discussed in the context of homogeneous turbulence [7].

**Acknowledgement:** This project was supported by the ANR-TRANSFLOW and the CPER-FEDER project BIONGINE. A. Talioua has benefited from a doctoral grant from Normandy Region.

[1]D. Coles, J. Fluid Mech, **21**, 385?425., 1965.
[2]C.D. Andereck, S. Liu, and H.L. Swinney, J. Fluid Mech, **164**, 155?183, 1986.
[3]A. Talioua, A. Prigent & I. Mutabazi. 23$^{ème}$ Congrès Français de Mécanique 2017.
[4]A. Goharzadeh, and I. Mutabazi, Eur. Phys.J. B, 19, 157?162, 2001.
[5]A. Prigent, G. Grégoire, H.Chaté, O. Dauchot, and W. van Saarloos , Eur. Phys. Lett, 89, 014501, 2012
[6]S.G. Huisman, R.C.A van der Veen, C.Sun, and D. Lohse, Nat. Commun, 5, 3820, 2014
[7]G.K. Batchelor, The theory of Homogeneous Turbulence. Cambridge University Press, 1953-P197.

# Transport process of large-scale circulation and turbulent fluctuations in wide gap Taylor-Couette flow.

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In this work turbulent structures in concentric rotating Taylor-Couette flow (TC) and its dependency on different parameters are investigated. Depending on the rotation rate of the cylinders, one is able to create huge amount of different flow cases and coherent structures inside the annulus. Eckhardt et al. [1] defined a transverse $u_z$ flux $J_{u_z}$ for pipe flow, a heat flux $J_\theta$ for Rayleigh-Bénard and angular motion flux $J_\omega = r^3(< u_r\omega >_{A,t} -\nu\partial r < \omega >_{A,t})$, where $< ... >_{A,t}$ denotes a spacial temporal average over a cylindrical surface of height $L$ at radius $r$, for Taylor-Couette flow, which has a similar analytical form. Analytically, $J_\omega$ has to be independent of all radii ($\partial_r J_\omega = 0$). So it is of great interest to quantify the angular motion flux $J_\omega$ as a parameter for the flow. At the wall the $J_\omega$ corresponds to the torque that the fluid works on the cylinders: Thus the dimensionless torque $G = T/(2\pi L\rho\nu^2) = \nu - 2J_\omega$ can be used to quantify the angular motion flux $J_\omega$. Measurement of the dimensionless torque in a wide gap Taylor-Couette geometry and its connection to the transport process of the large-scale circulation and the turbulent fluctuations is the purpose of this work.

In this investigation an experimental systems with radius ratio varying from $R1/R2 = 0.2$ to 0.5 is used. The inner cylinder (1) as well as outer one (2) rotate with angular velocities $\Omega_{1,2}$ in corotating ($\mu = \Omega_2/\Omega_1 > 0$) and counter rotating direction ($\mu < 0$). The results of the torque measurement show a peak at a slight counter rotation for different constant shear Reynolds numbers [2]. In the present paper different flow states and their influence to the torque are discussed. Visualisation of the structures as well as Particle Image Velocimetry are used methods for the analysis.

**Acknowledgement:** Financial support by Deutsche Forschungsgemeinschaft (DFG FOR1182 EG100/15-1,2) is gratefully acknowledged.

[1]B. Eckhardt, S. Grossmann, D. Lohse, *Fluxes and energy dissipation in thermal convection and shear flows.*, Europhys. Lett., Vol. 78, 24001, 2007

[2]S. Merbold, H.J. Brauckmann, C. Egbers, *Torque measurements and numerical determination in diferentially rotating wide gap Taylor-Couette flow,* Phys. Rev. E 87, 023014, 2013.

