22nd International Couette-Taylor Workshop

ICTW 2023

Barcelona, Spain | 28 - 30 June 2023

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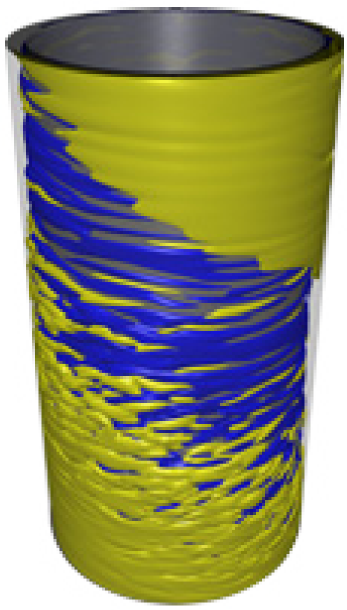

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FOREWORD

Welcome to the 22nd edition of the International Couette Taylor Workshop (ICTW23), hosted in Barcelona (28th-30th June 2023), by Universitat Politècnica de Catalunya. In this edition, we celebrate the centennial of the publication of G.I. Taylor’s paper entitled ‘Stability of a Viscous Liquid contained between Two Rotating Cylinders’, Phil. Trans. Roy. Soc. A, 223 (1923) VIII. One century later, this paper remains a cornerstone on which hydrodynamic stability theory has greatly developed.

Since the 1st edition of the ICTW, held in Leeds (UK) in 1979, thismeeting has gathered researchers from all around the worldrepresenting a wide range of disciplines including physics,mathematics and engineering. Although the first workshops wereexclusively dedicated to the Taylor-Couette flow, the research topicscovered at the ICTW meetings have progressively expanded during thelast three decades to include many other subjects such as non-lineardynamics, bifurcation theory, and instabilities arising incentrifugal, thermal convection, magnetohydrodynamic and shearflows. In this special edition, we count with nearly 80 contributionsby fluid dynamicists from all over the world, including three plenarytalks given by three of the most influential researchers in the fieldof hydrodynamic instability, namely Laurette Tuckerman (CNRS, France),Edgar Knobloch (UC Berkeley, US), and Dwight Barkley (University ofWarwick, UK).

Universitat Politècnica de Catalunya (UPC) is honored to host ICTW forthe second time in its long history, the first time twenty years past,organized by Francisco Marqués and Álvaro Meseguer. The organizingcommittee heartfully acknowledges the financial support of theGeneralitat de Catalunya (SGR-AGAUR), Ajuntament de Barcelona andUPC. Conference registration fees have been kept affordable for youngresearchers and others in need of financial support partly thanks tothe aforementioned funding.

We welcome you to Barcelona and we hope that ICTW2023 will befruitful, brimming with great talks, insightful discussions,groundbreaking research, collaborative endeavors, and memorableexperiences.

The local ICTW23 committee
Arantxa Alonso, Jezabel Curbelo, Francisco Marques, Fernando Mellibovsky and Alvaro Meseguer

ACKNOWLEDGEMENTS

The Conference organizers acknowledge the Support towards the organization of the ICTW 2023 Conference to the following organizations:

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Universitat Poltècnica de Catalunya (Department of Mathematics)

The Royal Society Publishing

Ajuntament de Barcelona

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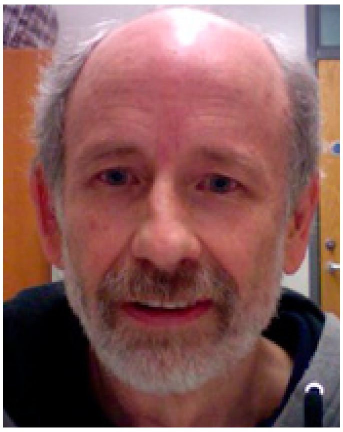
INVITED SPEAKERS

Dwight Barkley
University of Warwick, UK
Theory for turbulent-laminar patterns in Couette flow



Edgar Knobloch
UC Berkeley, US
Instability-driven turbulence

Laurette Tuckerman
Laboratoire de Physique et Mécanique des Milieux Hétérogènes, CNRS, ESPCI Paris, France
Couette-Taylor flow: history of a paradigm

SUMMARY

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PLENARY LECTURES

Title: Instability-driven turbulence

Abstract: In this talk I will survey recent progress in understanding instability-driven turbulence in both two (2D) and three (3D) dimensions. Turbulence in 3D is characterized by a forward transfer of energy, to small scales, while in 2D energy is transferred in the opposite direction, towards large scales. When driven by a prescribed stochastic force, the latter leads to the formation of large scale structures in the form of vortices or jets. When the turbulence is driven instead by a wavenumber-localized instability superposed on stochastic forcing, the inverse energy transfer may be arrested and no large scale condensate forms. We find that when a control parameter measuring the fraction of energy injected by instability is increased, the system undergoes two transitions. For a regular large-scale vortex condensate (LSC) forms. For shielded vortices (SVs) emerge and coexist with the condensate. At a second, larger value of the control parameter, the condensate breaks down, and a gas of weakly interacting vortices with broken symmetry spontaneously emerges, characterized by the preponderance of vortices of one sign only and suppressed inverse energy cascade. The number density of SVs in this broken symmetry state slowly increases via a random nucleation process. At late times a dense SV gas emerges, which persists back down to small values of, where it crystallizes to form a hexagonal lattice. It is observed that individual SVs are trapped in the lattice at small, up to a sharp threshold, above which the mean square displacement of SVs increases linearly with time and the system exhibits a nonequilibrium second order melting transition. These findings provide new evidence for a strong dependence of the phenomenology of 2D turbulence on the forcing.

I will compare this phenomenology with that observed in highly anisotropic but three-dimensional systems focusing on condensate formation in rapidly rotating Rayleigh-Benard convection via both reduced dynamics and direct numerical simulations (DNS) of the Navier-Stokes equation. I will conclude with a discussion of the boundary zonal flow (BZF) observed in both experiments and DNS in cylinders, its robustness under perturbation and its relation to the precessing wall modes present in this system. Finally, I will suggest a simple intervention that suppresses the BZF and its role in contaminating Nusselt number measurements in the laboratory, thereby enabling laboratory studies of geostrophic turbulence in laterally confined systems.

Speaker: Edgar Knobloch

Title: Theory for turbulent-laminar patterns in Couette flow

Abstract: Turbulence in wall-bounded shear flows exhibits a remarkable phenomenon:
spatially periodic patterns of alternating turbulent and laminar flow emerge spontaneously from uniform turbulence as the Reynolds number is decreased. These patterns are ubiquitous in subcritical shear flows and explaining them has been a long-standing challenge for understanding the route to turbulence. From a dynamical systems viewpoint, these patterns are fascinating because they appear in a highly fluctuating, highly nonlinear state. Here we report on a model obtained from projecting the Navier-Stokes equations onto a few vertical modes, with closure coming from modelling Reynolds stresses and dissipation. The resulting two-dimensional PDE model is expressed in 4 fields describing the large-scale flow, and 1 or 2 fields describing the turbulent kinetic energy. The model can be viewed as a generalized and more fully justified version of the Barkley model for pipe flow. The model captures the transition to periodic turbulent-laminar patterns, as well as other spatiotemporal dynamics found in transitional turbulence. This work is joint with Santiago Benavides.

Speaker: Dwight Barkley

SPECIAL SESSION

Taylor's 1923 Paper in the *Philosophical Transactions* – A Centennial Retrospective

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Abstract

The 22nd International Couette-Taylor Workshop coincides with the centennial of the publication of Taylor's pioneering paper(1923), which provides the basis for nearly all of the research presented at this conference. Too often, though, it is easy to overlook the details of this paper, which is not only foundational to the theory of hydrodynamic stability theory but so much more. The paper is considered by many as establishing the fundamental correctness of the Navier–Stokes equations and the no-slip boundary condition, which are the underlying concepts at the foundation of modern fluid mechanics. This and other notable aspects of Taylor's seminal paper will be covered including the motivation behind studying cylindrical Couette flow to understand stability, Taylor's remarkable experimental apparatus and meticulous experiments, his extraordinary insights into future research on what we now call Taylor-Couette flow, and even Nobel Prize winner Richard Feynman's summary of the "lesson" learned from Taylor's stability analysis.

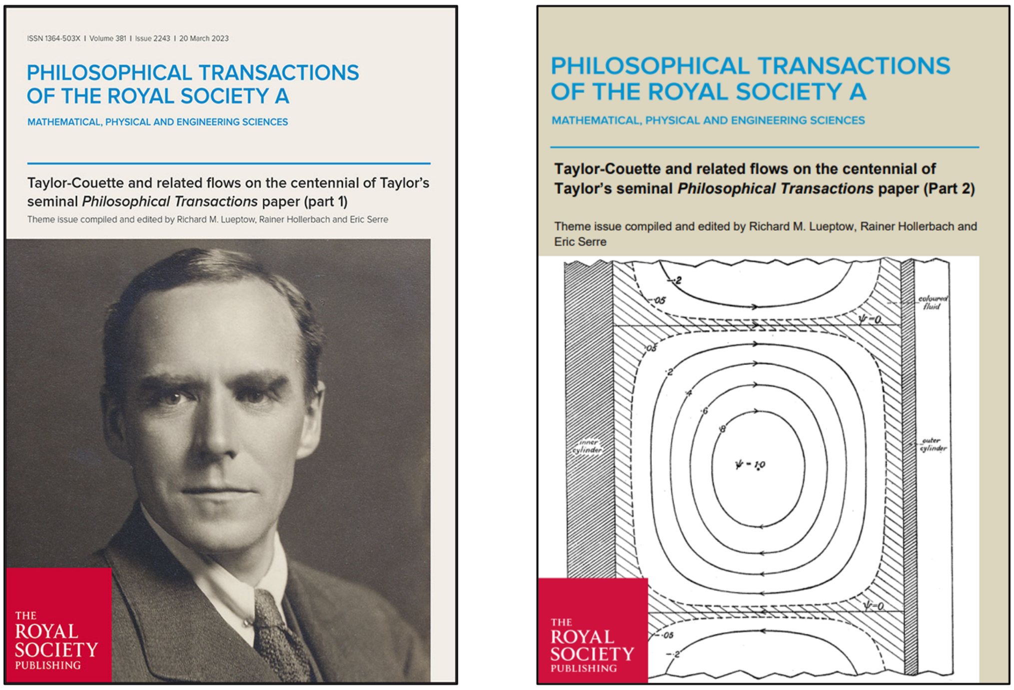

Figure 1: Theme issues of *Philosophical Transactions* on the centennial of Taylor's 1923 paper.

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WORKSHOP GENERAL SESSION CT

A computational local reduced-order method for a Rayleigh-Bénard problem

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Abstract

In this work a local reduced-order method is applied to a 2D Rayleigh-Bénard bifurcation problem. Local refers to the selection of the best POD basis for each value of the Rayleigh number through a k-means algorithm Hess *et al* (2019). The reduced-order method is a Galerkin projection of the incompressible Navier-Stokes and heat equations onto the local bases. Pressure is recovered through an enrichment of the velocity space. The local reduced-order method is used to compute several bifurcation diagrams of the problem for R in the interval [1000; 3000]. The method is benchmarked against a Legendre collocation scheme. Errors between the solutions of both methods are optimal, $O(10^{-3})$-$O(10^{-5})$. The local method is also compared to a standard global reduced-order method. In the performed numerical results, the local reduced-order method runs about 2.5 times faster than the global reduced-order method and 400 times faster than the Legendre collocation scheme.

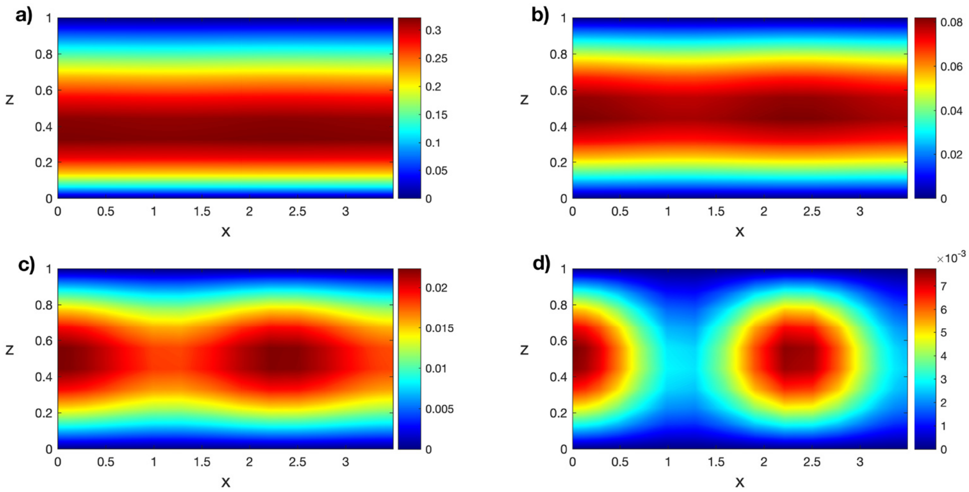

Figure 1: Isotherms of transitory state, Cortés *et al* (2022).

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A New class of higher order schemes for Navier-Stokes equations and application in rotating flows

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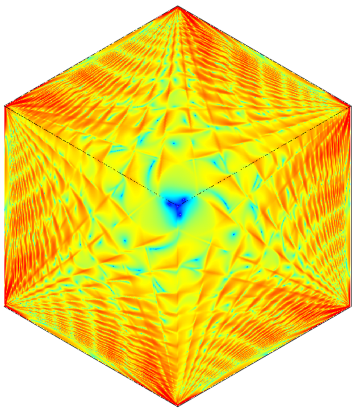
Abstract

A new class of time discretization schemes Wu,Huang,Shen (2022) for the Navier-Stokes equations with no-slip boundary conditions in rotating reference frame is constructed by combining the scalar auxiliary variable) SAV approach for general dissipative systems and the consistent splitting schemes. The time derivative is approximated by BDFk schemes and can be up to six-order accurate. The viscous force term, Coriolis force term and Euler force term are all treated implicitly. Then the governing equations are discretized in space using a Legendre-Galerkin spectral approach, which leads to a symmetric positive definite banded system with variable coefficients that can be solved efficiently by diagonalization procedures. A particular finding of these simulations is that, for flows with highly complex temporal and spatial structures, the third-order scheme is the most efficient choice for achieving a desired accuracy, as it is not only more accurate but also allows larger time steps than traditionally used second-order schemes. Delicate numerical simulations for highly complex rotating flows Lopez,Shen,Welfert,Wu (2022); Wu,Welfert,Lopez (2022) are presented to validate the new schemes.



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A parameter study of strato-rotational low-frequency modulations: impacts on momentum transfer and energy distribution

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Abstract

Previous comparisons of experimental data with non-linear numerical simulations of density stratified Taylor-Couette flows revealed non-linear interactions of strato-rotational instability (SRI) modes that lead to periodic changes in the SRI spirals and their axial propagation. These pattern changes are associated to low-frequency velocity modulations that are related to the dynamics of two competing spiral wave modes propagating in opposite directions. In the present exposition, a parameter study of the strato-rotational instability (SRI) is performed using Direct Numerical Simulations to evaluate the influence of the Reynolds numbers, the stratification, and of the container geometry on these SRI low-frequency modulations and spiral pattern changes. The results of this parameter study show that the modulations can be considered as a secondary instability that is not observed for all SRI unstable regimes. The findings are of interest when the Taylor-Couette model is related to star formation processes in accretion disks.

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A review on the transition mechanisms to turbulence in rotating disc boundary layers and cavities.

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Abstract

In his seminal article in 1923, Taylor demonstrated that in a viscous fluid between two coaxial rotating cylinders (Taylor–Couette flow), the curvature of the flow, or, equivalently, the centrifugal force, is a source of instability, potentially leading to vortices stacked in the annular gap (Taylor , 1923). In this work, we are rather interested in the stability of flows in rotating-disk cavities, which can be seen as flattened Taylor–Couette set-ups, of aspect ratios $\Gamma = h/\Delta R \ll 1$, with h the height of the cavity and $\Delta R = R_{out} - R_{in}$ the width of the annular gap. Studied for more than a century in the field of geophysics (Ekman , 1905) and still present in a wide variety of industrial systems to optimize (Launder, 2010), from electronic and automotive industry to turbo-machinery in aeronautics, flows over rotating disks present a great diversity of complex instability behaviours that make them a still attractive and relevant topic of research. While the primary instabilities are now well characterised experimentally, theoretically and numerically, their role in the transition mechanisms to turbulence remains an open question that still challenges the scientific community. In this presentation, we will review the main results of the literature related to the instabilities and the main scenarios currently assumed to describe the flow breakdown to turbulence over rotating single-disks and in rotating cavities, with two generic configurations for this latter: the rotor-stator cavity and the open co-rotating cavity with radial throughflow (Martinand, 2023). Although the cavities have some specificities mainly due to the flow confinement in both radial and axial directions that may introduce some feedback mechanisms between the boundary layers, we will try to show the links that exist between the configurations, both in terms of base flows and instability mechanisms and routes to turbulence that seem to emerge in the most recent studies.

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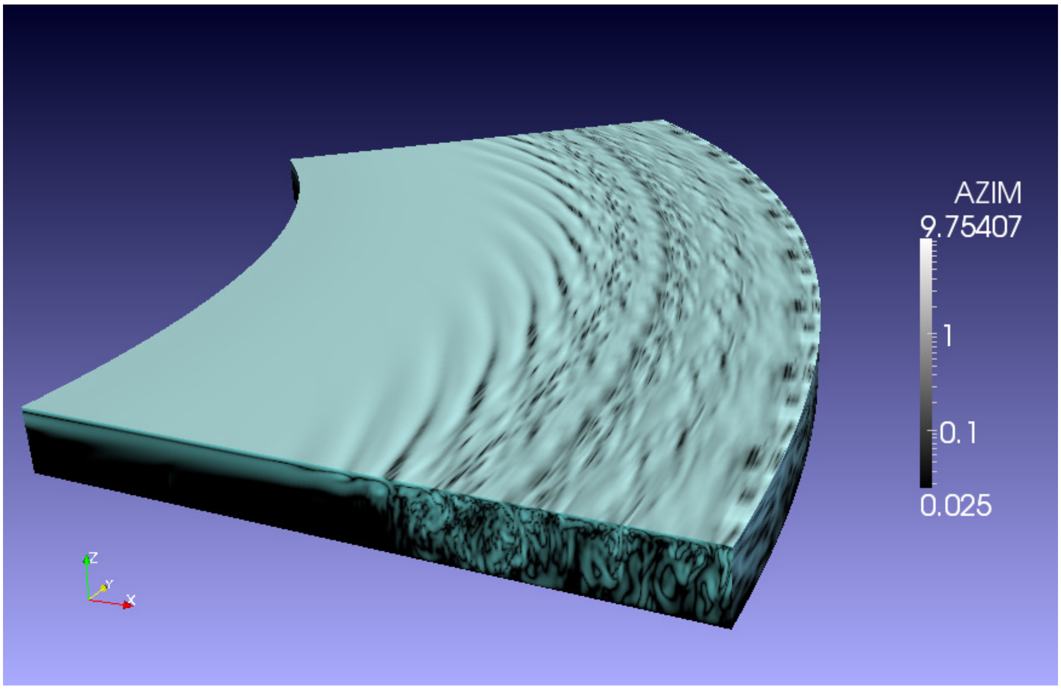

Figure 1: Transition to turbulence in the boundary layer of a rotating disk in an interdisk cavity with forced radial throughflow. Direct numerical simulation showing the vortical spiral structures followed downstream by a disordered state characteristic of turbulence. Velocity fluctuations. Only the upper half-part of the cavity is shown.

A Schwarz domain decomposition method with Legendre collocation applied to the Rayleigh-Bénard convection problem

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Abstract

Spectral methods, like Legendre collocation, are potent but ill-conditioned. Using a Schwarz domain decomposition (DD) method, the Legendre collocation method can be improved, Martínez *et al* (2022). The main idea of the DD method is to split the whole domain into several smaller subdomains where Legendre collocation can be applied. Doing so, coarse meshes can be used in each subdomain, avoiding the ill-conditioning. The total amount of collocation points can be increased by adding more subdomains.

The Rayleigh-Bénard convection problem is modeled with the incompressible Navier-Stokes equations coupled with a heat equation in a rectangular domain, Pla *et al* (2009). A Newton method is applied to eliminate the quadratic term. This approach is then re-arranged at each subdomain. New interface conditions between adjacent subdomains are imposed to guarantee the continuity of the solution. Finally, a Legendre collocation method is used independently over each subdomain.

With DD, Legendre collocation can solve more complex and large problems than using just Legendre. Solutions for large Rayleigh and aspect ratios (Γ) can be calculated (Figure 1). Even turbulence can be reached with DD.

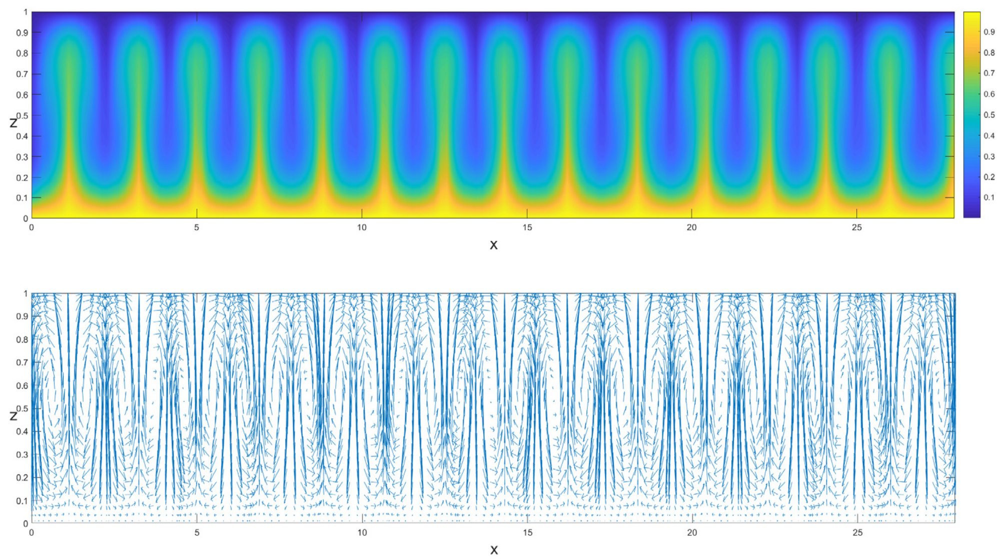

Figure 1: Isotherms and velocity field of a fluid with $Ra = 5000$ and $\Gamma = 27.96$. It was solved with 13×3 subdomains and a collocation mesh of size 18×12 in each subdomain.

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A Taylor-Couette experiment with inner rotating cylinder and applied dielectrophoretic force

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Abstract

The search of efficient methods to improve heat transfer rates in miniaturized system is of main importance in many technical applications. In particular, the use of the dielectrophoretic (DEP) force attracted attention for more than half a century (Landau (2013)). When an electric field is applied to a dielectric fluid, the latest undergoes an electrohydrodynamic (EHD) force. If the electric field applied is alternating with sufficiently high frequency, the EHD force reduces to the DEP force that is due to the differential polarization of particles and can be seen as the action of effective electric gravity on a density stratification. Thermo-electric convection can be induced by the DEP force when the electric Rayleigh number reaches a critical value.

The application of the DEP force is applied in a cylindrical annulus where the inner cylinder is rotating (see figure 1). The combined DEP and centrifugal forces leads to complex dynamic related to various mechanisms, and allows for active control of the circular Couette flow and of the associated heat transfer. An experiment is being built in the Brandenburg Technical University Cottbus-Senftenberg. The experiment set-up will be described, and preliminary results from linear stability analysis will be given.

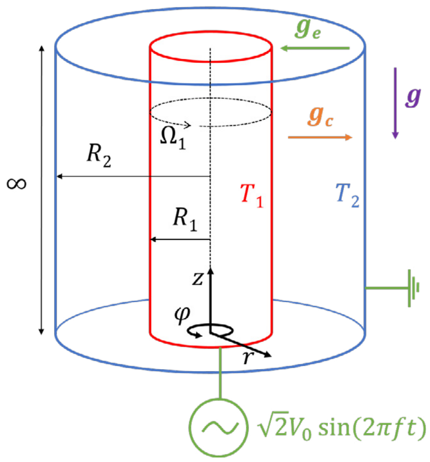

Figure 1: Schematic drawing of the cylindrical annulus with applied temperature difference between inner and outer cylinder, as well as an alternating radial electric field. $\boldsymbol{g}_e$ and $\boldsymbol{g}_c$ represent the electric gravity and the centrigugal acceleration, respectively.

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Angular momentum transport in a very wide gap TC geometry $\eta = 0.1$.

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Abstract

From the early work of Taylor (1923) until today, the TC flow was studied for different geometries, in this study the results are presented for TC flow in very wide gap geometry $\eta = 0.1$ which is rarely studied before Merbold et al. (2023), and the scope of the study is the counter-rotating regime. The flow was investigated for shear Reynolds number $2 \times 10^4 \leq Re_s \leq 1.31 \times 10^5$, and rotation rates $-0.06 \leq \mu \leq 0$. Using a High-speed Particle Image Velocimetry technique, u_r and u_ϕ the radial and azimuthal velocities, are measured at different heights, 10 above and 10 below the apparatus midheight, with axial distance $\Delta z = 4mm$ between each height. From the measured velocities, the dependence of the system's global response which can be quantified by the angular momentum transports, on the rotation ratio is studied. The results show that for the different studied Re_s cases, the angular momentum transport increases for slight counter-rotating rates, and achieves a maximum at $-0.011 \leq \mu_{max} \leq -0.007$, where this increase is due to the strengthening of the Large-scale circulation in the flow. This result is in agreement with the previously studied TC flows in narrower geometries. But in contrast to these studies, the angular momentum transport decreases for higher counter-rotation rates where it achieves a minimum and tends to increase again for higher counter-rotating rates where it is expected to achieve a second maximum as shown in figure 1. The space-time behavior of the flow was studied for the high counter-rotating cases, where we observe the existence of small-scale patterns next to the outer cylinder that travels inward through the gap. From our observations of the flow structures, especially the inward traveling patterns, the existence of a shear layer instability is assumed which causes the increase in the angular momentum transport at this high counter-rotating cases. Further, the spatial two-point auto-correlation coefficient of the azimuthal velocity fluctuation at different radial positions for the flows with different μ was studied. For the highest studied counter rotating case $\mu = -0.06$, the auto-correlation profiles for the flow next to the outer cylinder achieve a minimum for $\phi r/d \approx 1.25$, which is interpreted as the size of the newly observed patterns.

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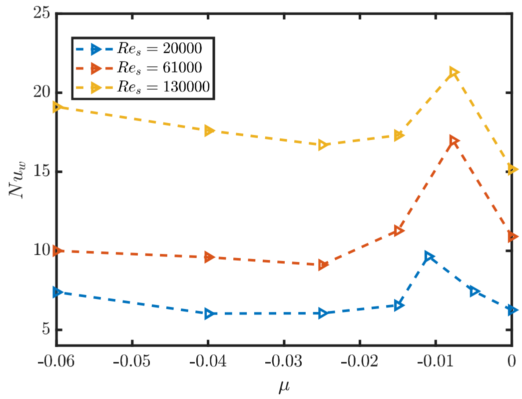

Figure 1: The variation of the angular momentum transport represented by Nu_ω for flow with different Re_s, at different rotation ratios (μ).

Asymptotic Ultimate Regime of Homogeneous Rayleigh-Bénard Convection on Logarithmic Lattices

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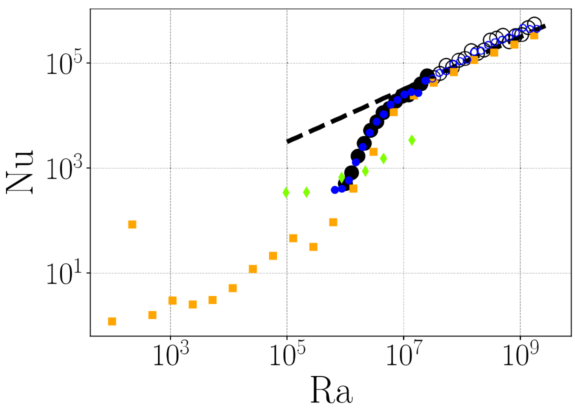
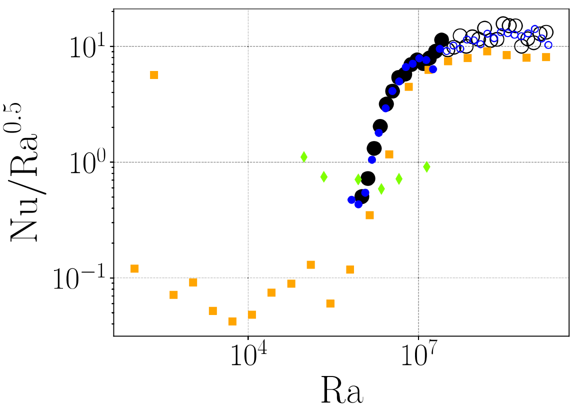
Abstract

We investigate how the heat flux Nu scales with the imposed temperature gradient Ra in Homogeneous Rayleigh-Bénard convection using 1, 2 and 3D simulations on logarithmic lattices. Logarithmic lattices are a new spectral decimation framework which enables us to span an unprecedented range of parameters (Ra, Re, Pr) and test existing theories using little computational power. We first show that known diverging solutions can be suppressed with a large-scale friction. In the turbulent regime, for Pr $\approx$ 1, the heat flux becomes independent of viscous processes ("asymptotic ultimate regime", Nu $\sim$ Ra$^{1/2}$ with no logarithmic correction). We recover scalings coherent with the theory developed by Grossmann & Lohse, for all situations where the large-scale frictions keep a constant magnitude with respect to viscous and diffusive dissipation. We also identify another turbulent friction dominated regime at Pr $\ll$ 1, where deviations from GL prediction are observed. These two friction dominated regimes may be relevant in some geophysical or astrophysical situations, where large scale friction arises due to rotation, stratification or magnetic field.



(a)



(b)

Figure 1: Non-dimensional heat transfer Nu vs Rayleigh number Ra in 3D for Pr = 1. (1a) Nu vs Ra. Filled symbols (resp. open) symbols have been used to discriminate between non-universal (resp. universal) friction dominated regimes. The dotted line corresponds to Nu $\sim \sqrt{\text{Ra}}$, corresponding to asymptotic ultimate regime scaling. (1b) Compensated plot Nu $/\sqrt{\text{Ra}}$ vs Ra.

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AtmoFlow: Convection in spherical shell with atmospheric boundary conditions

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Abstract

Convection of planetary interiors or atmospheres are usually investigated either by observations, numerical simulations or laboratory experiments. Since the early 60s geophysicists have started investigating such large-scale planetary flows with the support of small-scaled laboratory experiments that do not lose the overall physical meaning of the flow dynamics. Test beds have ranged from deferentially heated annuli to spherical shells. However, one of the classical experiment is the thermally driven annulus to investigate the thermal and momentum transport of baroclinic waves see Früh (2014); Scolan (2017). To investigate inner-core or mantel-convection of planets an experiment named GeoFlow was developed and served from 2008 to 2016 several successful runs on the International Space Station (ISS) Futterer (2013); Zaussinger (2013). This particular spherical shell experiment used an electric central force field to mimic terrestrial gravity whereas planetary rotation was performed by spherical shell rotation. Here, we present the followup experiment that is currently built at Airbus Defence and Space and named AtmoFlow. As the name already indicates, the experiment is developed to identify and understand the local formation of global planetary waves that contribute towards the large-scale thermal transport in atmospheres. Three projects phases are defined as no-rotation, solid body rotation and differential rotation. Theses phases arise out of three principles to first understand the electrically induced convection with atmospheric boundary conditions that mimic terrestrial gravitation, second the solid body rotation for planetary atmospheres similar to Earth and Mars and third differential rotation for deep atmospheres such as the Sun, Jupiter or Saturn with their gaseous composition. Here, we present the case for differential spherical shell rotation performed by numerical simulations using a finite volume technique to investigate a suitable parameter range of interest. The parameter space is defined by the rotational forcing and dielectric convective forcing and defined by the Taylor number and the electric Rayleigh number written as

$$Ta = \frac{4\Omega^2 L^4}{\nu^2}, \qquad Ra_E = \frac{e\epsilon_0\epsilon_r \Delta T V_0^2}{\rho\nu\kappa} \tag{1}$$

respectively, where Ω is angular velocity of the outer shell, L the gap width, ν the kinematic viscosity, e the thermal expansion of the dielectric fluid, ϵ_0 the permeability of free space, ϵ_r the relative permeability of the fluid, ΔT the temperature difference, V_0 the electric potnetial, ρ the density and κ the thermal diffusivity. The numerical model is solved dimensionsless using the rotational reference framework. To keep the CFL-number small solid body rotation is added via the Coriolis and centrifugal forces whereas the differential rotation uses a rotating condition at the inner wall. The major focus was to analyse the interplay of the rotational to convective forcing as such this study considered mainly the Keplerian flow regime and the regime close to the Rayleigh line, defined by the aspect ratio, $\eta = R_1/R_2$, and the angular velocity, Ω, of the system. Five differential rotation speeds defined by $\Omega_1 = \Omega_2/\gamma$ with $\gamma = \eta, \eta^{3/2}, \eta^2, \eta^2 \pm 5\%\eta$ and twelve different Rayleigh numbers are investigated for each rotation speed. The arising convective pattern formations are quantified by a Fast Fourier Transform analysis of the dominant convective mode and were classified into four regimes that narrowed the parameter range for the experimental study of the AmotFlow experiment.

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Coherent structures in elasto-inertial Taylor Couette flows

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Abstract

Taylor-Couette (TC) flow, the flow between two concentric cylinders with one or both of them rotating, has been studied extensively in the case of Newtonian fluids or in the case of viscoelastic instabilities. In the case of fluids of significant elasticity and negligible shear-thinning, known as Boger fluids, an abundance of transitions to elasto-inertial turbulence (EIT) have been reported: vortex merging and splitting transition (MST) (Lacassagne et al., 2020), flame-pattern (FP) for fluids of higher elasticity (Latrache and Mutabazi, 2021) or the hysteretic, solitary vortex pairs of diwhirls (DW) (Groisman and Steinberg, 1998). However, despite the extensive numerical work on EIT of TC flows (Song et al., 2021), the experimental work is limited in number and visualization experiments are used in most cases.

We report Particle Image Velocimetry (PIV) measurements of TC flows of Boger fluids. We examine a range of fluid elasticities ($El = 0.057 - 0.341$), in order to resolve the structural properties of the elasto-inertial transitions and turbulent flow states. The experimental data highlight the importance of vortex pairs as structural elements of viscoelastic flows, which based on their stability and interaction lead to different flow states, previously reported in the literature.

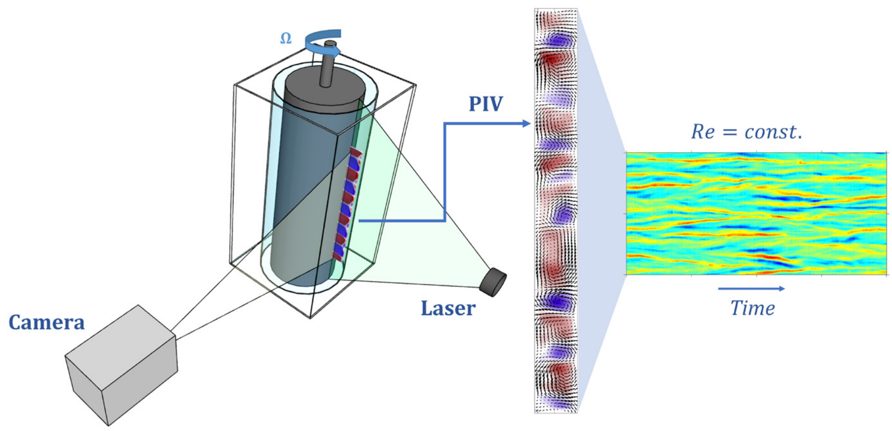

Figure 1: Taylor-Couette cell with Particle Image Velocimetry setup, a typical vector field for EIT and a spatiotemporal map extracted from the radial velocity measurements along the gap centreline. In the map, inflows are denoted by red colour and outflows by blue colour.

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Controlling secondary flows in Taylor-Couette flow using spanwise superhydrophobic surfaces

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Abstract

Turbulent shear flows are abundant in geophysical and astrophysical systems and in engineering-technology applications. They are often riddled with large-scale secondary flows that drastically modify the characteristics of the primary stream, preventing or enhancing mixing, mass, and heat transfer. In this manuscript, we study the possibility of modifying these secondary flows by using superhydrophobic surface treatments that reduce the local shear using experiments and numerical simulations. We focus on the canonical problem of Taylor-Couette flow, the flow between two coaxial and independently-rotating cylinders, which has robust secondary structures called Taylor rolls that persist even at significant levels of turbulence. We generate these rolls by rotating only the inner cylinder of the system, and show that a spanwise superhydrophobic treatment can weaken them by inducing additional secondary flows through surface heterogeneity, as long as the roll size can be fixed. The minimum hydrophobicity of the treatment required for this flow control is rationalized, and its effectiveness beyond the Reynolds numbers studied here is also discussed.

Convection in Salt Lakes

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Abstract

Salt lakes occur worldwide in arid environments and are spectacular geological features, displaying breathtaking patterns on their surface. In these lakes, the only outflow of fluid is due to evaporation and dissolved salts in the groundwater precipitate at the surface, leading to the growth of a salt crust. Under the right conditions, ridges can be observed in the crust, resulting in a remarkable polygonal pattern. Understanding the formation of these distinct polygonal patterns is key to monitoring the dust emission potential of salt lakes. We model salt lakes using a 3D porous medium which is subject to a uniform through-flow, parameterised by the Rayleigh number and the lake depth. This leads to a base state characterised by exponentially-distributed salinity that is unstable for large enough Rayleigh numbers and whose instability leads to buoyancy-driven convection. We simulate the dynamics numerically and analyse the sequential stages of the instability using characteristic properties of the system (e.g. average salinity fluxes, average and dominant pattern wavenumbers). Initially, linear growth away from the base state develops and patterns emerge in the surface flux of salinity. As nonlinearity becomes important, a net transport of salinity away from the surface builds. Eventually, plumes penetrate deep into the domain and the dynamics approach a chaotic but statistically-steady end-state, characterised by patterns which are strikingly similar to those observed in situ.

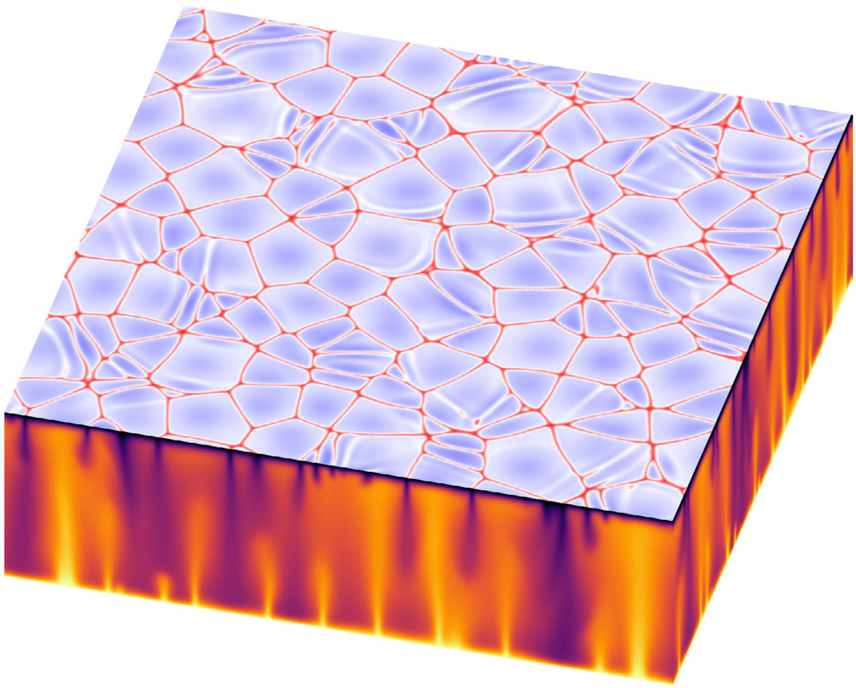

Figure 1: Snapshot of a simulation. Top face shows salinity flux into the surface (positive flux shown in red, negative in blue) and side faces show salinity (high salinity shown in purple, low in yellow).

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Couplings between Taylor vortices and a concentration boundary layer via osmotic pressure

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Abstract

Accumulation of retained material is inherent to separation processes, where a mixture is driven accross a semi-permeable membrane to filter out its constituents, and the source of several physico-chemical mechanisms deteriorating the performances. Dynamic filtration has been proposed for several years as a way to eleviate this accumulation, based on the assumption that hydrodynamic instabilities generated in the flow of carrier fluid will limit the accumulation in the vicinity of the semi-permeable membrane. Whereas improved performances have been experimentally observed, the ways the instabilities transport and remix the accumulated material remain incorrectly explained, because badly understood. A Taylor–Couette cell, whose gap between two semi-permeable cylinders is filled with a solution and swept by a superimposed radial flow, constitutes a good configuration to address the specific mechanism coupling the hydrodynamic instabilities and a concentration boundary layer. As shown in figure 1, all elements are independently controlled in this set-up. The imposed radial flow of pure solvent builds-up a concentration boundary layer which retroacts on the hydrodynamic mostly through the osmotic pressure. Centrifugal instabilities in the form of Taylor vortices are controlled by the rotation of the inner cylinder. The coupling materializes by the stirring of the concentration boundary layer by the vortices and the impact of the osmotic pressure on the dynamics of these vortices. As presented in Ben Dhia et al. (2022), these mechanisms are addressed by dedicated Direct Numerical Simulations carefully capturing the specific boundary conditions on the semi-permeable cylinders and weakly non-linear stability analyses. On the one hand, osmotic pressure is found to destabilize the Taylor vortices. On the other hand, the Taylor vortices are found to increase the transmembrane flux of pure solvent. These two effects can be accounted for by complex mechanisms combining the rejection of the solute at the semi-permeable membrane and the osmotic pressure, putting on firmer grounds the way dynamic filtration works and paving the way for future improvements of the process.

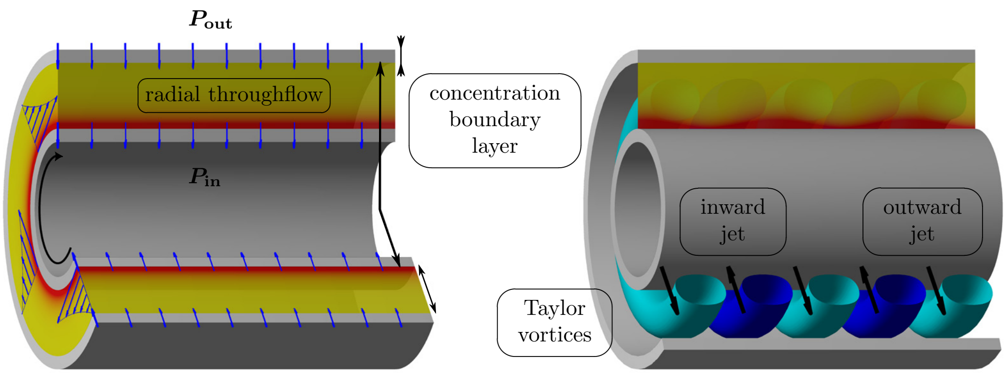

Figure 1: Left: Taylor–Couette cell with semi-permeable cylinders, superimposed radial flow and resulting concentration boundary layer. Right: Taylor vortices, generated by the rotation of the inner cylinder, stirring the concentration boundary layer.

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Decay of Mechanically Driven Axial Counter-Current in a High Speed Rotating Cylinder Using DSMC Simulations

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ABSTRACT

The decay of mechanically driven axial counter-current along the axial direction in a high speed rotating cylinder is studied for wall pressure P_w in the range 20 to 100 m-bar using two dimensional Direct Simulation Monte Carlo (DSMC) simulations [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. The shape & magnitude of the radial-profile of the axial mass flux is investigated quantitatively at various axial locations and the axial-decay is characterized by a universal exponential function with varying exponent & pre-exponential factor based on the wall pressure and hence the hold up. The analysis shows that as the wall pressure is increased from 20 to 100 m-bar, the shift in the inversion point (corresponds to zero axial mass flux) along the axial length is significant ((Pradhan & Kumaran, *J. Fluid Mech*., vol. 686, 2011, pp. 109-159); (Kumaran & Pradhan, *J. Fluid Mech*., vol. 753, 2014, pp. 307-359)). The analysis further indicates that the decay of axial counter-current influences both the flow profile efficiency (E_F) and the circulation efficiency (E_C) to a great extent, and plays an important role in deciding the separation performance of the gas centrifuge machine. The DSMC simulation results are compared with the analytical results for the decay length based on Dirac equation of high speed approximation $(Z_D = (1/ 2\eta)\,(1/(4.82\, A^6))\,((P_{wall}\, M_W)/(R_g\, T))\,(V_\theta\, R^2_{wall})\, [\, 1 + (((\gamma\text{-}1)\, M_W\, V_\theta^2)/(4\, \gamma\, R_g\, T))^2\,]^{1/2}$, and found good agreement (error within 15%). Here, Z_D is the decay length, η is the gas viscosity, A is the stratification parameter $A= (M_W\, V_\theta^2/(2\, R_g\, T))^{1/2}$, P_{wall} is the wall pressure, M_W is the molecular weight, R_g is the universal gas constant, T is the uniform gas temperature, V_θ is the peripheral velocity, R_{wall} is the radius of the cylinder, γ is the specific heat ratio (C_P/C_V), and the parameter B = $(((\gamma\text{-}1)\, M_W\, V_\theta^2)/(4\, \gamma\, R_g\, T))$ represents the ratio of adiabatic force to angular momentum force.

Keywords: High-speed rotating flow, Mechanically driven axial counter-current, Decay length, DSMC Simulations.

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Decomposition of the skin-friction coefficient of incompressible and compressible boundary layers

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Abstract

We show that the integral relation discovered by Fukagata et al. (2002) for the skin-friction coefficient of free-stream incompressible boundary layers simplifies to the von Kármán momentum integral equation when the upper integration bound along the wall-normal direction is taken asymptotically large (Ricco & Skote , 2022). If the upper bound is finite, the weighted contributions of the terms of the streamwise momentum equation depend spuriously on the bound itself. Analogously, the compressible versions of the Fukagata et al. (2002) identity reduce to the compressible von Kármán momentum integral equation. We discuss how the upper integration bound influences the physical interpretation of the terms in these compressible identities. We also prove that the family of infinite identities obtained by successive integrations also reduces to the von Kármán equation and it degenerates to the definition of skin-friction coefficient as the number of integrations grows asymptotically. The dependence on the number of repeated integrations is therefore also non-physical. We close our discussion by presenting the extension of the integral identity found by Elnahhas & Johnson (2022) for incompressible boundary layers to the compressible regime, showing how the contributions of the laminar skin-friction coefficient and the Favre-Reynolds stresses can be isolated (Xu et al. , 2023).

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Different Flow State Transition Processes of Taylor–Couette–Poiseuille Flow Based on Taylor Vortex

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Abstract

In order to investigate the flow state transition with two shear flows orthogonal to each other, we performed direct numerical simulations of Taylor–Couette–Poiseuille flow (TCPF), which is a combination of Taylor–Couette flow and axial pressure gradient drive. The control parameters were the Reynolds numbers Re_{in} and Re_{out}, based on the rotational velocities of the inner and outer cylinders, and the axial pressure gradient function $F(P)$, with a radius ratio of $\eta = 0.883$. It is known that the Taylor vortex appears in a Taylor–Couette flow, under the supercritical transition conditions of inner-cylinder rotation only and co-rotation of both cylinders (Taylor , 1923). However, in TCPF, we found that the flow state transition process for the Reynolds number of these two conditions, which are based on the same phenomenon, undergoes different flow state transitions.

For the first condition with only inner-cylinder rotation ($Re_{\mathrm{in}} = 130$ and $Re_{\mathrm{out}} = 0$), we observed that the Taylor vortex weakens as $F(P)$ increases, resulting in completely laminar flow. However, the flow field becomes unstable again, and the helical turbulence observed in the subcritical transition of the annular Poiseuille flow without cylinder rotation appears (Ishida , 2016). This is consistent with our previous report on the INT-based laminarization (Matsukawa , 2021)—here, INT represents a flow state with intermittent turbulent spots. In the second case ($Re_{\mathrm{in}} = 1000$ and $Re_{\mathrm{out}} = 500$), we observed that the Taylor vortex is noisy as $F(P)$ increases, and the checkerboard-like structure shown in Figure 1 is transformed into a stripe-like structure, leading to turbulence. The former result is interesting because it demonstrates a switch between supercritical and subcritical conditions, while the latter is a novel finding that the Taylor vortex-derived structure forms a checkerboard-like flow field.