# Experimental and numerical study of the flow produced in a vertical Taylor-Couette system submitted to a large radial temperature gradient

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The Taylor-Couette system has long been studied as a model for the study of the transition to turbulence in closed flows. In realistic situations, it is often necessary to take into account the presence of thermal effects. Thus, the first observation of the complications caused by these thermal effects is generally attributed to Taylor himself [1]. He reported in some cases the appearance of a spiral instead of the Taylor vortex flow. This phenomenon, not predicted by theory in the context of an isothermal fluid, was *a posteriori* associated with the presence of an axial flow created by a radial temperature gradient [2]. Here we describe and compare the results of experimental and numerical studies of the water flow produced in a Taylor-Couette system submitted to a large radial temperature gradient.

Our system is composed of two vertical coaxial cylinders maintained at different temperatures. The inner cylinder is rotated whereas the outer one is at rest. The flow can be described by $Ta$, $Gr$ and $Pr$: the Taylor, Grashof and Prandtl numbers. As soon as a radial temperature gradient is imposed between the cylinders, the flow takes the form of a vertical convective cell. When the inner cylinder starts to rotate, the circular Couette flow is added. Then, when the rotation of the inner cylinder is further increased and the Taylor number reaches a critical value which depends on $Gr$, this base flow is destabilized and leads to different states depending on $Gr$ [3].

For $Gr \neq 0$, two distincts behaviours can be observed according to the $Gr$. For $|Gr| \leq 800$ the pattern appearing at the onset of the first instability has already been described in [4]. The spiral only appears at the bottom of the cavity and has a regular time behaviour inducing the temporal frequency spectrum to be characterized by one single mode. For $|Gr| \geq 800$, the time behaviour of the pattern is no longer regular. A low frequency time modulation can be seen on the space-time diagrams. The pattern evolves from the bottom to the middle of the system. Its axial extension increases with the $Gr$ and reaches half the length of the system at $Gr = 4270$. For $|Gr| \geq 2500$, as soon as the Taylor number is slightly increased above its critical value (an increase of $\delta Ta = 0.4$ is sufficient), a pattern called solitary wave appears on the background of the modulated spiral. This solitary wave is a robust structure and persists even when Ta is further increased. It takes the form of one to three helical stripes depending on the Grashof number. Its helicity follows the same rules as the other patterns observed in the system [5] but it is much more intense than the modulated spiral which is barely visible in the same conditions. It extends vertically over 3/4 of the system from the top (bottom) when the inner (outer) cylinder is hotter and propagates following the inner cylinder rotation.

**Acknowledgement:** We thank the CPER-FEDER project BIOENGINE and LIA-ISTROF for their financial support.

[1]G.I. Taylor, Stability of a Viscous Liquid Contained between Two Rotating Cylinders, Phil. Trans. R. Soc. Lond. A 223, 289-343 (1923).

[2]R. Tagg, The Couette-Taylor problem, Nonlinear Science Today 4, 1-25 (1994).

[3]R. Guillerm, C. Kang, C. Savaro, V. Lepiller, A. Prigent, K.-S. Yang and I. Mutabazi, Flow regimes in a vertical Taylor-Couette system with a radial thermal gradient, Phys. Fluids 27, 094101 (2015).

[4]V. Lepiller, A. Goharzadeh, A. Prigent and I. Mutabazi, Weak temperature gradient effect on the stability of the circular Couette flow, Eur. Phys. J. B 61, 445-455 (2008).

[5]M. Ali and P.D. Weidman, On the stability of circular Couette flow with a radial heating, J. Fluid Mech. 220, 53-84 (1990).

# A large Thermal Turbulent Taylor-Couette facility: Investigation of the turbulence induced by simultaneous action of rotation and radial temperature gradient

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An innovative Taylor-Couette system has been designed to study the turbulence at high Reynolds and Grashof numbers generated by simultaneous action of rotation and radial temperature gradient. The outer cylinder is stationary and the inner cylinder has a maximum rotational frequency of 30 Hz achieving a maximum inner cylinder Reynolds number of $Re_i = 0.5 \times 10^6$. The inner radius of the outer transparent glass cylinder is 152.5 mm and the outer radius of the inner black anodized aluminum alloy cylinder is 132.5 mm, providing a gap width of 20 mm over a height of approximately 1 m. The temperatures of both cylinders are controlled independently with an accuracy of above 99% with heating provided at the inner cylinder to a maximum value of 40 °C and cooling of the outer cylinder to a minimum of 10 °C. The maximum temperature difference of 30 °C allows to attain a Grashof number of $\sim 10^6$. The system provides a full optical access at the side and from the bottom. As such, a preliminary study of the 2D-PIV measurements obtained in the $r - \theta$ plane near the bottom of cylinder are presented along with torque measurements.