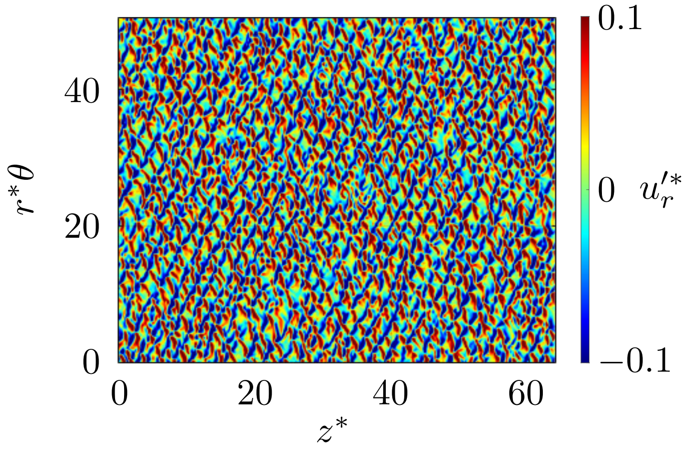

Figure 1: Instantaneous flow field in the z-θ plane visualized by the radial velocity fluctuation $u_r'^*$ at the mid-gap (r^*) for $Re_{\mathrm{in}} = 1000$, $Re_{\mathrm{out}} = 500$, and $F(P) = 5$. The vertical axis is azimuthal, the abscissa is the axial coordinate dimensionless by the gap width, and the pressure-driven flow is in the right direction.

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Direct numerical simulation of viscoelastic turbulent Taylor-Couette flow

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Abstract

Since the seminal work of Taylor (1923), the Taylor–Couette (TC) flow has served as a classic paradigm for studies of flow instability and pattern formation as well as turbulence dynamics in both Newtonian and non-Newtonian fluids. For non-Newtonian TC flows, the interactions between fluid elasticity induced by the viscoelasticity and inertia dramatically changed the turbulence dynamics. In order to study the inertio-elastic effects on the TC turbulence, we have performed extensive three-dimensional direct numerical simulations of viscoelastic TC flows over a broad range of $10^{-4} \leq Re \leq 10^4$ and $0 \leq Wi \leq 120$. Here, the Reynolds number Re and the Weissenberg number Wi are respective dimensionless measures of the inertial and elastic forces. Specifically, the sequence of flow transitions due to a continuous increase of fluid elasticity from classical Newtonian, to inertially and in turn to elastically dominated, and finally to the inertialess purely elastic turbulence, is presented. In each elastically modified turbulent flow state, the drag modification, coherent flow structures, velocity and elastic stress statistics, mechanism of turbulent kinetic energy production, spectral features as well as the self-sustaining cycles of turbulence, are also discussed (see a recent review Song (2023)).

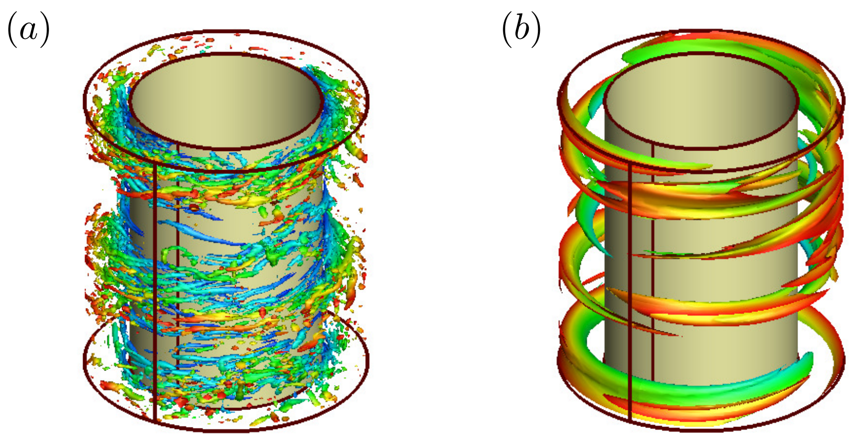

Figure 1: Instantaneous vortical structures visualized by Q-criterion with (a) $Q = 5$ for Newtonian TC turbulence at $Re = 10000, Wi = 0$ and (b) $Q = 0.001$ for inertio-elastic TC turbulence at $Re = 500, Wi = 30$ with only the inner cylinder rotation. The iso-surface is coloured by the distance to the inner cylinder wall.

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Direct path from turbulence to time-periodic solutions

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Abstract

We look for the origin of turbulent stripes in plane-Poiseuille flow by descending slowly in Reynolds number[1]. In domains large enough to allow for full localization, this descent ends around Re $\approx$ 650, below which stripes become short-lived, decaying quickly to laminar flow (Mukund et al., 2021). We avoid this "relaminarization barrier" within the setting of "minimal band units" (Tuckerman et al., 2020): working in a narrow periodic tilted domain where lifetimes of stripes are much larger, we are able to track turbulent stripes down to the onset of chaos. We find that the correlation dimension of the chaotic attractor drops rapidly with decreasing Re. Our descent ends with a stable relative periodic orbit, after which numerical continuation takes over and finds the origin: a lower branch travelling wave (Paranjape et al., 2020).

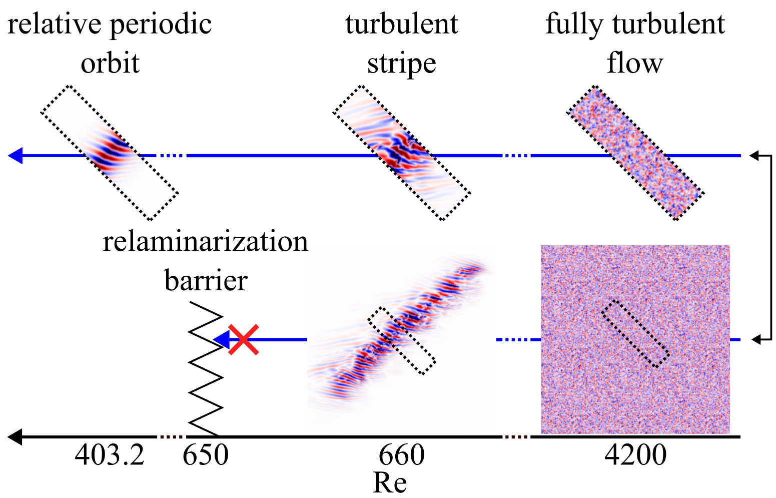

Figure 1: A sketch of the Re descent in a tilted domain vs. large non-tilted domains. Flow is from left to right.

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[1]The non-dimensionalization here is with the laminar centerline velocity, half-gap and kinematic viscosity

Drag modification by surfactant additives in high Reynolds-number Taylor–Couette turbulence

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Abstract

We experimentally investigate the modifications of wall frictional drag and mean velocity profile by the viscoelasticity of fluid in high Reynolds-number Taylor–Couette turbulence both for counter-rotation, i.e. positive angular velocity ratio $a = -\omega_o/\omega_i > 0$, and co-rotation, $a < 0$, of the inner and outer cylinders of a very large facility. Here, ω_i and ω_o are the angular velocities of the inner and outer cylinders. As working fluids, water and a dilute surfactant solution are examined. We conduct systematic measurements of the torque on the inner cylinder with varying a and the inner Reynolds number, $Re_i = r_i\omega_i(r_o - r_i)/\nu = O(10^4)$. Here, r_i and r_o, are the radii of the cylinders, and ν is the kinematic viscosity of fluid. Torque measurement shows that remarkable drag enhancement occurs due to the viscoelasticity of the solution in a relatively lower Re_i-regime, especially for the co-rotation and the pure inner cylinder rotation ($a \leq 0$), as reported by direct numerical simulations for $a = 0$ by Liu and Khomami (2013) and Song et al. (2019). On the other hand, drag reduction is observed at sufficiently high Re_i for $a > 0$. By defining a new Reynolds number, $Re = (r_i\omega_i - r_o\omega_o)(r_o - r_i)/\nu$, based on the shear rate $\dot{\gamma} = (r_i\omega_i - r_o\omega_o)/(r_o - r_i)$ in a bulk region, these results imply that we may understand the drag modification with respect to the time-scale λ of the viscoelasticity both for $a < 0$ and $a > 0$ in a unified manner by considering the Weissenberg number, $Wi = \lambda\dot{\gamma}$, for example. Concerning the modification of the mean azimuthal velocity profile, a remarkable quasi-solid-body rotational flow is sustained in a bulk region for the drag enhancement cases whereas, for the drag reduction cases, the mean flow structure seems to be modified only in the vicinity of the wall. The rotational angular velocity of the quasi-solid-body rotational flow shows a high correlation with the drag reduction ratio. At the workshop, we will present a more detailed discussion about the relationship between the drag modification and the quasi-solid-body rotational flow.

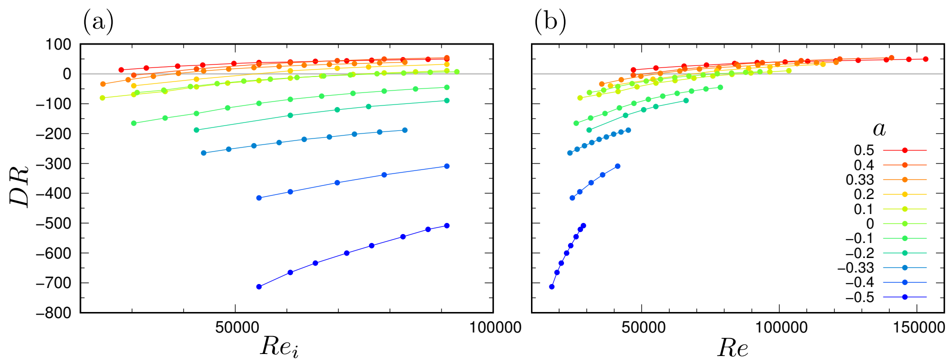

Figure 1: Drag reduction ratio DR, which is estimated from the torque measuments as a function of (a) the inner cylinder Reynolds number Re_i and (b) the Reynolds number Re based on the bulk shear rate. Color indicates the angular velocity ratio a: $a < 0$ and $a > 0$ mean the co- and counter-rotation of the cylinders. Note that remarkable drag enhancement ($DR < 0$) occurs for $a < 0$ while drag reduction does for $a > 0$.

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Dynamics of structures in transition to turbulence

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Abstract

In the transition regime in wall-bounded shear flows, active turbulence is characterized by coherent structures described by streamwise vortices (rolls) and modulations of the streamwise velocity (streaks). We investigate experimentally, in a plane Couette-Poiseuille channel (see figure 1A), the dynamics of these structures and the detailed interplay of their components. We study the decay of turbulence using a 'quench' protocol, i.e. an abrupt decrease of the Reynolds number *Re* from a fully turbulent state to a laminar regime and we show that the rolls decay faster than the streaks (Liu *et al.* 2021). Additionnaly, we investigate the waviness of streaks using vortex generators to induce unstable wavy streaks. We apply a spatial filter to separate the straight part and the wavy part of the streamwise velocity. The normal vorticity from this latter component (wavy vorticity), is used as a quantitative measurement of the waviness of the streaks Spanwise velocity (see (see figures 1B and 1C) is correlated to the increase of the waviness of the streaks, as expected from non-linear self-sustaining models (Waleffe 1997) . For streaks of low waviness, this value is smaller and related to the amplitude of the streak, as expected for linear lift-up.

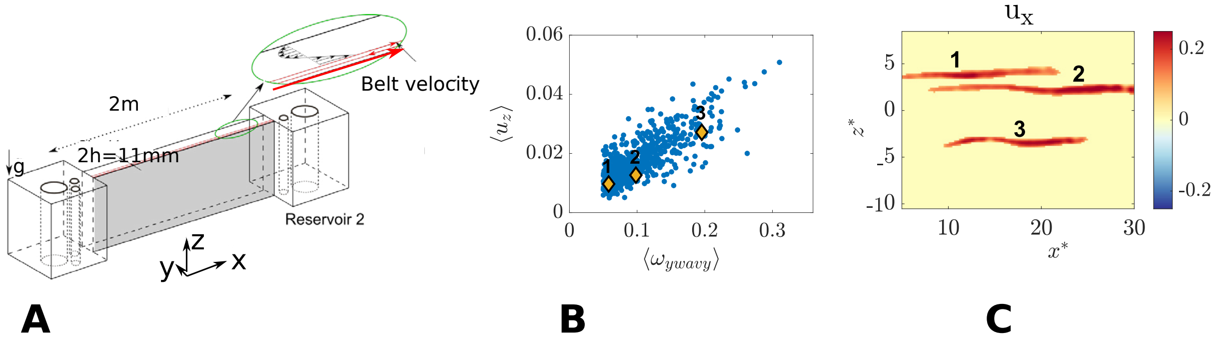

Figure 1: A: schematic view of the experimental set-up. B: Spanwise velocity as a function of the normal wavy vorticity. C: corresponding streaks.

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Effect of thermal diffusion on instabilities of stratified shear flows

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Abstract

In many naturally-occurring and engineering systems where fluid flow is coupled with heat transfer, it is important to understand the role of thermal diffusion. The thermal diffusion is characterised by the Prandtl number $Pr = \nu/\kappa$, which is the ratio between fluid kinematic viscosity ν and thermal diffusivity κ. Depending on situations, Pr varies significantly; for instance, the value of Pr is $Pr \sim O(10^{-6})$ in stellar interior, $Pr \sim O(10^{-2})$ in the liquid metal core of the Earth, $Pr \sim O(1)$ for the air, or $Pr \gg 1$ for oils. At low Pr, high thermal diffusivity tends to suppress the effect of stable stratification, as revealed in the study of shear instability where both the stratification and shear are along the vertical direction (Lignières *et al.*, 1999). Our study aims to explore further the effect of thermal diffusion in other configurations. For instance, we investigate as a first problem the horizontal shear instabilities with stratification in the vertical direction. The topic has relevance to the configuration in stellar radiation zones where the thermal diffusivity is high (i.e. a very small Pr as $Pr \sim O(10^{-6})$). We conduct linear stability analysis for a base flow in the hyperbolic tangent profile, which has two types of instability: the inflection-point and inertial instabilities. In the presentation, it will be discussed how these two instabilities are affected by the high thermal diffusivity (see e.g., Figure 1 and Park *et al.*, 2020). The second topic to be considered is Taylor-Couette (TC) flow with stable stratification in the axial direction. Centrifugal instability of the TC flow is known to be suppressed by the stratification (Boubnov *et al.*, 1995). For stratified TC flow, another instability known as the strato-rotational instability (SRI) also exists when the stratification is strong enough and perturbation is axisymmetric. In the presentation, it will be discussed how the centrifugal instability of stratified TC flow is destabilised while the SRI is suppressed as Pr decreases (Figure 1).

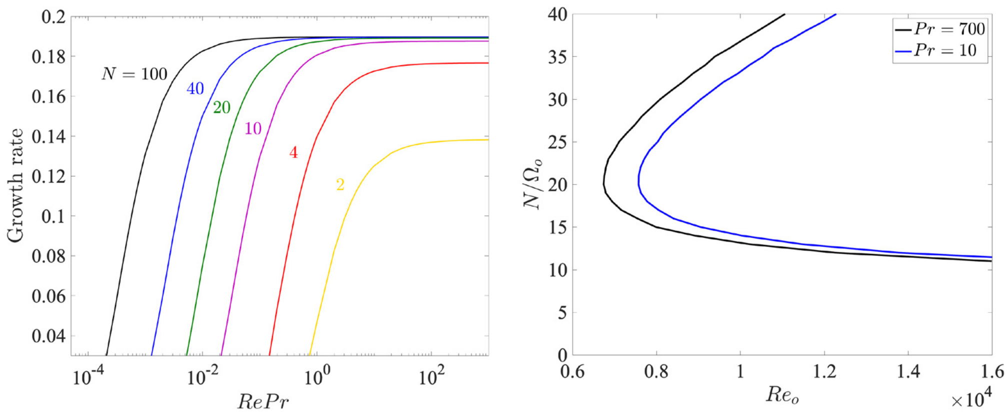

Figure 1: (Left) Growth rate of the inflectional instability versus the Péclet number $Pe = RePr$ for different Brunt-Väisälä frequency N. (Right) Neutral stability curves of the stratified TC flow with $\eta = R_i/R_o = 0.9$ for the SRI when the inner cylinder is at rest ($\Omega_i = 0$).

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Effects of large-scale circulation on two-fluid turbulent Taylor–Couette flows

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Abstract

We perform direct numerical simulations of two immiscible and incompressible fluids in a Taylor–Couette setup by means of the finite difference and the volume-of-fluid methods (see Figure 1 for a visualisation of the typical surface structure). Taylor number is fixed to 10^8, while the volume fraction of the secondary phase and the surface deformability (Weber number) are varied to investigate 1. how the interface modulates the background turbulence, and 2. how the flow fields affect the surface morphologies.

Due to the presence of the secondary phase, the normalised torque is always increased compared to the single-phase flow, which is related to the additional energy required to stretch the surface. We find that the secondary phase prefers to remain in the cores of the Taylor rolls, and this character is obvious for lower volume fraction and lower Weber number cases. Also, due to this concentration in the bulk region, the secondary phase plays little role in the convection of momentum, which describes the clear effect of the Taylor rolls on the dynamics.

When focusing on the independent surface structures, the averaged droplet size as a function of the Weber number reasonably follows the Kolmogorov-Hinze scaling (Kolmogorov (1949), Hinze (1955)). However, because of the large-scale circulation and the resulting wind, we observe that the droplets are more elongated and have more break-up near the walls. This results in the different surface morphologies in the boundary layers and in the bulk, whose spatial dependence is quantified by the local surface curvatures.

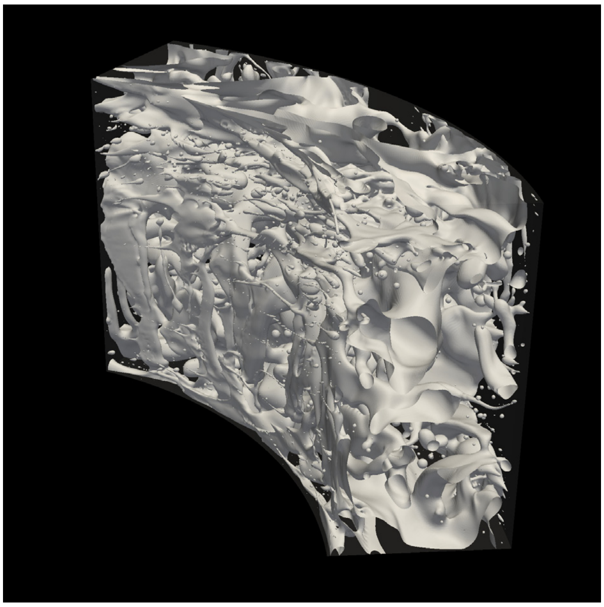

Figure 1: Interfacial structures in turbulent Taylor–Couette flow at $Ta = 10^8$, $\varphi = 30\%$ and $We_\tau = 4$.

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Excitation and evolution of compressible Görtler vortices triggered by elevated freestream vortical disturbances

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Abstract

We study unsteady Görtler vortices excited by free-stream vortical disturbances (FSVD) in compressible boundary layers. The receptivity mechanism in the linear regime has been recently studied by Viaro and Pierre (2019), who showed that compressible Görtler vortices are effectively induced by small-amplitude FSVD. In the present study, the focus is instead on the nonlinear development of compressible Görtler vortices exposed to elevated FSVD. The free-stream Mach number is an order-one quantity. The formation and evolution of the Görtler flow are governed by the compressible nonlinear boundary-region equations, supplemented by appropriate initial and boundary conditions which characterise the impact of the FSVD on the boundary layer. The curvature effect was studied for Görtler vortices excited by FSVD at $Tu = 2\%$ and Mach number 0.69, which refers to typical experimental conditions of turbomachinery applications (Arts , 1990). It is found that low-frequency, i.e. long-wavelength, components of the FSVD are the primary factor in the generation of the Görtler vortices. Although the FSVD consists of vortical disturbances, thermal fluctuations are excited in the boundary layer because of the momentum-energy coupling caused by compressibility. Figure 1 (a) shows the downstream development of the maximum r.m.s. of the streamwise velocity. The concave wall (positive G) is found to destabilise the flow, whereas the convex wall (negative G) has a stabilizing effect. The Blasius base flow is highly distorted by the excited vortices, especially at the outer edge of the boundary layer. Figure 1 (b) shows the nonlinear structure of Görtler vortices excited by the elevated FSVD.

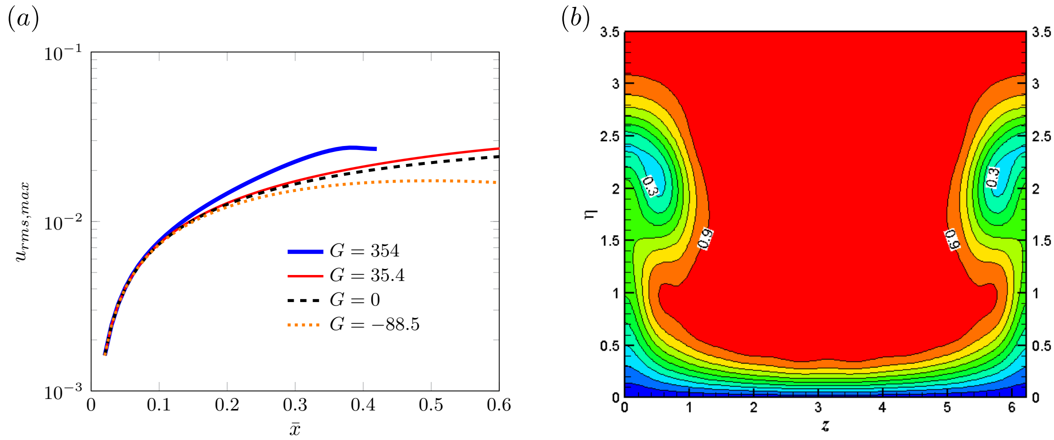

Figure 1: (a) Development of the maximum r.m.s. of streamwise velocity. (b) Contours of an instantaneous streamwise velocity in the $\eta - z$ plane for $G = 35.4$ at $\bar{x} = 1.0$. The increment of the contour values is $0.1U_\infty$.

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Experimental observation of the standard magnetorotational instability in a modified Taylor-Couette cell

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The standard magnetorotational instability (SMRI) has been regarded as the most promising instability responsible for the turbulence required to explain the fast accretion observed across the Universe. However, unlike other fundamental plasma processes such as Alfvén waves and magnetic reconnection which have been subsequently detected and studied in space and in the laboratory, SMRI remains unconfirmed even for its existence long after its proposal, despite its widespread applications in modelling including recent black hole imaging. Its direct detection has been hindered in observations due to its microscopic nature at astronomical distances, and in the laboratory due to stringent requirements and interferences from other processes. Here we report the first direct evidence showing that SMRI indeed exists in a novel laboratory setup where a uniform magnetic field is imposed along the axis of a differentially rotating flow of liquid metal confined radially between concentric cylinders and axially by copper end-rings. Through in situ measurement of the radial magnetic field B_r at the inner cylinder, onset of the axisymmetric SMRI is identified from the nonlinear increase of B_r beyond a critical magnetic Reynolds number. Further analysis reveals that the SMRI is accompanied by a nonaxisymmetric m=1 mode, which is a linear instability having an exponential growth at its onset. Further analysis excludes the possibility that the m=1 mode is the conventional Rayleigh instability or the Stewartson-Shercliff layer instability, implying that it could be a non-axisymmetric version of SMRI that breaks the rotational symmetry of the system. The experimental results are reproduced by nonlinear three-dimensional numerical simulations, which further show that SMRI causes the velocity and magnetic fields to contribute an outward flux of axial angular momentum in the bulk region, just as it does in accretion disks.

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Feigenbaum cascades and one dimensional map reduction in subcritical Taylor-Couette flow

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Abstract

Subcritical transition to turbulence in shear flows is characterised by the coexistence of laminar and non-trivial attractors, both of them stable, leading to metastability and space-time intermittency. As a matter of fact, these transitional scenarios are strongly dominated by exact coherent structures (ECS), i.e. travelling waves and periodic orbits, emanating from saddle-node bifurcations. While ECS upper branches usually participate in the formation of chaotic attractors, lower branches typically exhibit one unstable eigenvalue and act as a separatrix between the basins of attraction of laminar and non-trivial solutions, thus dictating the amplitude of the disturbances triggering transition (Mellibovsky & Eckhardt (2012); Kreilos & Eckhardt (2012)).