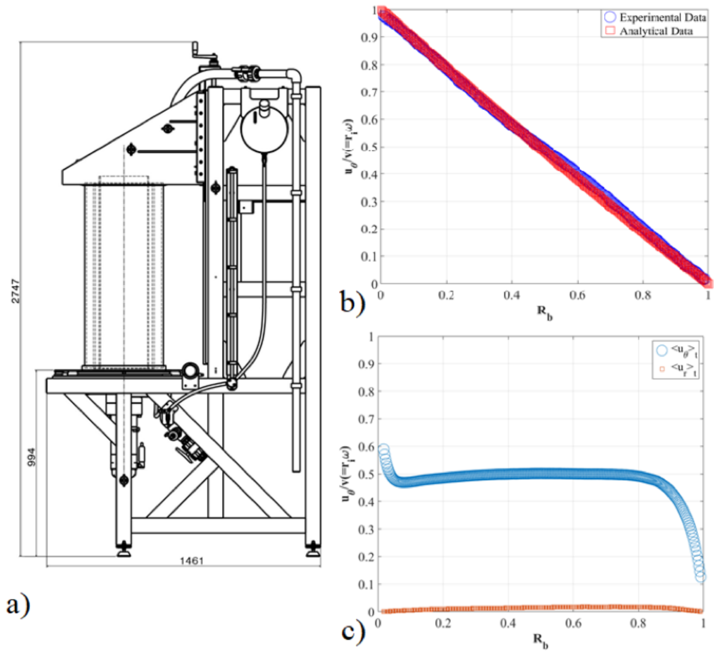


Figure 5: The Taylor Couette system (a) and 2D-PIV measurements in laminar (b) and turbulent(c) regions.

**Acknowledgement:** The present work was supported by the projects "DIAMECO" and the CPER-FEDER/ "BIOENGINE" of the Normandy Regional Council.

# Miscellaneous

# Thermomagnetic convection in thermally heated baroclinic annulus

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Convection in stellar or planetary interiors are fundamental features of geophysical flows. These large-scale convective flows are difficult to reproduce at laboratory scale as the driving force in a terrestrial laboratory is restricted to buoyancy in the vertical direction. A possible solution to produce a central force field is the utilisation of the Lorenz force[1] or the di-electric force[2]. Unless such experiments are carried out under micro-gravity conditions, they are still strongly affected by buoyancy. Here, we present an approach to simulate equivalent convection phenomena by utilizing ferrohydrodynamics of an electrically non-conducting but magnetisable fluid, as was demonstrated by Früh[3] in a 2-D section of a laboratory set-up for thermomagnetic convection in a non-rotating shell. This was later extended to a rotating spherical shell by Szabo and Früh[4] who rotated the system about its vertical axis ($\Omega$). A central force field is induced by a magnetised material in the centre of the domain. A body force towards the radial direction is induced by the magnetic material when the fluid exhibits variation in its magnetisation due to non-isothermal perturbations. This study presents a complementary study of such thermomagnetic convection but in a differentially-heated rotating annulus in contrast to the spherical shell. The baroclinic annulus ($r_i = 35$ mm, $r_o = 100$ mm) is filled with a magnetic fluid and the sidewall are maintained at different temperatures ($\Delta T$) . The convection is characterised via two main non-dimensional parameters the magnetic Rayleigh number - a ratio of Kelvin body force over viscous and thermal dissipation and the Taylor number - a ratio between Coriolis and viscous force:

$$\mathrm{Ra_M} = \frac{\mu_0 K |\nabla H| (r_o - r_i)^3 \ \Delta T}{\rho \nu \kappa}; \quad \mathrm{Ta} = \left( \frac{2\Omega (r_o - r_i)^2}{\nu} \right)^2$$

with $\mu_0$ the permeability of free space, $K = (\partial M / \partial T)_H$ the pyromagnetic coefficient, $\nabla H$ the magnetic field gradient, $\rho$ the density, $\nu$ the kinematic viscosity and $\kappa$ thermal diffusivity. The parametric numerical study covers a range of Ta and $\mathrm{Ra_m}$ up to $\approx 10^8$. Results suggest the development of convection cells very similar to baroclinic waves observed in the classical baroclinic annulus and are characterised by a non-dimensional parameter

$$\Theta_\mathrm{m} = \frac{\mu_0 K \Delta T H d}{\rho \Omega^2 L^3}$$

that was developed to quantify the thermomagnetic forcing in relation to the Coriolis term, as a magnetic equivalent to the Thermal Rossby number. The regime diagram shown below for this magnetic baroclinic annulus provides an overview over the flow regimes where the numbers indicate the dominant wave number of the flow, together with secondary wave modes where observed.

[1]Olson et al., *Phy. Earth. Plan. Sci.* **92**, 109 (1995).
[2]Futterer et al., *Acta Astronomica* **66**, 193 (2010).
[3]Früh, *Nonlin. Prog. Geophys.* **12**, 877 (2005).
[4]Szabo et al., *PAMM* **18**, 1 (2018).

# Bifurcations in rotating spherical shell convection under the influence of a weak differential rotation between the inner and outer spheres

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We numerically study convection phenomena in a rotating spherical shell which is heated from the inner sphere by imposing a constant temperature difference between its boundaries, and is subject to the action of a radially directed gravity force. In addition to the rotation of the fluid shell with angular velocity $\Omega$, a shear is generated by a weak differential rotation of the inner sphere with respect to the outer one, characterized by the parameter $\epsilon = \Delta\Omega/\Omega$, where $\Delta\Omega$ is the imposed angular velocity of the inner sphere in the frame rotating with angular velocity $\Omega$. Only small values of $\epsilon$, $|\epsilon| < 0.04$, are considered. There are indications that this type of configuration can be realized in astrophysical situation, as e.g. in the convection zones of the Earth-like planets, and can then determine the character of the magnetic dynamo processes there. The Ekman number is fixed to the moderately small value of $\mathrm{Ek} = 10^{-3}$. Starting from the unperturbed case of $\epsilon = 0$, for which the bifurcations were computed in detail recently [1] [2] [3], we study the influence of the imposed shear due to the weak additional rotation of the inner sphere. Besides purely quantitative modifications of the bifurcations that already occur for $\epsilon = 0$, new branches of rotating waves are found in the case of weak retrograte rotation of the inner sphere.

Increasing the Rayleigh number for fixed values of $\epsilon$ in the range $-0.03 \leq \epsilon \leq -0.008$, these nonaxisymmetric branches do not result from a linear instability of the axisymmetric basic flow but appear via saddle-node bifurcations. A particular feature of these new rotating waves is that their nonaxisymmetric components are weak. However, all modes are excited and no axial subsymmetries exist. Using a path-following technique both stable and unstable branches were traced systematically in the range of $|\epsilon| < 0.03$. As a next step we intend to study, for the case of electrically conducting fluids, the dynamo capabilities of these new rotating waves, in particular with respect to whether they can generate and maintain a magnetic field. This nonlinear dynamo action is already demonstrated for the unperturbed case, $\epsilon = 0$ [3].