First, we study in the subcritical Taylor-Couette flow the process by which the boundary between the two attractors acquires sensitivity to the initial conditions. Near to the saddle-node, we start by confirming the typical scenario described in the literature, where the separation role of the ECS lower branch persists up to a global bifurcation involving a boundary crisis (Ritter *et. al* (2016)). At this point, the global bifurcation causes the lower branch to move off the edge of the basin of attraction of the non-trivial state, so that when increasing the Reynolds number, the role of the edge state is then played by a chaotic saddle that appears independently of the travelling waves. Therefore, we analyse how the subsequent equilibria acting as edge states alternate, and demonstrate the importance of unstable solutions within chaotic saddles for understanding the dynamics.

Finally, we also analyse the stable chaotic attractor for the same parameter range and show that the dynamics can be very well approximated by a reduction in a one-dimensional discrete map on the Poincare section. We report two different period-doubling cascades at the onset of the chaos, being one of them much cleaner than those previously seen in fluid systems, and allowing us to confirm Feigenbaum's universal theory accurately (Feigenbaum (1978)). Moreover, the probability distribution produced by the chaos and the periodic points embedded in it can be reproduced surprisingly well by the one-dimensional map obtained by interpolation. Remarkably, this provides direct evidence for the existence of infinitely many periodic solutions in fluid chaos via Sharkovsky's theorem (Sharkovskii (1995)).

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Ferrofluidic wavy Taylor vortices under alternating magnetic field

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Abstract

Many natural and industrial flows are subject to time-dependent boundary conditions and temporal modulations (e.g. driving frequency), which significantly modify the dynamics compared with their static ounterparts. The present problem addresses ferrofluids (Rosensweig (1985)) in particular wavy vortex flow in Taylor-Couette geometry (Taylor (1923)), with the outer cylinder at rest in a spatially homogeneous magnetic field subject to an alternating modulation ($\mathbf{H} = [H_S + H_M \sin(\Omega_H t)]\mathbf{e}$). Using a modified Niklas approximation, the effect of frequency modulation on non-linear flow dynamics and appearing resonance phenomena are investigated in the context of either period doubling or inverse period doubling. Flow structures of particular interest in the present work are wavy Taylor vortex flows (wTVFs) (Wereley and Lueptow (1998)) (which already have a natural frequency) with main focus on resonance phenomena when the modulation frequency reaches multiples or ratios of the natural, that is characteristic, frequency of the studied flow states.

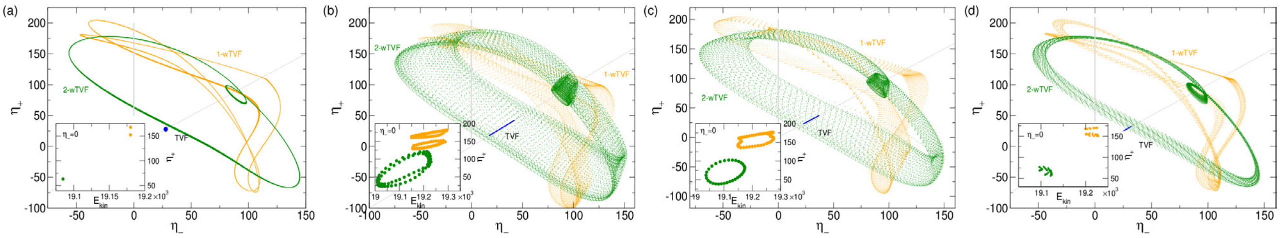

Figure 1: Phase portrait of 1-wTVF and 2-wTVF under axial magnetic field and different driving frequencies: (a) $\Omega_H = 0$, (b) $\Omega_H = 15$, (c) $\Omega_H = 30$, and (d) $\Omega_H = 100$.

If an alternating magnetic field is present, the flow become more complex (Fig. 1). To be precise, the complexity increases by one order. Due to the added time dependence, Taylor vortex flow (TVF) change from fixed point (fp) to limit-cycle (lc(, while 1-wTVF and 2-wTVF change from lc to quasi-periodic (qp) solutions living on a 2-torus (T2). The latter is visible in the observation of closed cycles within the Poincaré sections (E_{kin}, η_+) for $\eta_- = 0$ (insets in figure 1). With variation in the forcing frequency Ω_H of the alternating magnetic field the system undergoes different resonances, when Ω_H reaching integer multiples or ratios of the natural frequency of the wavy vortex flows. For $\Omega_H = 15$, about half the natural frequency for 2-wTVF ($\Omega_H = 30$), period doubling is found (Poincarć section (E_{kin}, η_+) in Fig. 1(b)). For larger Ω_H, after the resonance, the Poincaré sections again illustrate a single circle)(Fig. 1(c). An alternating field with the driving frequency $\Omega_H = 30$ forces the natural frequency of 2-wTVF. Meanwhile, $\Omega_H = 30$ is just double of the natural frequency (half of the period) of 1-wTVF, and one see a resonance with modified dynamics in half the natural period. In some way, this is like an inverse-period doubling described by Hana *et al.* (2016), although here it only appears at discrete frequency Ω_H and afterward disappear again.

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Flow field statistics of the supercritical turbulent spiral in counter-rotating Taylor-Couette flow

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The laminar/turbulent helical pattern (SPT) that arises in the supercritical parameter region of counter-rotating Taylor-Couette flow (TCF) for a narrow-gap system with radius ratio $\eta = r_\mathrm{i}/r_\mathrm{o} = 0.883$ (Andereck et al , 1986) has been studied numerically from a statistical viewpoint. Computations have been done in a parallelogram-annular domain shaped after a coordinate change that aligns one of the sides of the parallelogram with the statistically invariant (parallel) direction of the spiral, tilted 58.1° at midgap with respect to the apparatus axis. Flow field statistics, computed from extremely long time integrations in a frame of reference defined with the method of slices to spatially freeze the large-scale pattern of SPT, exhibit striking resemblance with the subcritical laminar/turbulent stripes observed in plane Couette flow (PCF Barkley and Tuckerman , 2007). Mean fluctuation kinetic energy E_turb concentrates in an azimuthally-drifting helical coil (figure 1a) that pinpoints the statistical location of the turbulent spiral. Within the turbulent core, the swirling motion induced by the transverse perturbation velocity field, illustrated through the streamfunction Ψ (figure 1b), spreads the parallel component of the velocity field U across the full annulus (figure 1c). The mean flow is particularly strong along the spiral fronts, with the extrema of U located precisely at the laminar-turbulent interfaces. The parallel turbulent forces F^U that drive U, which result from the divergence of the Reynolds stress fields, peak within the turbulent region, in the vicinity of both the inner and outer cylinder walls (figure 1d). In contrast with PCF, TCF is not invariant under combined streamwise and wall-normal reflections. While turbulent stripes in PCF are statistically steady, SPT is bound to rotate. Furthermore, there exists a centrifugally unstable region in the neighbourhood of the inner cylinder in the supercritical parameter region of TCF as we have studied. The effects of this centrifugal instability are visible in the fields of E_turb and F^U as elongated streamwise coloured bands extending in the streamwise direction from the turbulent core into the laminar region along the inner cylinder wall. These are the imprints of centrifugally-driven laminar spirals, which seem to play no major role in determining the mean statistical properties of SPT.

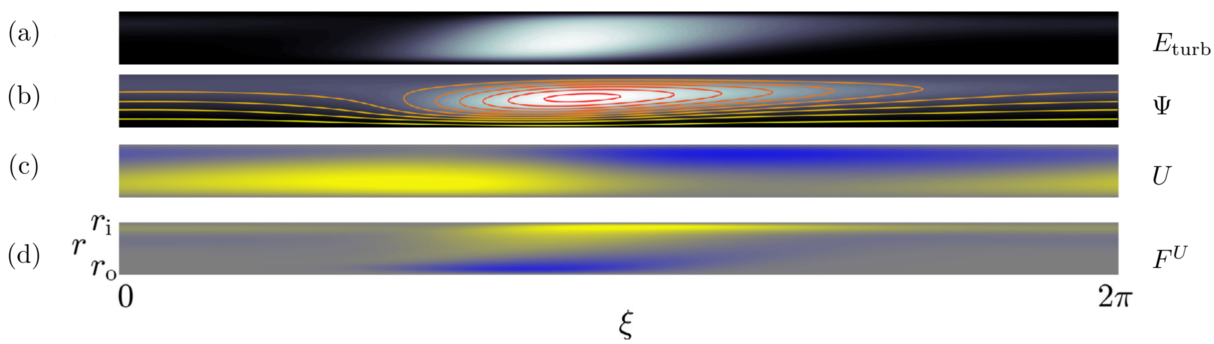

Figure 1: Flow field statistics of supercritical SPT. (a) Fluctuation kinetic energy density E_turb. (b) Streamfunction Ψ. (c) Parallel velocity component U. (d) Reynolds stress force F^U in the helically invariant direction. Colour levels increase from blue to yellow and black to white.

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GeoFlow vs. AtmoFlow: Numerical results

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Abstract

Buoyancy-driven convective flows play a crucial role in geophysics and atmosphere for global heat and momentum transport. We present the main numerical results for the worldwide recognized GeoFlow experiment Futterer (2013), Travnikov (2020) that is performed on the International Space Station (ISS) and AtmoFlow experiment Travnikov (2021) that is in the preparation phase. In both cases, a radial force field is produced due to the dielectrophoretic effect Mutabazi (2016). In the spherical geometry, the buoyancy force is $\sim \mathrm{V}_{\mathrm{rms}}^2 \Delta \mathrm{T} r^{-5}$, where $\mathrm{V}_{\mathrm{rms}}$ is the time averaged amplitude of the potential applied between spherical surfaces. Hence, we deal with the artificial gravity caused by the electric field. Furthermore, in contrast to the classical Rayleigh-Bénard convection, in which the temperature gradient is a control parameter we fix $\Delta\mathrm{T}$ and vary amplitude $\mathrm{V}_{\mathrm{rms}}$, i.e. we change gravity field. The Coriolis and centrifugal forces are taken into account as well. While in the GeoFlow experiment the inner and outer surfaces are maintained at constant temperatures, a laterally dependent thermal boundary conditions are used in the AtmoFlow. It is necessary because the solar radiation is responsible for the differential heating of the Earth's surface: the temperature has a maximin value at the equator and becomes colder in the vicinity of the poles. The flow depends on the Rayleigh number $\mathrm{Ra_E} = \frac{2\epsilon_0 \epsilon_r \gamma}{\rho\nu\kappa} \mathrm{V}_{\mathrm{rms}}^2 \Delta\mathrm{T}$, where ϵ_r is the permittivity, γ is the thermal permittivity, ρ is the density, ν is the kinematic viscosity, κ is the thermal diffusivity and Taylor number $\mathrm{Ta} = (\frac{2\Omega \mathrm{d}^2}{\nu})^2$, where Ω is the rotation rate of the spherical system and $\mathrm{d} = \mathrm{R}_2 - \mathrm{R}_1$ is the spherical gap width with inner radius R_1 and outer radius R_2. These two control parameters define the flow structure. The next important issue is the influence of the internal heating that is taken into account in the energy equation as a source term.

The base state is steady axisymmetric and equatorially symmetric. Whereas the basic flow has only one clockwise rotating vortex caused due to the influence of the centrifugal force in the GeoFlow case, the basic flow in the AtmoFlow project consists at particular $\mathrm{Ra_E}$ and Ta of two counter-clockwise rotating vortices, corresponding to the convective flow near the poles (polar cell) and equator (Hadley cell) which is in accordance with the classical atmospheric model.

Stability of the basic flow was investigated by means of linear theory. Critical Rayleigh number $\mathrm{Ra_{Ec}}$ was calculate as function on the Taylor number for the fixed $\Delta\mathrm{T}$. The new thermal boundary conditions lead to the unexpected dynamical features of the supercritical flows. Critical Rayleigh number increases with increasing in Taylor number in the GeoFlow case according to $\mathrm{Ra_{Ec}} \sim \mathrm{Ta}^{0.7}$ if the internal heating is negligible and according to $\mathrm{Ra_{Ec}} \sim \mathrm{Ta}$ if the internal heating becomes important. But in the AtmoFlow case the stability diagram has a closed shape, i.e. the range, in which the flow is stable to infinitesimal perturbations, bounded by the intervals $(0, \mathrm{Ta_c})$, $(0, \mathrm{Ra_{Ec}})$ and the stability curve.

The specific computer code Hollerbach (2000) based on very exact spectral methods has been developed to enable such investigations in the spherical geometry.

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Growing particles in Taylor–Couette turbulence

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Abstract

For relatively low Reynolds numbers, solid particles inserted in a Taylor–Couette flow with a dissimilar density to the working liquid have been shown to trigger new flow states [Dash et al., 2020, Baroudi et al., 2023]. In contrast, for the fully turbulent case ($\mathrm{Re} = \mathcal{O}(10^6)$) it was found that large solid particles, even for volume fractions up to 6%, have very little effect (within $\pm \approx 1\%$) on the torque required to drive the system [Bakhuis et al., 2018]. We expect, though, that for large volume fraction, where the particle-particle interactions get stronger, or for even larger volume fractions, where granular jamming occurs, that this will no longer be the case and that the drag will increase. To investigate this, we insert expanding particles made from superabsorbent polymers into the Twente Turbulent Taylor–Couette facility [van Gils et al., 2011]. For fixed Reynolds number of $\mathrm{Re} = 10^6$ we will show how the drag evolves over time as the particles absorb water and by this change their size from $d \approx 1.9\,\mathrm{mm}$ to their final size of $\approx 7\,\mathrm{mm}$, and correspondingly the global volume fraction increases.

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Heat transport and friction losses in rapid rotating electrical machinery

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Abstract

Thermal management is one of the key issues for electrified aircraft engines considering the environmental conditions, which vary significantly throughout the flight mission, as well as the stringent performance and safety requirements. A considerable amount of energy is converted into heat within an electric propulsion system by components of electrochemical conversion such as batteries or fuel cells, but also power electronics and electric motors. All of these components are highly sensitive to temperature gradients. The cooling of electric motors plays a crucial role in enabling electrified aero engines, as the gravimetric power density of the motor is highly dependent on the operating temperature. Beside pure air, other viscous and dense fluids or even multiphase sprays are conceivable to be used. Here the enthalpy of evaporation has the potential to significantly increase the power density of the electric motor. However, the effect of a dense fluid in the rotor-stator gap on the overall performance remains an open question to be addressed. The flow between concentric cylinders is well known as Taylor-Couette flow. At rapid rotation, the centrifugal instabilities and turbulent motions could improve the heat advection inside the gap. In contrast to that, an increase of the torque losses of the rotor (Merbold; Froitzheim) is expected. This could, on the one hand, increase the heat flux out of the system and on the other hand significantly reduce its efficiency.

How cooling fluid pumped axially through a rapidly rotating Taylor-Couette system (see Figure 1) affects both the heat transport as well as the friction losses inside an electric machine is investigated in this work. The influence of liquid coolants and multiphase sprays affecting the friction losses of the rotating machine is addressed. Methods to increase the heat transport and prevent high friction losses are designed and tested.

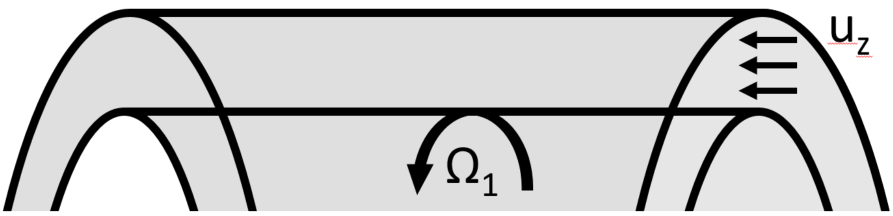

Figure 1: Sketch of the experimental setup.

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How do laminar-turbulent patterns emerge from turbulent shear flow ?

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Abstract

On one hand, the issue of the stability of turbulent shear flows to small perturbations is a long-debate questions in turbulence theory (Reynolds , 1967). On the other hand large-scale laminar-turbulent patterns have long been reported in planar or circular shear flows, and are found at marginally low Reynolds numbers close to turbulence becomes transient (see Figure 1). We reconcile these two concerns here by demonstrating, in the context of plane channel flow, that these laminar-turbulent patterns come from spatial modulations of the fully turbulent flow, themselves explained by a linear instability of the turbulent flow at sufficiently low Reynolds number. This numerical perturbative approach leads to the determination of an effective dispersion relation for the instability modes (Kashyap , 2022). The status of this linear instablity will be discussed for other wall-bounded flows and in the presence of turbulence closure models.

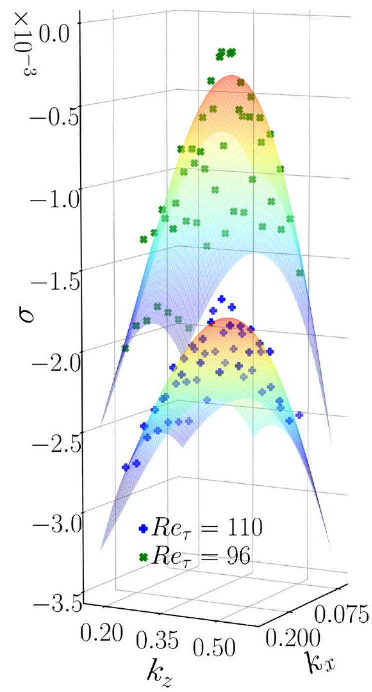

Figure 1: Relation dispersion $\sigma = f(k_x, k_z)$ for two values of Re_τ=110 and 96, with σ the growth rate of perturbations to the turbulent flow and k_x, k_z the streamwise and spanwise wavenumber, respectively.

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Impact of varying nutation angles on precessional flow inside a cylinder

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Abstract

The motion of fluid induced by precession plays a crucial role in a wide range of phenomena and applications, including spacecraft rotation, atmospheric vortices, and the flow dynamics within Earth's liquid outer core. It has also been implicated in the generation of dynamos observed in celestial bodies such as the ancient moon and the asteroid Vesta. The experimental aspect of precessional forcing is particularly fascinating because it offers a natural and efficient method of driving conducting fluid flows on a laboratory scale without needing a propeller or pump.

At the Helmholtz-Zentrum Dresden-Rossendorf (HZDR), the DRESDYN (DREsden Sodium facility for DYNamo and thermohydraulic studies) project is currently in progress, focusing on the construction of a precession dynamo experiment. This experiment involves a cylindrical container filled with liquid sodium, which is capable of rotating at frequencies of up to 10 Hz and precessing around the secondary axis at a rate of up to 1 Hz (Stefani 2019). In order to identify the parameter ranges that facilitate the onset of magnetic field excitation and gain a better understanding of the hydrodynamics involved in a precessing cylinder, a downscaled water experiment has been built (see Figure 1). By utilizing this experimental setup, a series of flow measurements have been performed at various precession angles using Ultrasonic Doppler Velocimetry (UDV). The evaluation of the flow in dependence on the axial and azimuthal directions is carried out through post-processing of the time-dependent measurement data.

Observations from the experiments reveal that the non-axisymmetric mode initially increases as the precession ratio rises, but this mode alone is insufficient to generate dynamo action in the experiment. However, an intriguing finding is the presence of a secondary axisymmetric mode within a narrow range of precession ratios, indicating significant potential for driving dynamo action in larger-scale experiments. This study examines the influence of precession angle and rotation direction (prograde or retrograde) on the dominant flow modes, quantifying their behavior by considering the rotation rate parameterized by the Reynolds number (Re) and the precession ratio ($\mathrm{Po} = \Omega_p/\Omega_c$). Following this, the experimental findings are compared with numerical results (Kumar 2023).

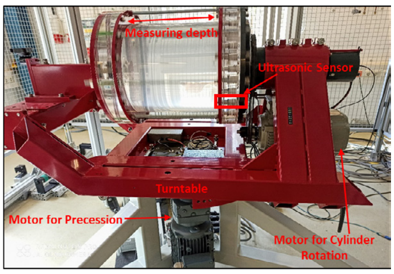

Figure 1: A down-scaled precession water experiment.

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Influence of heat transfers at the free surface of a thermally-driven rotating annulus

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Abstract

Differentially heated rotating annulus experiments are known to be able to mimic, at a laboratory scale, baroclinic waves related to the synoptic-scale perturbations in the mid-latitude atmosphere. Recently conducted experiments showed that the use of cavities with a shallow fluid depth seems to be able to reproduce some specific phenomena like inertia-gravity waves emission (3). The choice of experimental design with a large free surface leads to a more intense interaction between the free surface and its surrounding environment. Here we raise the issue on the impact of the free surface on the dynamics of the baroclinic flow. In particular, we focus on the influence of free surface heat transfer on the shallow baroclinic cavity considered in the paper of Rodda *et al.*(2). Newton's law is used to model the heat transfer, introducing two parameters: the heat exchange coefficient h and the ambient temperature T_q. Using Direct Numerical Simulation (1), we highlight the influence of the ambient temperature on the flow dynamics in the form of two mechanisms. Figure 1 shows several snapshots of the surface temperature, highlighting the diversity of patterns as a function of the parameters. First, we found that a sufficiently high ambient temperature leads to the suppression of baroclinic waves. Second, we observed that an ambient temperature lower than the average temperature of the cavity leads to the production of small fluctuations near the free surface.

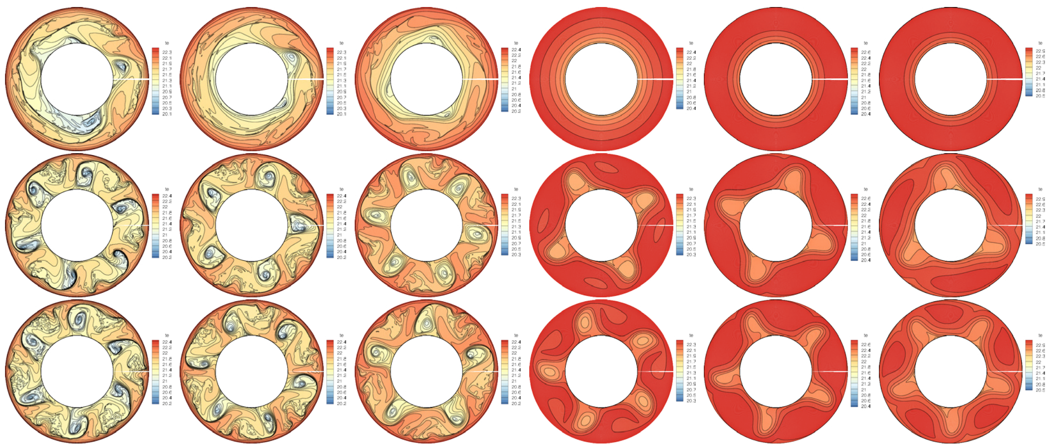

Figure 1: Influence of the surrounding temperature on the onset of baroclinic instability. Snapshots of the temperature surface by increasing the surrounding temperature from left to right $13.5 \leq T_q \leq 27.5°C$, and increasing the rotation rate from top to bottom $0.4 \leq \Omega \leq 0.6\, rpm$.

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Instabilities around a differentially rotating ellipsoid embedded in a rotating stratified fluid

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Abstract

To better predict Earth's climate evolution, the CO_2 and heat fluxes between the oceans and the atmosphere must be taken into account. These fluxes are governed by the vertical mixing in the ocean. But the measured mixing rate is 10 times smaller than necessary to balance the energy budget of the oceans: this calls for new, local mechanisms of mixing. At the edge of meso-scale eddies, an horizontal layering is observed, corresponding to density steps Hua et al (2013). This is a local signature of an increased vertical mixing. To quantify its influence we need to determine the origin of the underlying instability/ies.

To model this geophysical flow, a heated solid ellipsoid differentially rotates anticyclonically in a rotating stratified medium. We numerically and experimentally study this setup to assess the intensity and the structures of instabilities around the ellipsoid in the different regions of the Rossby, Froude, Ekman, Prandtl and Schmidt numbers space.

The numerical analysis is conducted using the pseudo-spectral eigenvalue problem solver Dedalus dedalus (2020). The experimental apparatus uses a rotating cylindrical tank of 1 m in diameter. The base flow is analytically computed for any aspect ratio from 0 to infinity. Various types of instabilities are observed, including baroclinic, double diffusive, convective and centrifugal ones, see e.g. Fig. 1. Their efficiency and relevance to explain the observed mixing are systematically assessed.

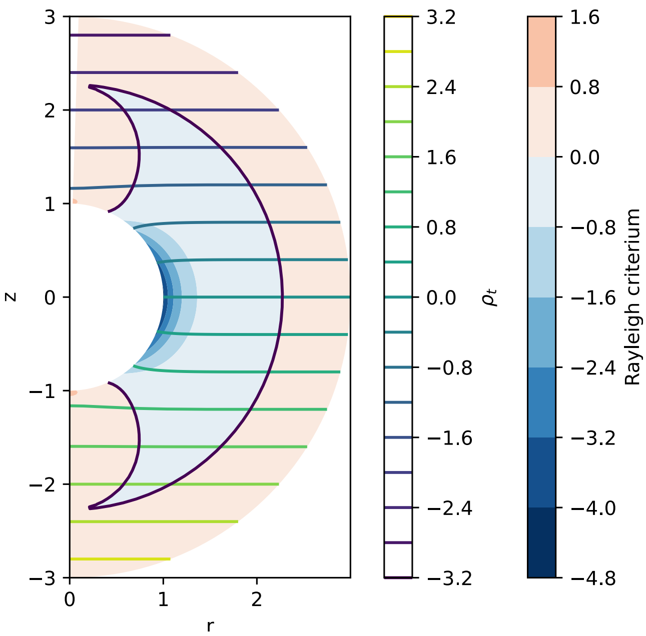

Figure 1: Rayleigh criterion map around a rotating sphere for Ro $= -10$, Fr $= 0.32$.

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Instability modes in viscoelastic Taylor-Couette flows with different rotation regimes

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Abstract

Different instability modes are predicted and observed in the viscoelastic Taylor-Couette flows for different rotation regimes of the cylindrical annulus. The inner cylinder has the radius a, the radius of the outer cylinder b, the angular frequency of the inner cylinder is Ω_i, that of the outer cylinder is Ω_o. The basic solvent is a mixture of water and PEG (polyethylene glycol) to which we have added PEO (polyethylene oxyde) in different concentrations up to $1000\,ppm$ to generate working solution of density ρ, kinematic viscosity ν. The PEG has been added in order to obtain very viscous solvent to ensure almost constant viscosity of the solution. Viscoelastic solutions with constant viscosity are called Boger fluids and can be described by the Oldrody-B model (Bird (1977); Larson (1992)). Rheological measurements have allowed to determine the viscosity ν and the relaxation time τ of the solution (Bai (2023)). The control parameters are the rotation ratio $\mu = \Omega_o/\Omega_i$, the Taylor number $Ta = Re\sqrt{d/R}$ where $Re = \Omega R d/\nu$ with $R \in [a, b]$ depending on the rotation of the inner or the outer cylinder, the viscosity ratio $S = \nu/\nu_0$ and and elasticity $E = \tau/\tau_\nu$. Linear stability analysis has allowed to determine the diagrams of critical states in the plane (E, Ta) for different rotation regimes (Bai (2015, 2022, 2023)) : $\mu = 0$, $\mu = \eta^{3/2}$, $\mu = \eta^3$ and $\mu = \infty$. Experiments have confirmed theoretical results in most of cases. Three different states have been confirmed : stationary vortices analog to Taylor-vortices for low values of the elasticity E, disordered patterns for large values of E (see Figure 1) and ribbons states formed of counter-propagating spirals for intermediate values of E (Latrache (2016, 2021)). The role of viscosity ratio has been analyzed in more details. In the case of the sole rotating inner cylinder ($\mu = 0$), the evolution of the ribbons states and of the disordered vortices has been characterized using PIV measurements.

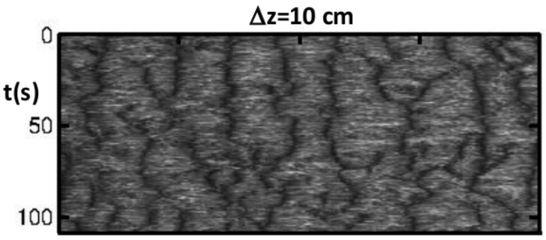

Figure 1: Space-time plot of disordered patterns

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Instability of spiral Poiseuille flow with either inner or outer cylinder rotation.

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Abstract

Spiral Poiseuille Flow (SPF) refers to the flow between two concentric cylinders, induced by cylinder rotation and an axial pressure gradient. This flow can result in Tollmien-Schlichting type and centrifugal instabilities (Meseguer & Marques 2002; Cotrell & Pearlstein 2004). The stability of the SPF, with either a rotating inner cylinder (IRSPF) or a rotating outer cylinder (ORSPF), is of great interest from both theoretical and practical perspectives. The IRSPF is characterized by a centrifugally unstable azimuthal flow, while the ORSPF is characterized by a centrifugally stable azimuthal flow. Despite this difference, we have found that the stability behavior of the IRSPF and ORSPF exhibits a remarkable similarity at low and intermediate swirls. However, both cases differ significantly at higher rotation rates. To study this problem, we formulated it using a curvature parameter and a swirl parameter, which describes the ratio between the azimuthal and axial velocity. Using linear stability analysis, we conducted extensive computations covering 77 (IRSPF) and 108 (ORSPF) different values of the curvature parameter ranging from 0.0025 to 0.785. The swirl parameter range considered was from 10^{-5} to 10^{5} for both the IRSPF and the ORSPF. The results were used to generate phase maps, which fully cover the stability behavior of both flow cases as a function of curvature parameter and swirl parameter. For the first time, we introduced a method to analyze and identify instability mechanisms. Specifically, we analyzed the budgets of the Reynolds shear stresses and used the concept of the critical layer for non-axisymmetric disturbances. Using these identification methods, we were able to identify three regions associated with different instability characteristics in the phase maps. We found that within the first region, a Tollmien-Schlichting mechanism was present, while in the second region, a centrifugal instability mechanism was present for both the IRSPF and the ORSPF. The centrifugal instability mechanism led to a sharp decrease in the critical Reynolds number with increasing swirl parameter. In the third region, the stability behavior of the IRSPF and ORSPF differed significantly. It was shown that the underlying reason for this difference is that centrifugal effects have an opposite effect on the production of Reynolds shear stresses in the IRSPF and ORSPF within the third region.

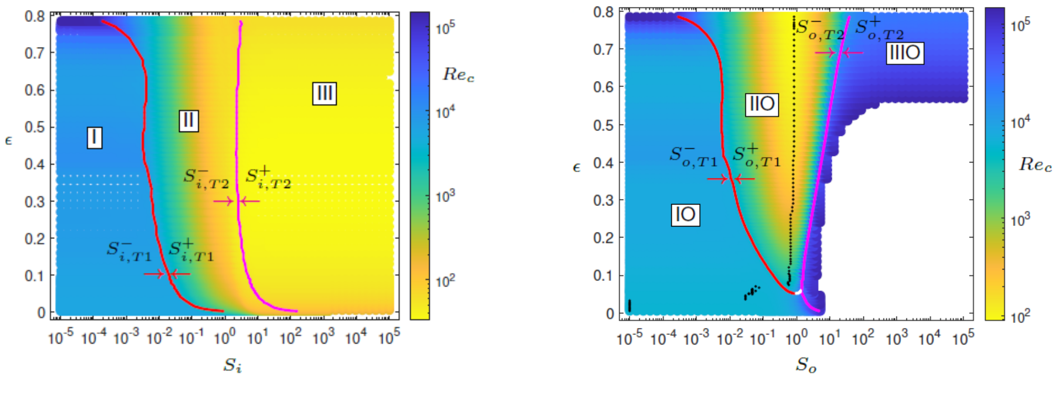

Figure 1: Critical Reynolds number (Re_c) as function of curvature parameter ϵ and swirl parameter (S_i, S_o). a) IRSPF b) ORSPF

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Laminarising turbulence by minimising transient growth

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Abstract

Turbulent friction drag is an important factor limiting the performance of many fluids engineering systems, which has led to extensive research for both active and passive methods for drag reduction. Kühnen (2018) found that a flattened base profile can make the turbulence decay, and attributed this to reduced transient growth. Transient growth, related to the non-orthogonality of normal modes, is thought to be essential for sustaining turbulence for linear stable flow. Motivated by these points, this paper adopted the recent development of variational methods to design the optimal base flow by minising transient growth, to eliminate turbulence at $Re = 2400$ and $Re = 3000$. The body force is then calculated corresponded to the modified optimal base flow and introduced to transient turbulence. 30 arbitrary turbulent initial conditions are used to check the robustness of the body force. The flattened base profile which can laminarise turbulence is firstly reproduced theoretically by reducing optimal transient growth in $m = 1$ at $Re = 2400$. A quite promising net-power saving (about %33) is obtained, while the most net-power saving of the body force constructed by Song (2014) can achieve is about %32. Further attempt to eliminate turbulence at $Re = 3000$ failed when optimisation reduces transient growth of only the first azimuthal wave number. It is found that the base flow constructed by Song (2014), which is proved to be efficient for laminarising turbulence, reduces the transient growth of all low azimuthal wave numbers. Inspired by this point, it is realized that the streaks of higher wave number ($m > 1$) may be still *active* enough to sustain turbulence. With increased Reynolds number, the wave number of the active streak becomes larger. Thus, the key point to eliminate turbulence is making sure that all active streaks cannot be sustained. To achieve this, it is necessary to figure out to what extent the transient growth should be reduced to prevent the formation of an active streak. The minimal-unit numerical experiment is taken then to find this critical transient growth at $Re = 3000$. The full, half pipe, one third and quarter pipe are used to find the threshold of transient growth of $m = 1, 2, 3, 4$. When a quarter pipe is used, the turbulence cannot be sustained, meaning the streaks of first three wave number are active at this Reynolds number. The variational method is adopted again to design the base flow, with a new objective functional constructed to achieve reducing the transient growth of each active wave number. The results show that the body force calculated according to the optimal base flow can effectively laminarise turbulence at $Re = 3000$. Also, a little higher net-power saving (about %28) can be obtained, compared with the body force designed by Song (2014)(about %27). Although the net-power saving of our body force does not improve a lot, the significant outcomes are the theoretical method we used to construct the base profile and the deeper understanding to the sustaining mechanism of turbulence.

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Local instabilities of a circular Couette flow in a vertical annulus with a radial heating

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Abstract

In many physical and engineering applications one needs to consider an axial flow together with the azimuthal motion to model, e.g., tornadoes, trailing vortices, and swirling flows in combustion chambers. In addition, radial temperature gradient needs often to be taken into account in the studies of tropical cyclones (Emanuel , 2018) and flows in cyclone cooling systems of gas turbines (Seibold et al. , 2022).

The problem of stability of helical flows without thermal gradient, in a pure hydrodynamical setting, has been studied earlier, e.g. by Leibovich and Stewartson (1983) who considered the problem for an unbounded, homogeneous and incompressible inviscid fluid subject to infinitesimal three-dimensional disturbances. By using an asymptotic analysis for large azimuthal wavenumbers, they were able to obtain a sufficient condition for instability, generalizing the Rayleigh criterion for centrifugal instability. Eckhoff (1984) extended the criterion to inviscid and compressible flows with geometric optics approach of Eckhoff and Storesletten (1978). Billant and Gallaire (2013) derived a unified criterion for the centrifugal instabilities of vortices and swirling jets recovering the Eckhoff-Leibovich-Stewartson (ELS) criterion when the axial flow is finite and its profile is sufficiently different from the angular velocity profile.

In (Kirillov and Mutabazi , 2017) the method of geometric optics stability analysis has been applied to the linear stability of circular Couette flow with a centrifugal buoyancy induced by a radial temperature gradient in the absence of natural gravity (Meyer et al. , 2021). Axisymmetric and nonaxisymmetric perturbations were considered and both the thermal diffusivity and the kinematic viscosity of the fluid were taken into account revealing instabilities both at low and high values of the Prandtl number, including the visco-diffusive version of the Goldreich-Schubert-Fricke (GSF) instability.

In the present work, a short-wavelength local stability analysis is performed of a helical base flow of an incompressible viscous fluid with radial temperature gradient and an Archimedean buoyancy, see e.g. (Yoshikawa et al. , 2013), in an attempt to further extend the ELS criterion. In particular, a newly derived explicit generalized Rayleigh criterion that combines the ELS criterion for instability of helical flows and the GSF criterion for the instability of azimuthal flows with radial temperature gradient, will be presented. Comparison will be made with available results from linear stability analysis (Meyer et al. , 2015), direct numerical simulations and from experiments (Guillerm et al. , 2015; Kang et al. , 2022) for a fixed value of the radius ratio ($\eta = 0.8$).

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Localized layers of turbulence in stratified horizontally sheared Poiseuille flow

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Abstract

This article presents a numerical analysis of the instability developing in horizontally sheared Poiseuille flow, when stratification extends along the vertical direction. Our study builds up on the previous work that originally detected the linear instability of such configuration, by means of experiments, theoretical analysis and numerical simulations (Le Gal et al., 2021). We extend hereafter this former investigation beyond linear theory, investigating nonlinear regimes with direct numerical simulations for a Froude number of 2 and a Schmidt number of 1. We notice that the flow loses its vertical homogeneity through a secondary bifurcation, due to harmonic resonances, and further describe this symmetry-breaking mechanism in the vicinity of the instability threshold. When departing away from this limit, we observe a series of bursting events that break down the flow into disordered motions driven by localized shear instabilities. This intermittent dynamics leads to the coexistence of horizontal localized layers of stratified turbulence surrounded by quiescent regions of meandering waves as can be observed on Figure 1.

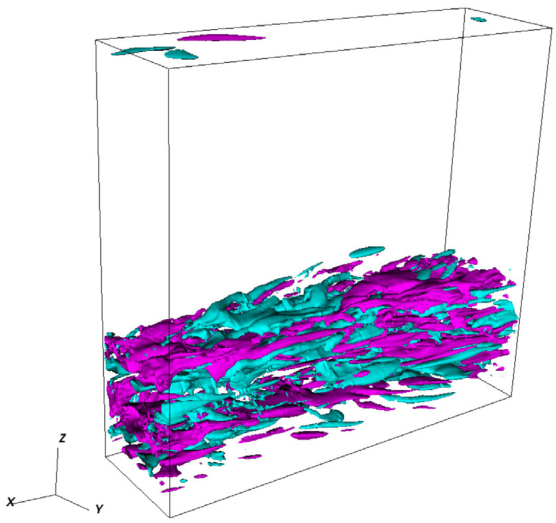

Figure 1: Turbulent layer of the stratified Poiseuille flow simulated by our numerical computation at a Reynolds number Re = 5000. It represents the associated iso-contours of wallnormal velocity. Positive (negative) iso-contours are represented in light purple (light blue) regardless of their magnitude.

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Longitudinal instability in start-stop Taylor–Couette flow

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Abstract

Applying a rapid start-stop to the outer cylinder of the Couette–Taylor system, structures approximately aligned with the axis have been observed. In recent experiments the instability has been observed to arise during the decelerating phase. It was observed only with a narrow gap ($\delta = 6$ mm, $r_i/r_o = 0.97$), and the dependence of the wavelength on the initial acceleration rate was recorded.

Here we report numerical observation of this instability. It is found that linear instability exists in 2-dimensional (z-independent) calculations, but that it could easily be missed in this idealised case – the component of the perturbation which grows rapidly during the deceleration phase is rapidly destroyed in the acceleration phase relative to other disturbances, and is thus swamped. Introducing the disturbance at later stages helps to isolate the growing mode.

In the classic work of Coles (1965), similar instability was observed, but mentioned only in passing. In a footnote, its appearance was attributed, 'probably', to Tollmein instability. Initial calculations suggest this to be unlikely, given a discrepancy of wavelengths, but further calculations are in progress. We briefly discuss the instability with respect to other unsteady Taylor–Couette flows, with modulated cylinder rotation or abrupt stoppage, e.g. Singh and Prigent (2021)

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MHD turbulent Taylor-Couette flow with end walls in axial magnetic field

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Abstract

Turbulent Taylor-Couette (TC) flow of liquid metal in the axial magnetic field is performed to understand the effect of the Hartmann number (Ha) proportional to the magnetic flux density. The inner cylinder rotates and the outer one is at rest, whereas the end walls, i.e., upper and lower walls, are stationary. The radius ratio, aspect ratio and Reynolds number are set to 0.5, 1.0 and 8000, respectively. Large-eddy simulation is conducted using the coherent structure model for the subgrid-scale stress tensor proposed by Kobayashi (2005) which realizes the laminarization by the Lorentz force as seen in Kobayashi *et al.* (2012).

Figure 1 shows vortex structures extracted by the iso-surfaces of the second invariant $Q = 0.25$ of velocity gradient tensor for $Ha = 0$, 50, 70 and 100, where a positive Q value indicates vortex structures At $Ha = 0$, the orientations of the vortices exhibit in the azimuthal direction owing to the stretching by the mean shear flow. At $Ha = 50$, the vortices are suppressed by the Lorentz force. For $Ha = 70$ and 100, the orientations of the vortices change to the axial direction. The vortices become the so-called quasi-two-dimensional (Q2D) vortices that align to the direction of the applied magnetic field as explained in Sommeria & Moreau (1982). It is found that the Q2D vortices emerge even in the TC flow. Figure 2 visualizes the contours of instantaneous azimuthal velocity in the vicinity of the inner wall for $Ha = 0$, 50, 70 and 100. For $Ha = 0$ and 30, the high and low-speed streaky structures are advected with the flow velocity. For $Ha = 70$ and 100, the low-speed streaky structures are suppressed and the high-speed streaky structures have triplet structures. Those structures move slowly although the flow velocities near the inner wall are higher than those for $Ha = 0$ and 50.

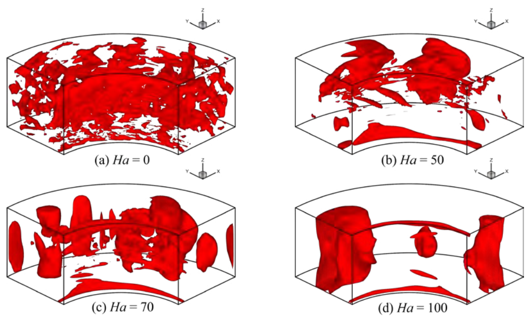

Figure 1: Iso-surfaces of the second invariant $Q = 0.25$ of velocity gradient tensor for $Ha = 0$, 50, 70 and 100.

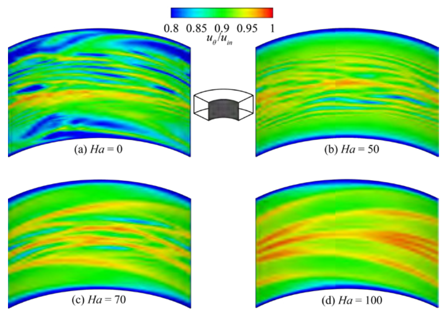

Figure 2: Contours of instantaneous azimuthal velocity in the vicinity of inner wall for $Ha = 0$, 50, 70 and 100.

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Multiple states in turbulent large-aspect-ratio thermal convection: What determines the number of rolls?

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Abstract

Recent findings suggest that wall-bounded turbulent flow can take different statistically stationary turbulent states, with different transport properties, even for the very same values of the control parameters. What state the system takes depends on the initial conditions. Here we analyze the multiple states in the large-aspect ratio (Γ) two-dimensional turbulent Rayleigh–Bénard flow with no-slip plates and horizontally periodic boundary conditions as a model system. We determine the number n of convection rolls, their mean aspect ratios $\Gamma_r = \Gamma/n$, and the corresponding transport properties of the flow (i.e., the Nusselt number Nu and Reynolds number Re), as function of the control parameters Rayleigh (Ra) and Prandtl number (Pr). The effective scaling exponent β in $Nu \sim Ra^\beta$ is found to depend on the realized state and thus Γ_r, with a larger value for the smaller Γ_r.

By making use of Poincaré–Friedrichs inequalities, one can derive that for two-dimensional Rayleigh–Bénard convection with no-slip boundary conditions at the plates, Γ_r can take values only within a quite restricted range, $0.6 < \Gamma_r < 1.7$ (see section V-B in Ref. [1]). For specific values of Ra and Pr, this estimate can be refined, which leads to a more precise Γ_r window for the realizable turbulent states, see Ref. [2]. The theoretical results are in excellent agreement with our numerical finding $2/3 \le \Gamma_r \le 4/3$, where the lower threshold is approached for the larger Ra [2].

We currently plan to extend the method to Taylor–Couette turbulence, where we also expect to find multiple states with Taylor number dependent roll aspect ratios Γ_r, as experimentally found in Ref. [3] for a strongly turbulent case.

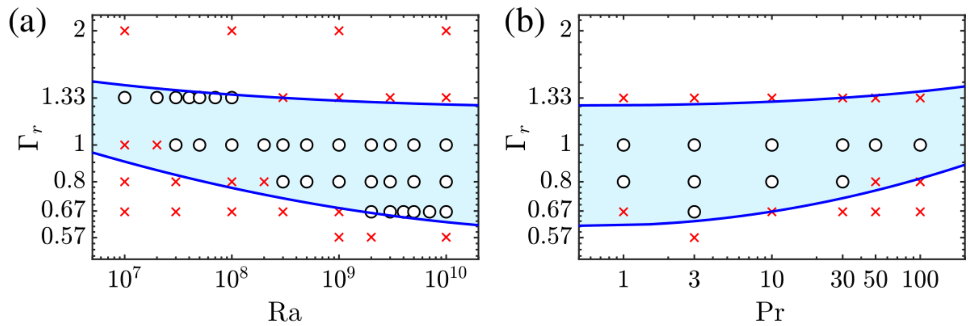

Figure 1: Phase diagram in the (a) $Ra - \Gamma_r$ and (b) $Pr - \Gamma_r$ parameter space for no-slip boundary conditions: (a) $Pr = 10$, $\Gamma = 8$; (b) $Ra = 10^9$, $\Gamma = 8$. Black circles denote that the corresponding roll state is stable, whereas red crosses mean that it is not stable. The theoretical estimates for the transitions between the regimes are shown as solid lines. Adapted from Ref. [2].

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New laboratory experiments to study the large-scale circulation and climate dynamics

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Abstract

The large-scale flows of the oceans and the atmosphere are driven by a non-uniform surface heating over latitude and rotation. The former is responsible for large-scale convective processes like the Hadley cell. The latter generates the atmospheric westerlies. The differentially heated rotating annulus experiment includes both effects, convection and rotation, and is considered as an analog to the large-scale atmospheric circulation. In this experiment, in contrast to the Taylor-Couette (TC) setup, the azimuthal mean flow is generated by the radial heating contrast and not by differential rotation. The experiment has much in common with radially heated TC systems. However, to reach similarity with the atmosphere, the aspect ratio between height and width needs to be small.

Here we contrast two rather new experiments particularly designed for studying the atmospheric large-scale circulation. One of the experiments, the differentially heated rotating annulus at BTU Cottbus, has a classical “Hide-setup” with an cooled inner cylinder and a heated outer wall (2). However, the atmosphere is characterized by heating at the bottom in the tropics and cooling at the top of the polar latitudes. This particular forcing is not correctly reproduced in the Hide-setup and this motivates to use a design that includes heating and cooling at different vertical levels (3; 4). We compare results from both experimental designs, showing common features but also qualitative and quantitative differences. We further present data that highlight the usefulness of the experiments in the context of climate dynamics and extreme events (1).

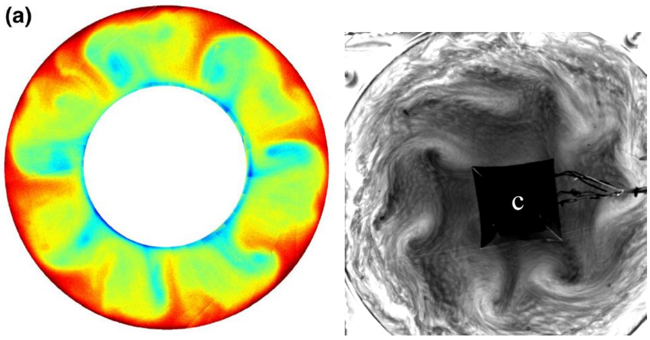

Figure 1: Surface temperature of the BTU experiment in the regular wave regime (left). Surface flow of the Perm “dishpan” experiment in the irregular wave regime (right). Here the surface flow is visualized by aluminum flakes.