[1]F. Feudel, N. Seehafer, L. S. Tuckerman and M. Gellert, *Multistability in rotating spherical shell convection, Phys. Rev. E* ***87****, 023021 (2013).*

[2]F. Feudel, L. S. Tuckerman, M. Gellert and N. Seehafer, *Bifurcations of rotating waves in rotating spherical shell convection, Phys. Rev. E* ***92****, 053015 (2015).*

[3]F. Feudel , L. S. Tuckerman, M. Zaks and R. Hollerbach, *Hysteresis of dynamos in rotating spherical shell convection, Phys. Rev. Fluids* ***2****, 053902 (2017).*

# Flows in precessing cubes

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We investigate with numerical simulations the dynamo properties of liquid flows in precessing cubes. There are some similarities with the flow in precessing spheres. Instabilities in the form of triad resonances are observed. The flow is turbulent far above the onset of instability. Surprisingly, the turbulent flow simplifies to a single vortex for certain control parameters.

One motivation for studying these flows is the dynamo effect, either in celestial bodies or in the experiment under construction in Dresden. The variability of precession driven flows (inertial modes, vortices, hysteresis loops etc.) complicate the extrapolation of the numerical results to the lower Ekman numbers realized in astrophysics or the laboratory. Up to now, we do not know a set of parameters for which we are confident that the Dresden experiment will lead to self excited magnetic fields.

# Directed percolation in pipe flow

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The circumstance that pipe flows are turbulent in practice, while theoretical arguments imply they should remain laminar, has posed a major challenge in fluid mechanics. Recent mounting evidence that the onset of turbulence can be explained as a directed percolation phase transition finally offers a solution to the problem[1]. However the extremely large time scales intrinsic to the transition in pipe flow make direct observations and a characterization of the universality class virtually impossible[2].We here circumvent these limitations by measuring all processes relevant to turbulence proliferation in experiments and by subsequently implementing them in a simple one dimensional model. The model clearly shows that longer range interactions between turbulent clusters, which had recently been found in experiments[3],strongly reduce the scaling range. At Reynolds numbers modestly close to the transition point the turbulent puff pattern enters a crystalline state that does not resemble the stochastic characteristics of a directed percolation process. Even closer to the transition point however, when considering excessive spatial (tube length exceeding $10^8$ pipe diameters) and temporal scales, the stochastic nature is recovered. As shown the transition in pipe flow hence falls into the directed.

[1]Lemoult et al., Nature Physics 12, 254 (2016)
[2]Avila et al., Science 333, 192 (2011)
[3]Mukund and Hof, Journal of Fluid Mechanics 839, 76 (2018)

# Convection of a phase change material in a rectangular cavity: numerical investigation.

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Convective flows with an interface with phase change material is observed in both the natural environment such as melting of sea ice, basal melting, magma chambers, or in the built environment such as underfloor heating, ceiling cooling, Trombe wall, when such equipment features a phase change layer. For the horizontal case heated from below, non-trivial effect have been reported at the interface between the liquid part and the solid domain. The mathematical Stefan condition have been proven to lead to complex pattern dynamics[1] Furthermore the critical Rayleigh number depends on the thickness of the solid layer[2]. Experiments [3] exhibit either roll or hexagonal patterns at steady state. The vertical case is both of interest for energy storage and geophysics[4][5]. In the present work we simulate both vertical and horizontal case for experimental parameters of heptadecane, as this model phase change fluid is widely used in investigations on phase change phenomena. Furthermore, heptadecane exhibits comparable or higher ratio $L/c_p$ than water, and thus allow easier experiments. Hereby $L$ is the latent heat of fusion and $c_p$ is the specific heat capacity at constant pressure of the liquid. We thus investigate numerically both the liquid domain and the solid domain so that finite thickness effects are taken into account. Temperature dependency of mat props are included. We perform the study in COMSOL Multiphysics 5.3 with a front tracking method. A 2d vertical geometry in agreement with the experimental setup is chosen due to the low Grashof number. We also investigate the horizontal case. Flow patterns and Nusselt numbers at boundaries are reported. Thermal imbalance is compared to solidification front displacement. The results are compared to preliminary experimental results.