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Nonlinear axisymmetric Taylor-Couette flow between counter-rotating cylinders in the narrow gap limit

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Abstract

The Cartesian representation of the Taylor-Couette system in the vanishing gap limit by Nagata (2023) is applied to the case of counter-rotating cylinders, where the ratio, $\mu = \omega_o/\omega_i$, of the angular velocities, ω_i and ω_o, of the inner and the outer cylinders located at the radius r_i and r_o, respectively, is fixed at -1, namely $\omega_o = -\omega_i$. When the radius ratio, $\eta \equiv r_i/r_o \to 1$, the disturbed fluid motion is governed, in dimensionless form, by

$$\nabla \cdot \check{\boldsymbol{u}} = 0, \tag{1}$$

$$\partial_t \check{\boldsymbol{u}} + (\check{\boldsymbol{u}} \cdot \nabla)\check{\boldsymbol{u}} + Qz\tilde{u}_x \boldsymbol{k} = -\nabla \check{p} + \frac{1}{\mathscr{R}}\Delta \check{\boldsymbol{u}}, \tag{2}$$

where $\check{\boldsymbol{u}} = (\check{u}_x, \check{u}_y.\check{u}_z)$ is the velocity disturbance in the azimuthal (x), axial (y) and wall-normal (z) directions with the unit vectors $(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{k})$ corresponding to their directions, and $\check{p}$ is the pressure disturbance. Note that the Coriolis term, $\Omega \boldsymbol{j} \times \check{\boldsymbol{u}}$, which is included in Nagata (2023), is absent in (2), since the average angular velocity, and therefore, Ω is zero. The total velocity is expressed by $\boldsymbol{u} = U_B(z)\boldsymbol{i} + \check{\boldsymbol{u}}$, with the basic velocity $U_B(z)\boldsymbol{i} = -\mathscr{R}z\boldsymbol{i}$, where z varies from -1 to 1. $\mathscr{R}$ is the Reynolds number which is related to the difference of ω_i and ω_o, and Q results from the curvature term, u_θ^2/r, in the radial momentum equation, $\partial_t u_r + u_r \partial_r u_r + \cdots - u_\theta^2/r = \cdots$, for $\boldsymbol{u} = (u_r, u_\theta, u_\zeta)$ in the cylindrical coordinate system (r, θ, ζ).

We find that the critical state for the onset of axisymmetric instability is determined by the product of Q and $\mathscr{R}$ only, namely, the instability sets in at $\tau \equiv Q\mathscr{R} = \tau_c$. This means that although our system approaches that of plane Couette flow as $Q \to 0$ as indicated in (2), the critical state exists even at $\mathscr{R} \to \infty$.

After confirming the above statement numerically by our linear stability analysis, we proceed to calculate nonlinear axisymmetric flows numerically. It is found that the bifurcation of nonlinear axisymmetric flows is supercritical, $\tau \geq \tau_c$, and that, in particular, its mean flow is distorted asymmetrically across the gap as shown in Figure 1, due to the symmetry-breaking term, $Qz\check{u}_x\boldsymbol{k}$, in (2). Other nonlinear properties of the axisymmetric flows shall be discussed in the Workshop.

The current paper supplements the work by Nagata (2023), in which the analysis on the case of counter-rotating cylinders, $\mu = -1$, is excluded because the relation between Q and Ω, *i.e.*, $Q = 2(\mu - 1)\Omega/(1 + \mu)$, is singular, and, moreover, the Taylor number $T = \Omega(\mathscr{R} - \Omega)$ does not take part in the analysis since $T \equiv 0$ when $\Omega = 0$.

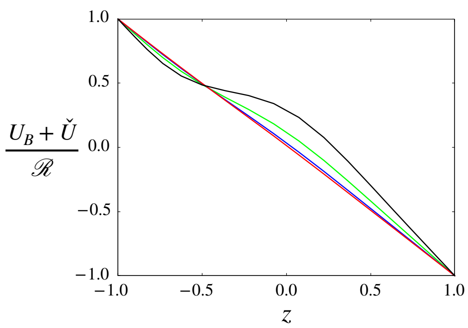

Figure 1: Asymmetrically distorted mean flows normalized by the Reynolds number $\mathscr{R}$ for the supercritical axisymmetric flows, $\tau \geq \tau_c$, with the axial wavenumber $\beta = 1.999$. $\tau = 2350$ (red), 2500 (blue), 3000 (green) and 5000 (black). $\tau_c = 2332.824$. $\check{U}(z)\boldsymbol{i} = <\check{\boldsymbol{u}}>$.

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Nonlinear Evolution of Magnetorotational Instability in a Magnetized Taylor-Couette Flow: Scaling Properties and Relation to Upcoming DRESDYN-MRI Experiment

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Abstract

Magnetorotational instability (MRI) is considered as the most likely mechanism driving angular momentum transport in astrophysical disks. Because of its importance in astrophysics, there has been great interest and efforts to detect MRI in laboratory over the last two decades with varied success. In preparation for upcoming liquid sodium DRESDYN-MRI experiments, recently we have performed global linear analysis of the standard MRI (SMRI) in an infinitely long cylindrical Taylor-Couette (TC) flow with an imposed axial magnetic field, showing that SMRI can in principle be well detected in those ranges of Lundquist (Lu), Reynolds (Re) and magnetic Raynolds (Rm) numbers accessible in these experiments (Mishra, Mamatsashvili, and Stefani (2022)). In this follow-up study also related to DRESDYN-MRI experiments, we focused on the nonlinear evolution and saturation properties of SMRI and analyzed its scaling behavior with respect to various parameters of the basic TC flow. We conducted a detailed analysis over the extensive ranges of $Lu \in [1.5, 15.5]$, $Rm \in [8.5, 37.1]$ and $Re \in [10^3, 10^5]$. For fixed Rm, we investigated the nonlinear dynamics of SMRI for small magnetic Prandtl numbers Pm down to $Pm \sim 10^{-4}$, aiming ultimately for those very small values of Pm typical of liquid sodium used in the experiments. In the saturated state, the magnetic energy of SMRI and associated torque exerted on the cylinders, characterising angular momentum transport, both increase with Rm for fixed (Lu, Re), while for fixed (Lu, Rm), the magnetic energy decreases and torque increases with increasing Re. We also studied the scaling of the magnetic energy and torque in the saturated state as a function of Re and found a power-law dependence of the form $Re^{-0.6...-0.5}$ for the magnetic energy and $Re^{0.4...0.5}$ for the torque at all sets of (Lu, Rm) and sufficiently high $Re \geq 4000$ (see 1). We also characterized the dependence on Lundquist number and the ratio of outer to inner cylinder angular velocities. Extrapolating the scaling laws to very high, experimental values $Re \gtrsim 10^6$, we estimated the rms of velocity and magnetic field perturbations, $0.5 - 0.94\ ms^{-1}$ and $0.45 - 0.97\ mT$, respectively, which can be expected in the experiments. These scaling laws will be instrumental in the subsequent analysis for a finite length TC flow with endcaps and comparison of numerical results with those obtained from the DRESDYN-MRI experiments in order to conclusively and unambiguously identify SMRI in laboratory.

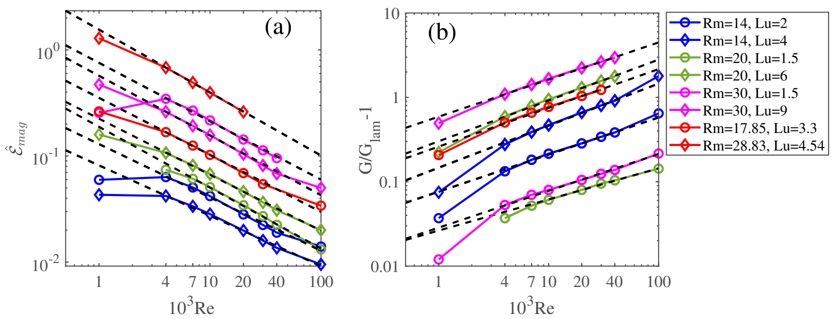

Figure 1: Scaling of (a) magnetic energy in saturated state $\hat{\mathcal{E}}_{mag}$, (b) normalised turbulent torque $G/G_{lam} - 1$ of SMRI for various values of (Lu, Rm). Black dashed lines denotes the fitting of power law of the form Re^a, where mean a is equal to -0.5 and 0.5 for $\hat{\mathcal{E}}_{mag}$ and $G/G_{lam} - 1$, respectively.

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Nonlinear instability of a wide-gap spherical Couette flow in the presence of weak noise

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Abstract

The flow of a viscous incompressible fluid between the rotating inner sphere and fixed outer one is under consideration. The spherical gap is equal in width to the inner sphere radius. We study numerically the transition between supercritical flow to subcritical one. White noise with equal excitation of all frequencies is introduced into the flow by adding fluctuations, completely chaotic in time and with zero mean, to the rotational rate of the inner sphere. The studies conducted are important for understanding the effect of time-dependent rotational rates of large-scale geophysical flows such as those in the atmosphere and mantle of the Earth.

Mean flow generation under noise action was found to occur larger for the subcritical flows as compared to the flows after first instability. Similar generation of mean flows is well studied in the case of periodic in time oscillations of rotational rates (see Koch at al. (2013), Cebron at al. (2021)). A slight decrease in the critical Reynolds number, corresponding to the onset of the first instability in the form of travelling azimuthal waves, was found under the action of additional weak noise. This result was obtained from the Reynolds number dependences of oscillation amplitudes, root mean square deviations and mean values of azimuthal velocities for Reynolds numbers exceeding the critical value.

Three-dimensional calculations in this case are very expensive. Although the dependence of the flow velocity oscillation amplitudes on Re number in noise free case is well-known (Landau, Lifshitz (1987)) it is unknown in the presence of noise (Lissandrello et al. (2015)). We have proposed a new approach to simplify the three-dimensional calculations of the flow stability limit location in the presence of noise. This approach based on analysis of the exponential damping of the oscillations amplitudes at the Re numbers less than the critical value. We have demonstrated the possibility of reduction of the calculation time steps by using the proposed method. The results obtained by foregoing methods and with proposed approach, demonstrate good agreement. We suppose that this new approach will be useful also for another time-dependent cases, for example, for periodic oscillations of the rotational rate. This may be the subject for further research.

This study was carried out with the funding of a grant from the Russian Science Foundation, project 23-29-00051

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Novel localized states in binary fluid convection in slightly inclined rectangular cells

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Abstract

We study the effect of a slight inclination of the cell on the localized steady states (*convectons*) that arise in binary fluid convection in elongated rectangular cells heated from below. Convectons organize in snaking branches that evolve towards cell filling states as the amplitude increases. Using numerical continuation we follow the low amplitude part of these solution branches with increasing thermal gradients. Instead of connecting to the origin, the branches lead to new localized solutions with different spatial structure. The numerical continuation of these solutions allowing the inclination angle to vary, reveals new families of spatially localized steady states that coexist for the same values of the inclination angle and heating. Strikingly, these new families of coexisting states exist also for the non-inclined cell.

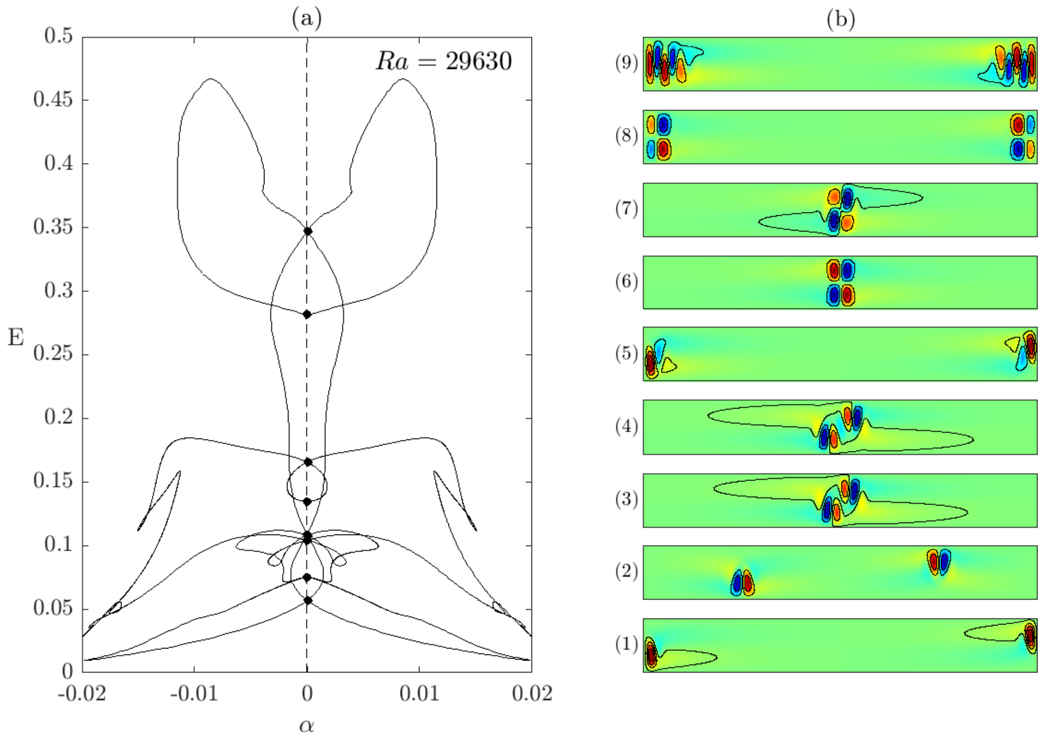

Figure 1: (a) Complex solution branch obtained by numerical continuation in α of the steady small amplitude odd localized state at $Ra = 29630$. (b) Contour plots of the stream function at the locations indicated in panel (a) and where the number of each solution increases from bottom to top.

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Numerical simulation of Taylor-Couette flow under dielectrophoretic force

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Abstract

We consider the hydrodynamical behavior of a dielectric fluid contained in a cylinder annulus under applied voltage and temperature gradient between inner and outer wall. This setting gives rise to a resulting body force, being a superposition of buoyancy and dielectrophoretic force (DEP). The situation can be modeled by means of thermal electrohydrodynamical (TEHD) Boussinesq equations. Owing to the mathematical description, this is a challenging three-dimensional nonlinear multi-physics problem we address with finite elements.
In the typical scenario for a vertical annulus, the fluid motion reaches a stable state that consists of a certain number of axially aligned, columnar-formed vortices (Seelig (2019)). Such vortices contribute to enhanced radial heat transfer (Gerstner (2020)). For a horizontal annulus, a single, stable jet typically forms at the top, where the corresponding fluid velocity increases with a voltage increase. To complement ongoing experimental research, we simulate both scenarios with an additional centrifugal acceleration corresponding to a rotating inner cylinder while the outer cylinder always remains at rest. In particular, we investigate the stability of numerical solutions in terms of the phase diagram spanned by applied voltage and Taylor number. We also explore non-adiabatic thermal boundary conditions, their impact on flow stability and quantitative agreement with experimental results.

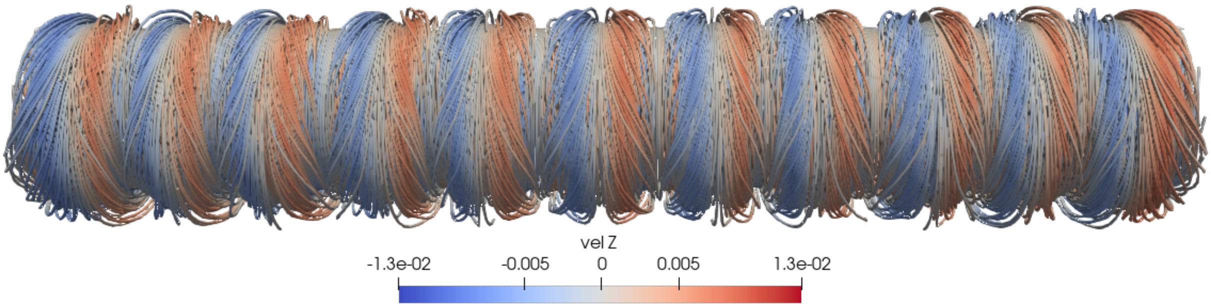

Figure 1: Velocity streamlines for TEHD Boussinesq flow in a cylindrical annulus with a rotating inner cylinder under radial gravity and $\Delta T = 1\text{K}, V_p = 8\text{kV}$, $\text{Ta} = 100$. Coloring indicates axial velocity (m/s).

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On assessing the control of transition to turbulence: the example of plane Couette flow

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Abstract

Transition to turbulence is a basic fluid instability that can be triggered by the presence of internal shear within the flow. Depending on the application, either the laminar flow or turbulence is preferred: fluid transport is more efficient when the flow is laminar due to lower wall friction while turbulence can be advantageous in mixing processes. In either case, being able to enhance or suppress the effects of turbulence is crucial to improve the efficiency of many fluid flows.

In plane Couette flow, transition to turbulence takes place subcritically: the laminar flow is linearly stable but transition can be initiated by a suitably large perturbation. Our approach to tackle the flow control problem is not to try to directly control the turbulent flow properties but rather to control the robustness of the laminar flow. Where turbulence is undesired, we aim to increase the latter, thereby reducing the risks of transition and statistically alleviating its effects.

Unfortunately, assessing the robustness of the laminar flow is not straightforward: whether a perturbation will decay or trigger transition depends on its amplitude but also on its shape. The finite-amplitude nature of the instability implies that we need an integral understanding of the basin of attraction of the laminar flow. To achieve it, we partition perturbations from the laminar flow according to the value of their kinetic energy. For each energy partition, we calculate numerically the probability that randomly shaped perturbations decay or laminarize. We represent the results via the laminarization probability as a function of the perturbation energy, which gives a measure of the relative size of the basin of attraction of the laminar flow. We apply this protocol to several values of the Reynolds number to confirm the fact that the sensitivity of the laminar flow to perturbation increases with the Reynolds number and to establish a benchmark against which the efficiency of flow control strategies can be tested (Pershin *et al.*, 2020). We then control the flow by adding in-phase, spanwise oscillations to the walls, a well-established strategy used to control developed turbulence (Quadrio & Ricco, 2004) and to stabilize the laminar flow by increasing the minimal energy required to trigger turbulence (Rabin *et al.*, 2014). Reproducing the computation of the laminarization probability for a range of control parameter values (oscillation amplitude and frequency), we determine optimal control conditions depending on various objectives, such as preventing turbulence at all costs and obtaining the most energetically efficient flow (Pershin *et al.*, 2022). Computing the laminarization probability accurately may involve expensive computations but methods based on Bayesian inference (Pershin *et al.*, 2022) and machine-learning (Pershin *et al.*, 2023) are being developed that could reduce the computing time substantially.

The protocol introduced here is versatile and can be tuned by the user to include specific flow knowledge (e.g. perturbation profiles) and to optimize control parameter values against different objectives. The same methodology can be used to control any finite-amplitude instability, in fluids or elsewhere.

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On high Taylor number Taylor vortices in Taylor-Couette flow

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Abstract

Axisymmetric steady solutions of Taylor-Couette flow, known as Taylor vortices (Taylor 1923; Davey 1962), are studied numerically and theoretically focusing on the high Taylor number regime. As the axial period of the solution shortens from about the gap, the Nusselt number (the torque on the cylinder walls normalised by its laminar value) goes through two peaks before returning to laminar flow. In this process, the asymptotic nature of the solution changes in four stages, as revealed by the asymptotic analysis.

When the aspect ratio of the roll cell is about unity, the solution quantitatively well captures the characteristics of the classical turbulence regime in the experiments and DNSs summarised in Grossmann et al. (2016). Theoretically, the Nusselt number of the solution is proportional to the quarter power of the Taylor number. It is surprising that a single unstable steady-state solution can approximate turbulence to some extent. On the other hand, the maximised Nusselt number obtained by shortening the axial period can reach the experimental value around the onset of the ultimate turbulence regime, although at higher Taylor numbers the theoretical predictions eventually underestimate the experimental values. This suggests that ultimate turbulence has a mechanism that cannot be represented by steady axisymmetric flow.

An important consequence of the asymptotic analyses is that the mean angular momentum should become uniform in the core region unless the axial period is too short. The theoretical scaling laws deduced for the steady solutions can be carried over to Rayleigh-Bénard convection.

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On New Linear Sub-Critical Oblique Modes – an Extension of Squires Theorem for Spatial Instabilities

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Abstract

In his fundamental theorem, Squire (1933) showed that for time-evolving perturbations, 2D instabilities occur at the smallest Reynolds number, which is usually called the critical Reynolds number. We recently showed that this is not necessarily so for spatially evolving 3D modes. For this we introduced both a complex streamwise and spanwise wavenumbers α, $\beta \in \mathbb{C}$ and $\omega \in \mathbb{R}$ (see (1; 2)),

$$v'(x, y, z, t) = \phi(y)\mathrm{e}^{i(\alpha x+\beta z-\omega t)} \tag{1}$$

where the former gives rise to oblique 3D modes. In Fig. 1(a), one can see such a mode in which in the $x-z$-plane a neutral stability line (NSL) exists, which is oblique to the main flow direction.

Extending Squires idea by invoking symmetry methods in parameter space we show that oblique 3D instabilities at a Reynolds number below the critical 2D Reynolds number may exist. In Figure 1(b), one can see that based on this extended approach, it is indeed possible to detect corresponding modes using a direct numerical simulation and here this is for the plane Couette flow.

Other than for temporally evolving modes, however, for spatially evolving modes the additional condition of *group velocity* (GV) $\boldsymbol{v}_g$ must be taken into account, which states that the GV has to propagate in the direction of the spatially increasing mode. As shown in Figure 1(a), for 3D instabilities the vector $\boldsymbol{v}_g$ of the GV must thus point into the unstable region, i.e. cross the above mentioned NSL in the $x-z$-plane.

We have worked out the above extension of Squire's theory based on Lie symmetries and will present it at the meeting as well as further details on the direction of the GV for the case of Couette flow and/or the Asymptotic Suction Boundary layer.

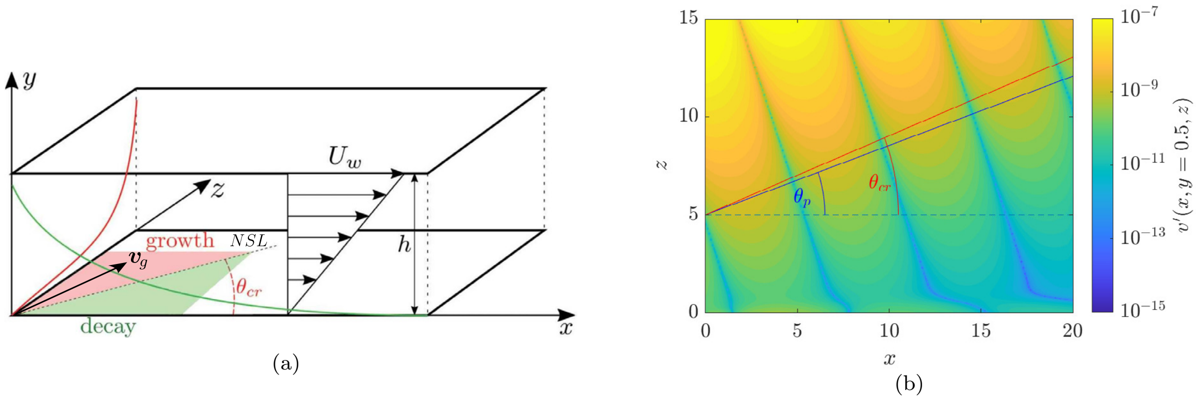

Figure 1: (a) Sketch of the oblique spatial 3D modes, where for illustration they decay in x-direction (red) and increase in z-direction (green). From equation (1) we see that this results in a neutral stability line (NSL), along which modes are unchanged; (b) Example of DNS verification of oblique spatial 3D modes in a Couette flow.

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On Symmetry breaking in Taylor-Couette System

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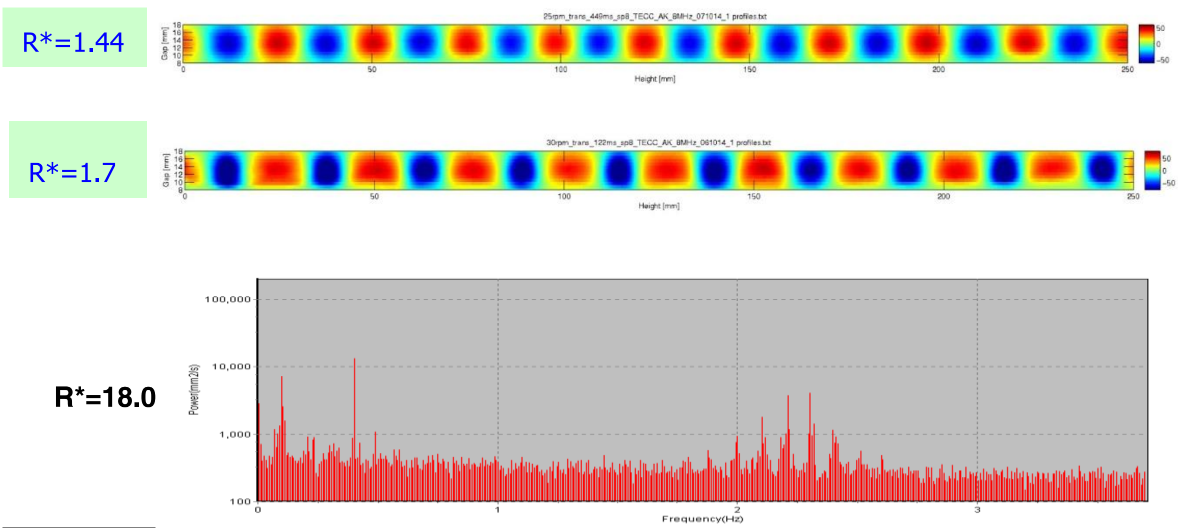
Abstract

Taylor Couette flow is characterized by its spatial periodicity, often treated in various types of symmetry. They are treated as shift symmetry and shift-reflect symmetry in a landmark numerical simulation by Markus[1] and Coughlin[2], and so-called periodic boundary condition is used in most of numerical works such as the DNS calculation by Ostilla[3]. By experimental observation of flow field in the whole column area, $V_r(r,z)$, such symmetries are shown to be valid in small range of R* (reduced Re number), but a reflect symmetry is easily broken. This is shown in quantitative way of velocity profile for the whole length of axis at mid-gap location and it is verified only for TVF, but not for WVF. In considering such symmetry breaking scenario, one old experimental observation of appearance of multiplet structure of power spectrum indicates an invalidity of periodical boundary condition, which is commonly used in numerical work.