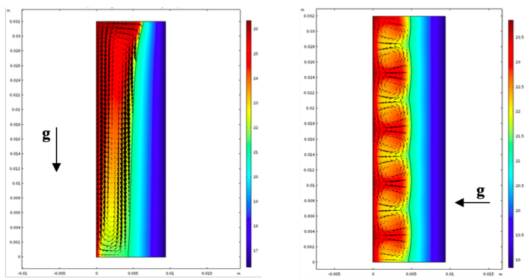

Figure 6: Temperature field for vertical and horizontal cases.

**Acknowledgement:** This work is a part of the RIN-FIVATHE project, funded by the Normandy Regional Council.

[1]Vasil, G., & Proctor, M. (2011). *Dynamic bifurcations and pattern formation in melting-boundary convection.* Journal of Fluid Mechanics, 686, 77-108. doi:10.1017/jfm.2011.284

[2]Favier, B., Purseed, J., & Duchemin, L. (2019). *Rayleigh-Bénard convection with a melting boundary.* Journal of Fluid Mechanics, 858, 437-473. doi:10.1017/jfm.2018.773

[3]Davis, S., Müller, U., & Dietsche, C., *Pattern selection in single-component systems coupling Bérnard convection and solidification*, J. Fluid Mech. 144, 133-151. DOI:10.1017/S0022112084001543 (1984)

[4]Kerr, R., & McConnochie, C. (2015). *Dissolution of a vertical solid surface by turbulent compositional convection.* Journal of Fluid Mechanics, 765, 211-228. doi:10.1017/jfm.2014.722

[5]Zeinelabdeina, R., Omera, S., Gana, G. (2018). *Critical review of latent heat storage systems for free cooling in buildings.* Renewable and Sustainable Energy Reviews 82, 2843-2868

# Convection of phase change material in a rectangular cavity: an experimental investigation.

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Phase change phenomena are present in a large number of natural processes (ice melting, magma chambers, basal melting), but are also of interest to improve performances of building applications (air conditioning, Trombe wall, thermal collector, underfloor heating) and industrial applications (heat storage, electrical vehicles, electronic cooling)[1]. For such applications, phase change materials (PCM) have been appealing in recent years as thermal energy storage systems and thermal management applications are of increasing concern [2], [3], [4]. PCM exhibit high latent heat storage capacity together with a small volume change during the melting and solidification processes. It is generally recognized that the dynamics of such phase change processes are largely influenced by natural convection when observed [5], [6]. In this study we investigate the influence of convection in the n-Heptadecane. This choice of PCM is motivated by their latent heat and heat capacity ratio ($L/C_p$) which is comparable or better than that of water. This allows exploration of high values of Stefan number. We observed the solid-liquid interface in a fluid layer between two isothermal vertical boundaries (Figure 1). The observed flow has the form of a reversed L-shape mono-cellular flow. Front movement is analyzed to evaluate heat transfer.

Figure 7: Photograph of the solid-liquid interface.

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[1]T. A. Kowalewski and D. Gobin, *Phase Change with Convection: Modelling and Validation.* Springer-Verlag Wien New York, 2004.

[2]S. Drissi, T. C. Ling, and K. H. Mo, *Thermal efficiency and durability performances of paraffinic phase change materials with enhanced thermal conductivity ? A review*, Thermochim. Acta 673, 198?210 (2019).

[3]Y. Cui, J. Xie, J. Liu, and S. Pan, *Review of Phase Change Materials Integrated in Building Walls for Energy Saving*, Procedia Eng.121, 763?770 (2015).

[4]M. M. Farid, A. M. Khudhair, S. A. K. Razack, and S. Al-Hallaj, *A review on phase change energy storage: Materials and applications*, Energy Convers. Manag. 45 (9?10), 1597–1615(2004).

[5]B. Favier, J. Purseed, and L. Duchemin, *Rayleigh-Bnard convection with a melting boundary*, J. Fluid Mech. 858, 437?473 (2019).

[6]G. M. Vasil and M. R. E. Proctor, *Dynamic bifurcations and pattern formation in melting-boundary convection*, J. Fluid Mech.686, 77?108 (2011).