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A simple model for arbitrary pollution effects on swirling free-surface flows

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Abstract

The boundary condition at the air-water interface plays a major role in the stability of a rotating flow with a free surface. We consider here a generic configuration to investigate such effects both experimentally and numerically. For the flow driven by a rotating disc in a fixed cylindrical vessel partially filled with water, the standard free-slip condition in numerical simulations does not predict the instability threshold found experimentally. The unavoidable surface contamination changes the stresses at the interface and has a strong impact on the velocity field, at least when H, the fluid height, is small compared to R, the disc radius. The possible effect of unidentified pollutants at the interface can be modelled using an advection-diffusion equation and a closure equation linking the surface tension to their concentration. This modelling has been proposed in Faugaret et al. (2020)

A even simpler numerical model without superficial transport of the surfactants, adaptable into any code for single-phase flows has been proposed in Faugaret et al. (2022). The model does not possess any free parameter and is independent on the closure model for surfactants. For the stationary axisymmetric base flow, the radial velocity at the interface is set to zero whereas the usual stress-free boundary conditions are retained for the perturbations. For a geometrical aspect ratio $G = H/R$ equal to 1/4, known to display ambiguous behaviour regarding stability thresholds, the modal selection as well as a nonlinear stability island found in the experiments (see Figure 1) are well reproduced by the model, both qualitatively and quantitatively. We present experimental and numerical results in a systematic study for G ranging from 0.1 to 2. By varying the aspect ratio, we describe the modal selection of the primary instability. We show that the simple model is robust over the entire range studied.

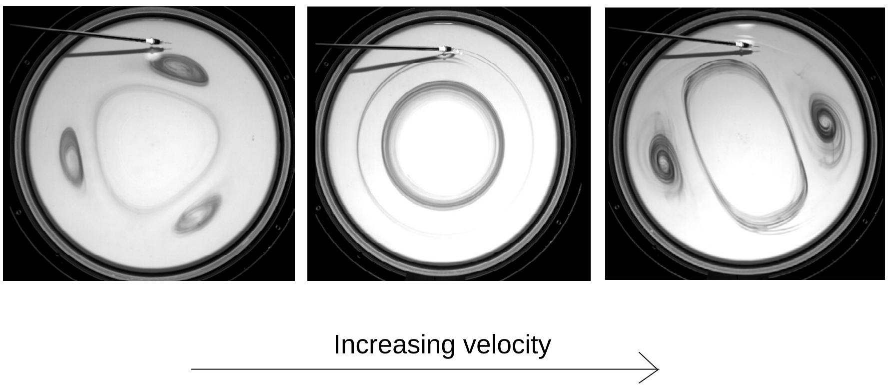

Figure 1: Illustration of the stability island.

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On the wanderings of a ludion in a corral: in search of a quantum analogy

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Abstract

We have recently described (Le Gal et al., 2022) the resonance of the vertical oscillations of a ludion (or Descartes diver) in a stably stratified fluid together with the internal gravity waves it emits and its bifurcation to horizontal swimming. Now, in search of a quantum hydrodynamic analogy and possible associated pilot wave dynamics (Couder et al., 2005; Bush, 2015), we analyze the motions of a ludion in a cylindrical container (a corral) in the hope of revealing a possible interaction between its swimming and its own internal gravity wave field. According to the ratio of the forcing frequency to the Brunt-Väisälä frequency N, the ludion can chaotically explore the horizontal cylindrical section where it is constrained on average. Although the statistical study would have required recordings over days, the analysis of the trajectories recorded during several hours seems to show that certain radii of curvature are well privileged, a phenomenon reminiscent of Couder walkers (Couder et al., 2005; Bush, 2015). For a particularly long record (16 hours) of the ludion dynamics in a corral of 30 cm in diameter, the color coding of the chaotic trajectory proportional to the instantaneous horizontal speed of the diver reveals as expected a faint but real target pattern (see Figure 1) with a slightly lower speed along a first yellowish rings at the periphery of the corral and another one at a radius $\approx 5cm$. This pattern may indeed be the ghost of one of the eigenmodes of the corral. In line with these results, a Proper Orthogonal Decomposition (POD) of the synthetic Schlieren images of the waves emitted by the ludion during its chaotic excursion shows large-scale gravity eigenmodes of the cylindrical corral. Without drawing any definitive conclusions from this study, we are hopeful that a wave-driven or a wave-influenced particle dynamics exists also in our system and hence opens the way to a new hydrodynamic quantum analogy.

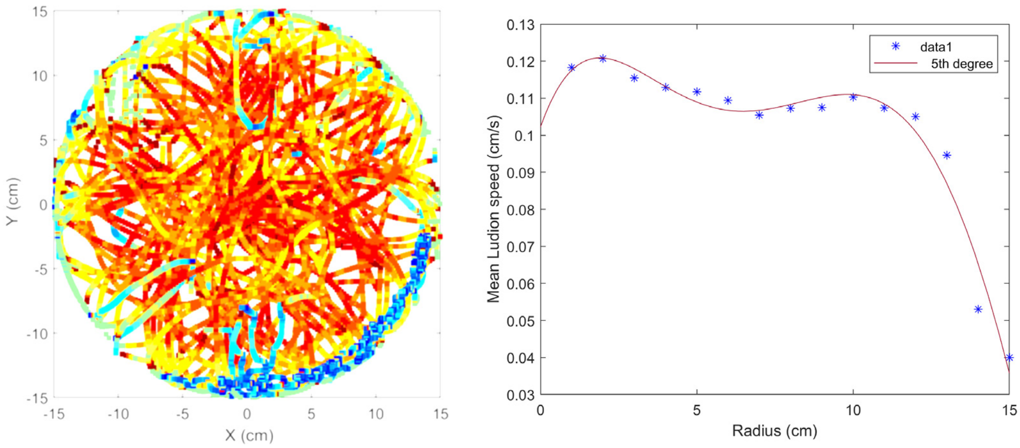

Figure 1: Left: Trajectory of the ludion in a corral 30 cm in diameter, where the color coding is proportionnal to the instantaneous horizontal speed. A faint target pattern which may be the ghost of one of the eigenmodes of the corral, can be detected (two yellowish rings at the periphery of the corral and at a radius $\approx 5cm$). Right: Mean speed of the ludion averaged along the azimuth direction.

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Parametrically forced rapidly rotating flows in cuboids

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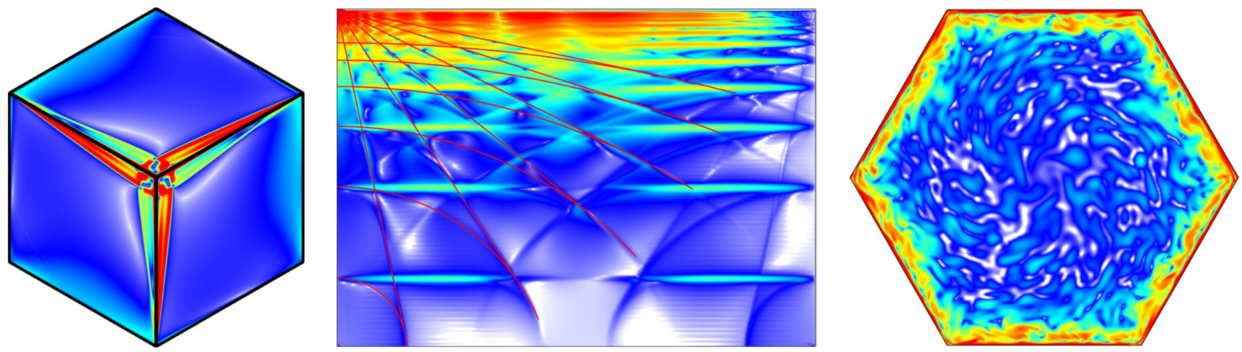
Abstract

The flows in rapidly rotating cubical containers subjected to small-amplitude parametric forcing, such as libration or precession, are investigated numerically. Depending on the orientation of the container, the response flows may be dominated by resonantly excited cavity modes or thin beams emitted from some of the edges and vertices of the container. For some frequency ranges, these beams may focus onto edges or onto inertial wave attractors in the interior. A overview of some of our work along with more recent results will be presented.



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Rayleigh-Bénard convection rolls determine the shape evolution of an ice block melting from below

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Abstract

We numerically study the melting process of a solid layer heated from below such that a liquid melt layer develops underneath. The objective is to quantitatively describe and understand the emerging topology of the structures (characterized by the amplitude and wavelength), which evolve out of an initially smooth surface. By performing both two-dimensional (achieving Rayleigh number up to $Ra = 10^{11}$) and three-dimensional (achieving Rayleigh number up to $Ra = 10^{9}$) direct numerical simulations with an advanced finite difference solver coupled to the phase-field method, we show how the interface roughness is spontaneously generated by thermal convection. With increasing height of the melt the convective flow intensifies and eventually even becomes turbulent. As a consequence the interface becomes rougher but still coupled to the flow topology. The emerging structure of the interface coincides with the regions of rising hot plumes and descending cold plumes. We find that the roughness amplitude scales with the mean height of the liquid layer. We derive this scaling from the Stefan boundary condition and relate it to the non-uniform distribution of heat flux at the interface. For 2D cases, we further quantify the horizontal length scale of the morphology, based on the theoretical upper and lower bounds given for the size of convective cells known from Ref. [1]. These bounds well agree with our simulation results. Our findings highlight the key connection between the morphology of the melting solid and the convective flow structures in the melt beneath. More details on our work can be found in Ref. [2].

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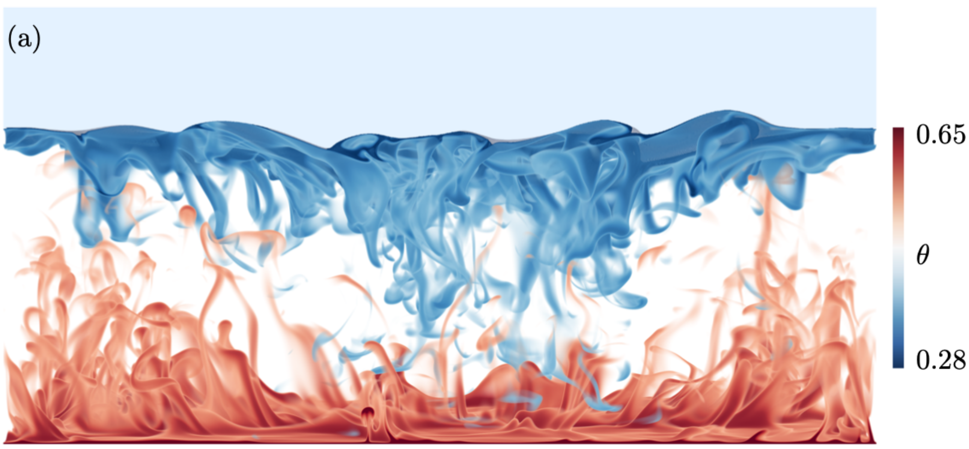

Figure 1: Visualizations of the 3D numerical simulation at $Ra = 10^9$: Instantaneous 3D temperature field at $t = 1200\ t_f$. Light blue color above the flow field represents the solid ice phase $\phi > 1/2$.

Receptivity of Compressible Boundary Layers on Flat and Concave Porous Surfaces

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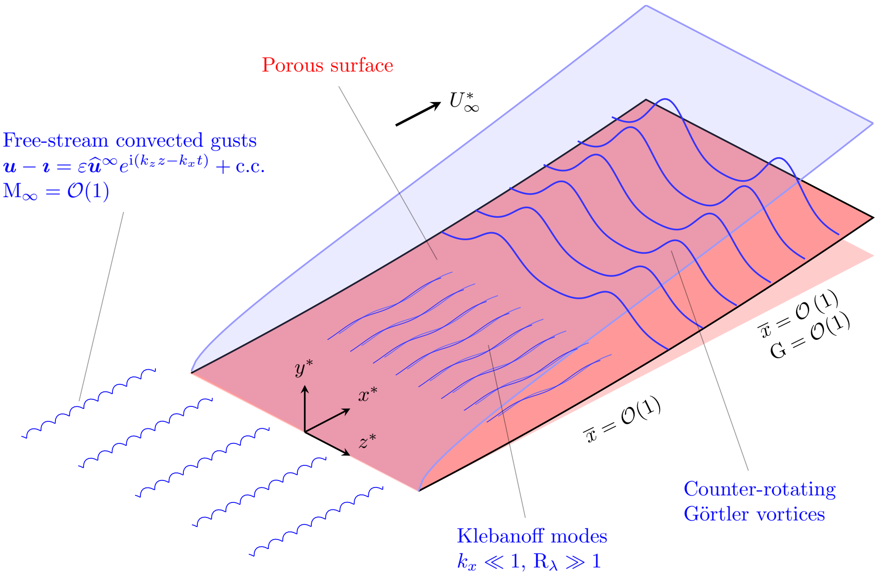
Abstract

The effect of wall permeability on the response of pre-transitional compressible boundary layers perturbed by free-stream vortical disturbances is investigated via asymptotic methods and numerically by solving the unsteady boundary-region equations. A porous wall with regularly-spaced cylindrical pores couples the pressure and wall-normal velocity fluctuations at the wall. The growth of the excited low-frequency, streamwise-elongated laminar streaks, known as Klebanoff modes, is reduced when the spanwise diffusion is negligible. The curvature of the wall forces the Klebanoff modes to evolve into streamwise-aligned, spanwise-counterrotating Görtler vortices. As the flow evolves dowmstream, the growth of the Görtler vortices is first slightly damped, then enhanced and eventually reduced. For a range of frequencies and spanwise wavelengths, the Klebanoff modes evolve into oblique Tollmien-Schlichting waves through a leading-edge-adjustment receptivity mechanism. The wavenumber of these waves is only slightly modified by a permeable wall, while the growth rate increases, thus confirming previous experimental results. The underlying physical mechanism is explained by a triple-deck analysis, which shows that the onset of Tollmien-Schlichting waves shifts upstream over a permeable wall. The triple-deck results show excellent quantitative agreement with the numerical solution of the boundary-region equations.



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Regularized four-sided cavity flows: A spectral bifurcation benchmark implemented in Julia

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Abstract

Driven cavity flows are commonly used as benchmarks to validate Navier-Stokes solvers. These problems can test spatial discretization methodologies such as finite elements, finite differences, and spectral methods. They also assess a variety of boundary condition implementations and time-stepping schemes. The simple lid-driven cavity flow has received considerable attention. This flow is steady for high Reynolds numbers, with the first instability occurring within a large uncertainty interval (7500, 8100) [Kuhlmann (2018)].

More recent variants, such as the four-sided version of the cavity flow, have been proposed [Wahba (2009)]. In this problem, lids move with the same velocity profile and parallel lids move in opposite directions. Later works tested different numerical techniques and studied the bifurcations with linear stability analysis, arc-length continuation, and time-stepping [Perumal (2011), Cadou (2012), Chen (2013)]. This cavity has the computational advantage of exhibiting a variety of bifurcations at low or moderate Reynolds numbers.

Still, the problem suffers from corner singularities due to the discontinuous boundary conditions and affects the exponential convergence of spectral methods. This work presents a regularized version of the four-sided cavity flow to address the issue. A spectral Chebyshev discretization of the flow problem is implemented in Julia, an open-source, high-performance language for scientific computing. A developed Julia module provides a reproducible example of the proposed cavity.

The regularized four-sided lid-driven cavity shows most of the primary bifurcation scenarios. The flow undergoes instabilities, such as pitchfork, saddle-node (fold), and Hopf. Predicting the precise location of the bifurcations could present an amenable Navier-Stokes bifurcation benchmark when testing and comparing different schemes and implementations.

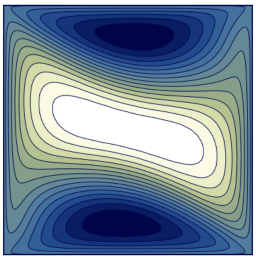

Figure 1: Asymmetric solution on a 64×64 grid at Reynolds 100

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Reproducing Spatio-Temporal Intermittency of Turbulent Puffs with Domany–Kinzel Model

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Abstract

In wall-bounded shear flows, localized turbulence forms intermittently on a large scale in a laminar-based flow, where turbulence is globally sustained at very low Reynolds numbers. For example, in a pipe flow near the criticality, localized turbulence, also called turbulent puffs, aligns approximately every $50D$ (D: pipe diameter), which causes the puffs to split, collide, and decay(1). Even the branching of localized turbulence in a Couette flow is also more stochastic. Furthermore, for this subcritical type of transition, the universality of directed percolation (DP) has been actively discussed in terms of the statistical characteristics regarding the spatio-temporal intermittency (STI) of localized turbulence(2; 3). Also, low-dimensional models of puff growth in terms of dynamical systems have been proposed(4). However, we have no model to reproduce the behaviour of localized turbulence and its dependence on channel geometry.

We investigated the dependence of the STIs of turbulent puffs in annular Couette flow (ACF) on the flow cross-section geometries near a lower criticality and reproduced their distributions using the Domany–Kinzel model as a percolation model. The ACF is a wall-bounded flow with fluid between coaxial double cylinders, driven by axial sliding of the inner cylinder. Since it is preferred to form a quasi-one-dimensional distribution of turbulent puffs, we targeted highly curved annular pipes with a radius ratio of the inner and outer cylinders ($\eta = r_{\rm in}/r_{\rm out}$) of less than 0.3. The flow cross-section geometries are shown in Figure 1, which are similar to a pipe, with some differences. Note that in the present simulations for the Navier–Stokes equations, the direct numerical solutions were applied without any turbulence models.

There are significant differences in the thickness and branching of the STIs, which indicate the length and behaviour of turbulent puffs, for $\eta = 0.05$–0.3, as shown in Figure 1 (left). In particular, for low η, the turbulent puffs tend to be highly split and pair annihilated after puff collisions, but for larger η, two puffs collide and merge into one. The Domany-Kinzel model, as a two-variable stochastic model, was adopted to reproduce these various STIs(5). The present model can control puff advection (splitting) and merging with probabilities p_1 and p_2, respectively, whereas the DP toy model has a single variable. Figure 1 (right) demonstrates that the channel geometry dependency of STI distributions is reproduced in detail.

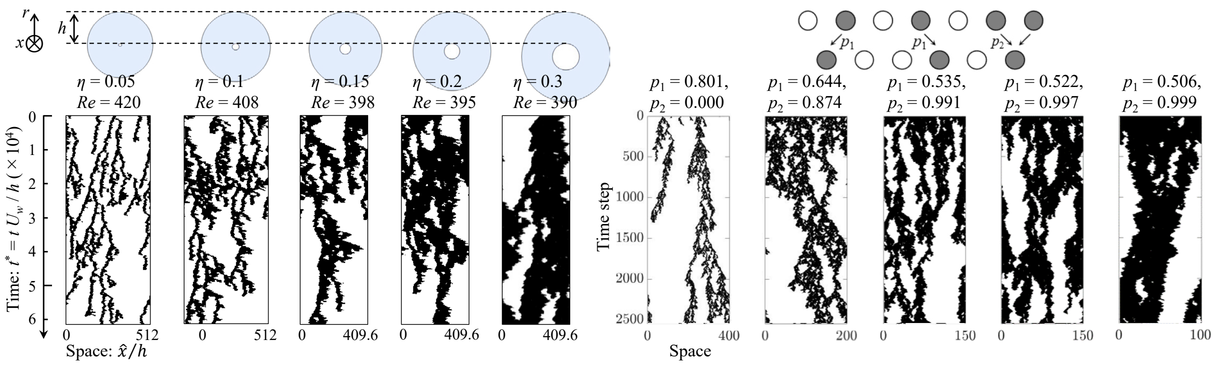

Figure 1: (Left) Space-time diagrams of turbulent puffs near the criticality in the annular Couette flow with $\eta = 0.05$–0.3. Black shows turbulence according to the criterion $\langle u'_{r\,\rm rms}\rangle_\theta/U_w \geq 0.01$, but below that, white is laminar state. (Right) Qualitatively the same as the left, but the diagrams of (1+1)-D Domany–Kinzel model with independent two stochastic variables as advection and merging controlled by the probabilities p_1 and p_2.

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Robust methods for constructing periodic orbits in wall-bounded shear flows

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Abstract

The spatiotemporally chaotic dynamics of a turbulent flow is underpinned by the unstable non-chaotic invariant solutions embedded in the state space of the governing equations. Extracting invariant solutions, therefore, is the key for studying turbulence in the dynamical systems framework. Invariant solutions such as equilibria, periodic orbits, etc. can be constructed by solving a minimization problem over the space-time fields with prescribed temporal behavior: minimization of a cost function that quantifies the deviation of a space-time field from being a solution to the evolution equations at each and every point in space and time. The optimization approach does not suffer from sensitivity to the initial guess and small convergence radius, which are the main drawbacks associated with the alternative Newton-based shooting methods.

Despite the advantages of the optimization approach, its application to 3D wall-bounded flows remains challenging. One challenge is to deal with a very high-dimensional problem, and the other is to deal with the non-linear, non-local pressure term which is not easily accessible in the presence of walls, if possible at all. The adjoint-based minimization techniques introduced by Farazmand (2016) and Azimi *et al.* (2022) scale linearly with the size of the problem, thus allow us to apply them to very high-dimensional problems. However, the application of these minimization techniques has been limited to the 2D Kolmogorov flow where the doubly periodic domain enables us to handle the pressure term (Farazmand (2016) and Parker and Schneider (2022)). We propose a Jacobian-free algorithm based on these adjoint-based methods for constructing invariant solutions of wall-bounded fluid flows without requiring to construct the pressure field explicitly. We demonstrate the feasibility of the algorithm by constructing equilibria and periodic orbits in plane Couette flow and inclined layer convection (see Figure 1). We also propose a data-driven procedure based on dynamic mode decomposition for accelerating the convergence of the adjoint-descent algorithm.

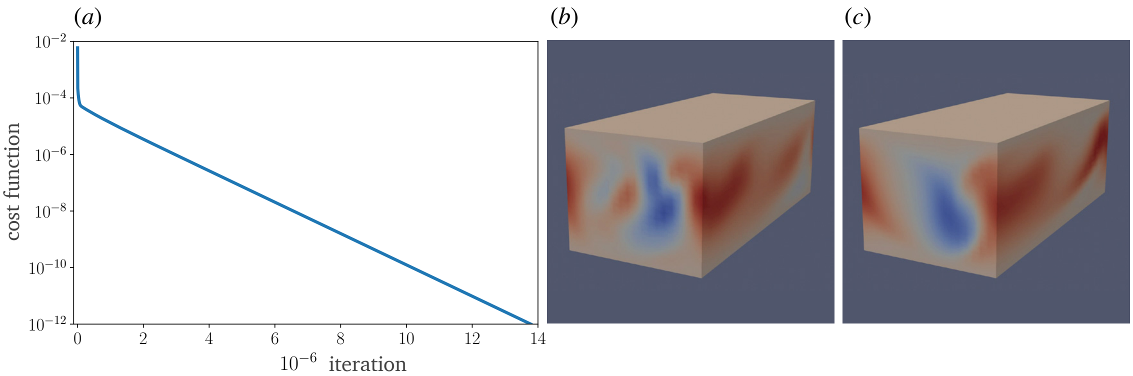

Figure 1: Minimization of the cost function evolves a flow field taken from direct numerical simulation of a chaotic plane Couette flow, panel (b), towards a true equilibrium solution, panel (c). Contour plots display the wall-normal component of the velocity.

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Rotating spherical shell convection under the influence of an externally imposed differential rotation

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Abstract

We investigate numerically bifurcations of convection phenomena in a rotating spherical shell heated by imposing a constant temperature difference across the spherical gap and driven by a radially directed gravity force. In addition to a global rotation of the fluid shell a supplementary differential rotation between both spheres is considered to study its impact on the convection pattern. This setup serves as an appropriate model of convection phenomena in geophysical and astrophysical applications as in the outer core of planets or in the stellar convection zones.

Beside simulations, path-following techniques are applied to compute the solution branches (Mamun and Tuckerman, 1995), which are presented in the bifurcation diagram in Figure 1. At low temperature an axially symmetric basic flow (black line) is generated which resembles that of the spherical Couette flow. Increasing the Rayleigh number successive symmetry breaking Hopf bifurcations generate firstly rotating waves (RWs) and secondly modulated rotating waves (MRWs) with a dominant azimuthal mode number m=3 (solid blue lines). By further increase of the Rayleigh number a new stable RW branch with no symmetry, $m = 1$ (solid red line), appears in a saddle node bifurcation. The stable m=3 MRWs and the arising stable m=1 RWs are coexisting along a certain interval of the Rayleigh number creating a region of bistability. However finally the new non-symmetric $m = 1$ solutions survive as the only stable branch which also maximises the heat transfer quantified by the Nusselt number. A more accurate study demonstrates that this scenario is the result of a homoclinic bifurcation in which the stable $m = 3$ MRWs collide with unstable $m = 1$ RWs, analogous to the situation in a homoclinic bifurcation between a stable fixed point and an unstable periodic orbit in the framework of ordinary differential equations.

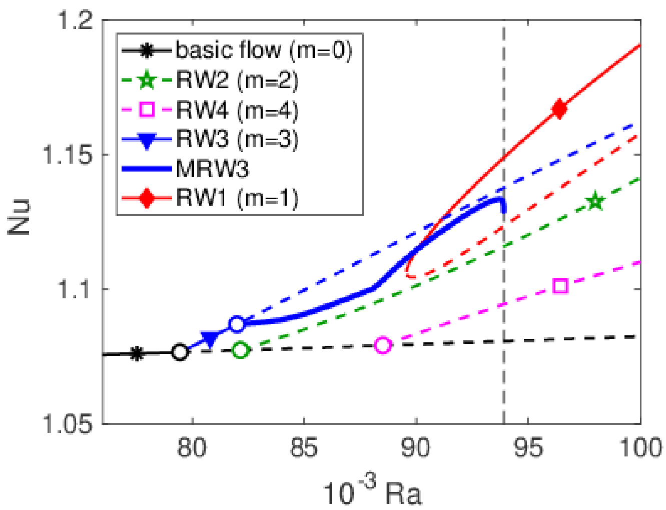

Figure 1: Bifurcation diagram presenting the solution branches in a plot of the Nusselt number versus the Rayleigh number. Solid (dotted) lines represent stable (unstable) branches.

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Scalings for eccentric Taylor–Couette–Poiseuille flow

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Abstract

We study instabilities of the flow between two eccentric cylinders where the inner one is rotating, the outer one is fixed and a pressure gradient along the axis of the cylinders gives an axial flow (eccentric Taylor–Couette–Poiseuille flow) as an extension of studies on Taylor–Couette flow. The flow is characterised by three parameters: rotational and axial Reynolds numbers $Re_\Omega = a\Omega d/\nu$, $Re_z = W_b d/\nu$ and eccentricity $e = c/d$. Here, the gap ($d = b - a \approx 15$ mm) is defined as the difference of radii of the outer and inner cylinders, and c is the offset of the two cylinders' axes, respectively, as shown in Figure 1. Ω, W_b and ν denote the inner cylinder's rotation rate, axial bulk velocity and kinematic viscosity. Due to these three independent parameters, it is expected that the flow becomes highly complex. Our aim is to understand the flow and to extract the essential physical parameters.

The axial length of our experimental setup is approximately $100d$ with $a/b = 0.5$. The fluid is water and through reflective-flake flow visualizations we studied the onset of instability. For a given Re_z and e, we carefully increased the Re_Ω to determine the critical Re_Ω for which the flow instability structure begins to appear. The results shown in Fig. 2(a) indicate that the observed critical points agree with linear stability analysis by Takeuchi and Jankowski (1981); Leclercq et al. (2013).

Now, we re-scale these neutral/critical curves using new scalings: a modified Reynolds number $Re'_\Omega \equiv V_b\Delta/\nu$ and a bulk velocity ratio W_b/V_b, where V_b is the bulk azimuthal velocity obtained from Leclercq et al. (2013) and $\Delta \equiv d(1-e)$ is the narrow gap. In Fig. 2(b), the same data shown in Fig. 2(a) are re-plotted as a function of Re'_Ω and W_b/V_b and collapse on a single curve. It clearly indicates that the instability of the whole flow is dominated by the narrow-gap flow, which is strongly influenced by the three-dimensionality of the mean flow quantified by W_b/V_b. The two slopes in $W_b/V_b \lesssim 1$ and $W_b/V_b \gtrsim 2$ seem to be dominated by different instability mechanisms: centrifugal and shear instabilities, respectively. In the talk, we will also discuss these scalings in similar three-dimensional canonical flows, e.g., flow around a rotating cone in axial flow (the cylinder can be regarded as one limit of the cone, having an apex angle of 0°).

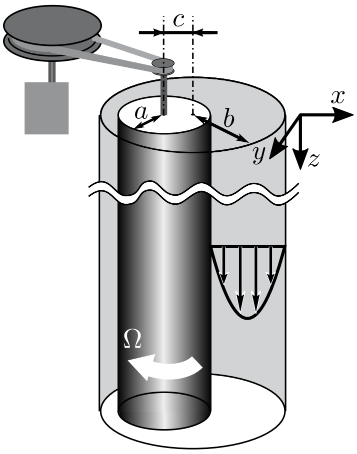

Figure 1: eccentric Taylor-Couette-Poiseuille (eTCP) flow system

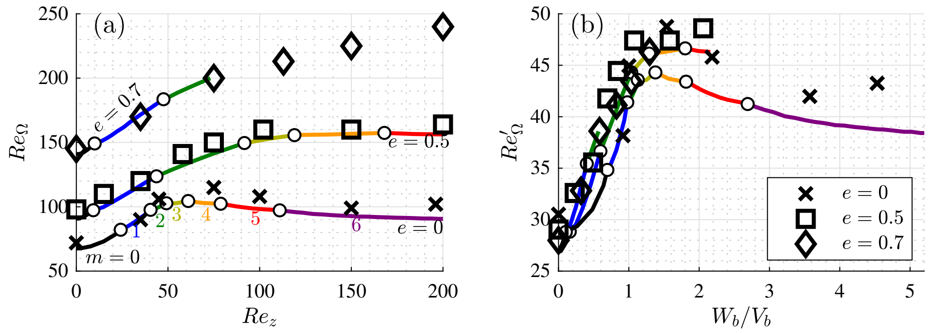

Figure 2: Critical points from the present visualizations (markers: $e = 0$; $\times$, $e = 0.5$; $\square$, $e = 0.7$; $\diamond$) and neutral curves from the linear stability analysis (Takeuchi and Jankowski , 1981; Leclercq et al. , 2013) (coloured lines) plotted as a function of (a) axial and rotational Reynolds numbers, Re_z and Re_Ω, respectively; and (b) the bulk velocity ratio W_b/V_b and the modified Reynolds number Re'_Ω. In (a) and (b), the same data are shown. The colours of the lines indicate the azimuthal wave numbers m of the most unstable modes and the white circles show the switching points of m.

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Search for unstable relative periodic orbits in plane Poiseuille flow using symmetry-reduced dynamic mode decomposition

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Abstract

Within the dynamical systems approach to turbulence, state-space structures such as unstable periodic orbits (UPOs) embedded in the chaotic attractor are known to carry information about the dynamics of the system and therefore provide a tool for its description. UPOs are usually found by Newton searches, and constructing good initial data is challenging. A commonly used technique to generate such initial data involves detecting recurrence events by comparing future with past flow states using their L_2-distance (Cvitanović *et al.* (2010)). A drawback of this method is the need for the trajectory to shadow the UPO for at least one of its cycles, which becomes less likely for higher Reynolds numbers. Furthermore, one only obtains local-in-time information. A method that bypasses both issues is based on dynamic mode decomposition (DMD), where initial guesses are constructed using a few dynamic modes corresponding to dominant frequencies identified from the data Page *et al.* (2020). However, in the presence of continuous symmetries, DMD fails to provide accurate approximations of the dynamics. To address this, we combine symmetry-reduced DMD (SRDMD), an approach recently developed by Marensi *et al.* (2023) with sparsity promotion Jovanović *et al.* (2012). In doing so, we construct optimal low-dimensional representations of the data that are global objects, and each instant in time can be chosen as an initial guess. We apply the method to data obtained by direct numerical simulation of 3d plane Poiseuille flow at friction Reynolds number $\mathrm{Re}_\tau = 50$, taking a shift symmetry in streamwise direction explicitly into account. We demonstrate, that the obtained unstable relative periodic orbits (URPOs) cover relevant regions of the systems state space, suggesting their importance for a possible description of the flow. Furthermore, we emphasise the advantage of this approach compared to the recurrent flow analysis, since (SR)DMD provides a set of initial guesses contained in a reconstructed trajectory and therefore, enables multi-shooting methods to operate on a global object.

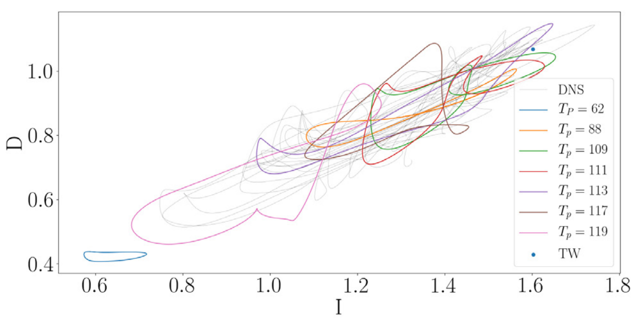

Figure 1: State space in a two-dimensional projection of the energy production plotted against the dissipation. The DNS time series is shown in grey. The coloured lines show the first cycle of each URPO.

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Self-sustained Coherent Structures Underlying Spiral Turbulence in Taylor–Couette Flow

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Abstract

Self-sustaining process (SSP) of coherent structures in the absence of linear instability of the laminar flow has been the topic for many scientific activities since the paper published by Waleffe (1997). Comparing to merely shear-driven flows, the self-sustainment of exact coherent structures in Taylor-Couette flow (TCF) is more involved because of the interplay of shear and rotation. *Spiral turbulence* (SPT) can persist in the supercritical regime of counter-rotating TCF, beyond the linear instability of the laminar circular Couette flow (Prigent et al. (2002); Meseguer et al. (2009)), meaning that both the shear and the centrifugal instabilities contribute to the generation of streamwise (azimuthal) vorticity. This fact has gone largely unnoticed in the literature, where the origin of the stripe can be solely explained by the stability of both the basic flow and the autonomous vortex emerged from the SSP.

We report a self-sustained *drifting-rotating wave* (DRW) generated via a saddle-node bifurcation in the absence of linear instability of the base flow in counter-rotating Taylor-Couette flow (Wang et al., 2022). The DRW is captured in minimal computational box with two of whose sides aligned with the cylindrical helix described by the spiral pattern. Newton-Krylov continuation, along with Arnoldi eigenvalue methods are used to converge the DRW solutions, and monitor their linear stability, respectively. It is found that these DRW are linearly stable in a very narrow region of parameter space, close to the saddle-node bifurcation where they are created. The stable DRW solutions undergo a Hopf bifurcation, generating periodic solutions that eventually lead to a chaotic attractor via period doubling cascade. The SSP is proved to be at work in the subcritical regime, as roll and streak constituents of the DRW trigger the azimuthally-dependent wave component and are, at the same time, regenerated by it.

We manage to track the DRW solutions up to the supercritical regime where the SPT exists. These DRW solutions are then replicated in the azimuthal direction so that they fill in a narrow parallelogram domain revolving around the apparatus perimeter. Self-sustained vortices eventually concentrate into a localized pattern which satisfactorily reproduces the topology and properties of the SPT calculated in a large periodic domain of sufficient aspect ratio that is representative of the real system.

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Solitary-like and modulated wavepackets in the Couette-Taylor with a radial temperature gradient

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Abstract

Numerical and experimental studies of the flow in a large aspect ratio Couette-Taylor system with a rotating inner cylinder and a fixed radial temperature gradient are performed. The base flow state is a superposition of an azimuthal flow induced by rotation and an axial large convective cell induced by the temperature gradient. For a relatively large temperature gradient, the rotation rate of the inner cylinder destabilizes the convective cell to give rise to traveling wave pattern through a subcritical bifurcation. This wave pattern is associated to a temperature mode and it consists of helical vortices traveling in the annulus. In a small range of the rotation rate, helical vortices have longitudinal meandering leading to the formation of kinks randomly distributed, leading to spatio-temporal disordered patterns. The flow becomes regular for a large interval of rotation rate. The friction, the momentum and the heat transfer coefficients are computed and found to be independent of the heating direction (Kang et al. 2023).

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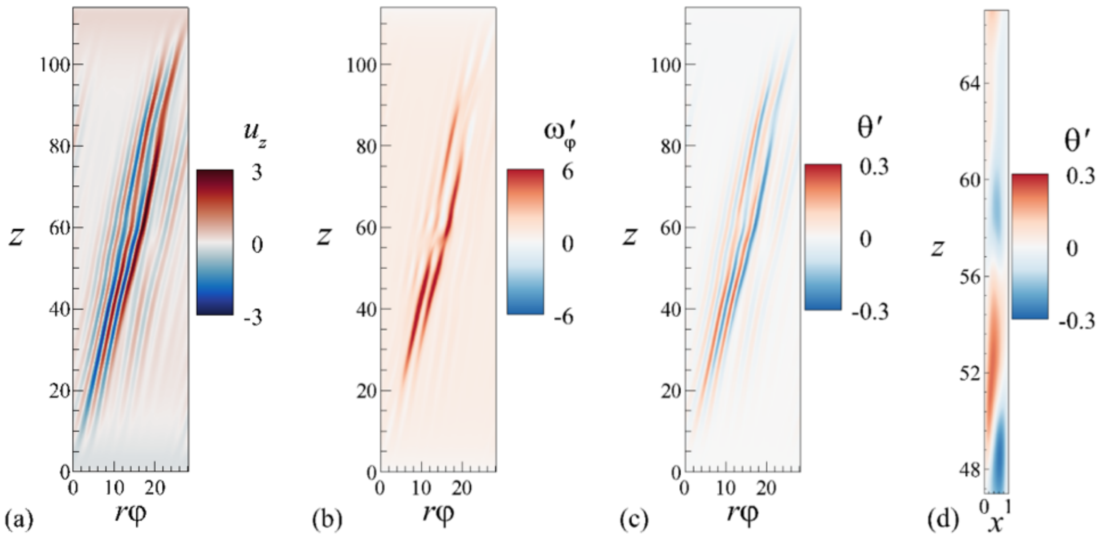

Figure 1: Localized wavepacket

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Stability of oblique liquid curtains with surface tension

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Abstract

Oblique liquid curtains (those ejected from an orifice at an angle to the vertical) are examined under the assumption that the Froude number is large. As shown by Benilov (2019, 2021), their structure depends on the Weber number: if $We < 1$ (strong surface tension), the Navier–Stokes equations admit asymptotic solutions describing curtains bending upwards, i.e., against gravity.

In the present work, it is shown that such curtains are unstable with respect to small perturbations of the flow parameters at the outlet: they give rise to a disturbance travelling downstream and becoming singular near the curtain's terminal point (where the liquid runs out of the initial supply of kinetic energy). It is argued that, since the instability is spatially localised, the curtain can be stabilised by a properly positioned collection nozzle. All curtains with $We > 1$ bend downwards and are shown to be stable.

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Study On Discrimination of Mode Development Process of Taylor Vortex Flow Using Various Physical Quantities

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Abstract

In recent years, technology that harnesses the unlimited potential of microorganisms has become important as a modest but long-lasting technology. In order to maximize the power of microorganisms, it is necessary to control the flow of culture medium to mix them uniformly, light, carbon dioxide. Taylor vortices are considered suitable for agitated culture of plant and animal cells or microorganisms because they are easy to create and are resistant to disturbances, stable, and have little local shear flow. In this study, we constructed a system that can automatically discriminate the flow mode using numerical results of Taylor vortex flow generated between rotating double cylinders as input data by using deep learning.

By comparing the loss and accuracy rate of test data for various physical quantities and comparing the accuracy rate and loss of training data, the physical quantities that can efficiently predict the mode development process of the Taylor vortex were shown.

The results show that among the various physical quantities, the radius u is the most accurate when comparing the final loss after learning and the accuracy rate, and can efficiently predict mode development process of the Taylor vortex.

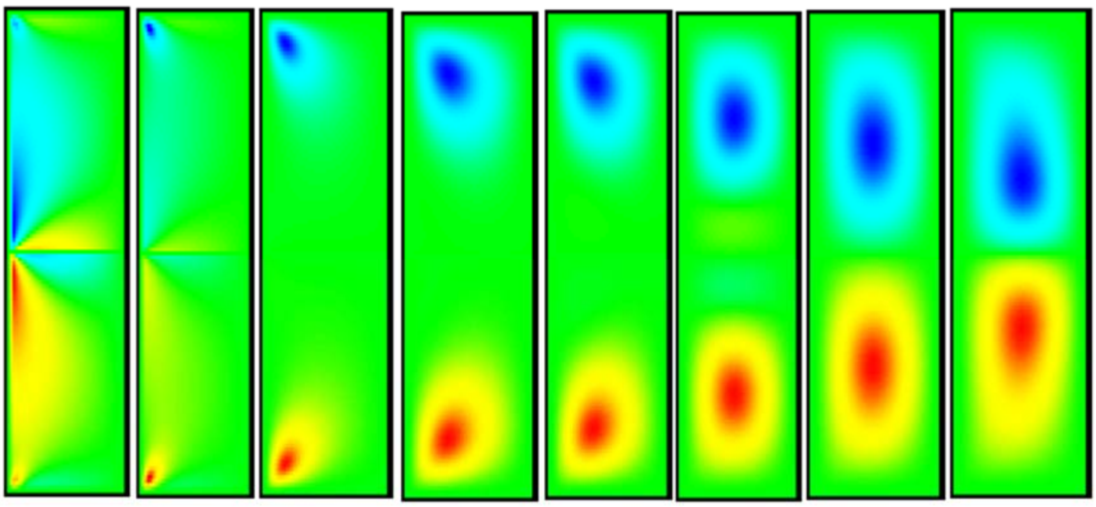

Fig. 1 Taylor Vortex Development Process

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Subcritical dynamics of axisymmetric rotor-stator flow

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Abstract

Rotor-stator flows have been studied extensively in the past. There have been many experimental observations of coexistence of both circular rolls and spiral arms (Schouveiler et al., 1998; Gauthier et al., 1999). The origin of the latter is well understood (Gelfgat, 2015) while that of the former is not. Such rolls display chaotic and sometimes transient dynamics (Lopez et al., 2009). Linear stability analysis performed by (Daube and Le Quéré, 2002) for an height/radius ratio of 0.1 revealed a Hopf bifurcation around $Re = 3000$, a value much higher than found experimentally, and the existence of a subcritical branch. We revisit this transitional flow using numerical simulation and dynamical systems tools. Additional results concerning the first axisymmetric Hopf bifurcation will be presented. For lower values of Re, at least three flow regimes are identified - base flow, turbulent state and an edge state separating the two. Contrarily to expectations, this edge state features several incommensurate frequencies, involves inertial waves, and does not originate directly from the Hopf bifurcation point. The turbulent solutions (top branch in figure 1a) are also investigated. Evidence will be shown that lifetime distributions are exponential above some value of Re. We will review the analogies in the subcritical transition process between this flow and more common three-dimensional open shear flows such as pipe, channels and Taylor-Couette flows.

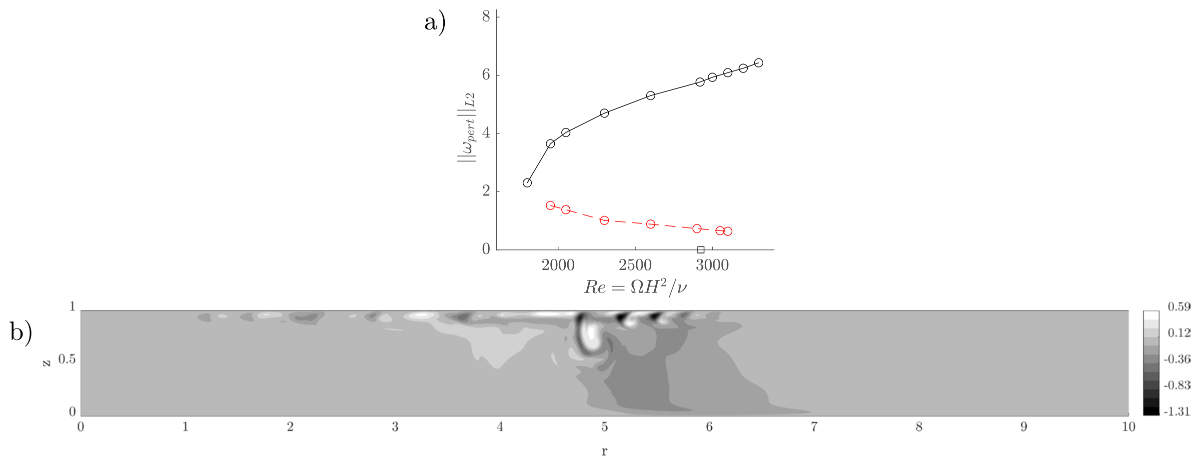

Figure 1: (a) Bifurcation diagram, azimuthal vorticity perturbation norm versus Reynolds number based on height H (b) Meridional cut of the azimuthal velocity of the turbulent roll regime (axis on the left, rotating wall at the bottom, shroud rotating).

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Superharmonic and Triadic Resonances in a Horizontally Oscillated Stratified Cavity

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Abstract

The response of a stably stratified fluid-filled two-dimensional square container to harmonic horizontal oscillations is examined as the forcing amplitude is increased. For the studied forcing frequency, the response flow at very small forcing amplitudes is a synchronous periodic flow with piecewise constant vorticity in regions delineated by the characteristics emanating from the corners of the container, regularized by viscosity Grayer, et al. (2021). The second temporal harmonic of the forced response flow resonantly excites an intrinsic mode of the stratified container Thorpe (1968), whose magnitude grows as the square of the forcing amplitude. Above a critical forcing amplitude, a sequence of pairs of other container modes are excited via triadic resonances with the second-harmonic driven mode. The flows are computed from the Navier–Stokes–Boussinesq equations and the ensuing dynamics are analyzed using Fourier techniques Buchta, et al. (2021), providing a comprehensive picture of the transition to internal wave turbulence.

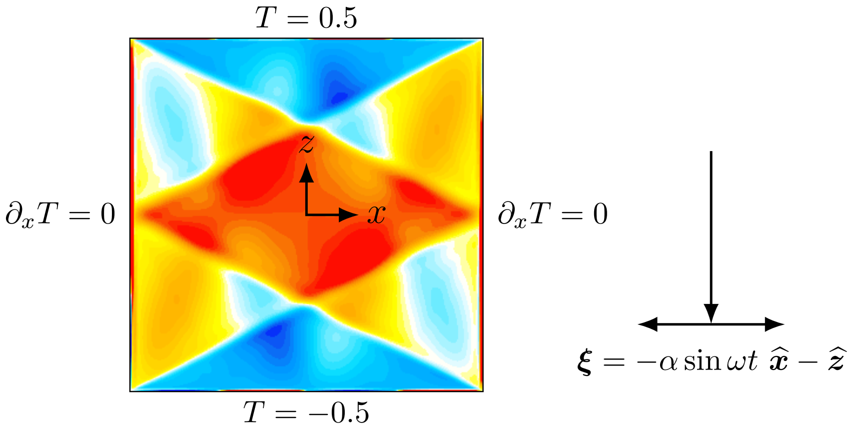

Figure 1: A schematic of the setup with the clear influence of the second temporal harmonic. The vorticity is illustrated.

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The effect of curvature and centrifugal forces on the transition in pipe flow

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Abstract

Being aware of the many unsuccessful attempts to detect linear instabilities for simple shear flows such as pipe, channel and planar Couette flow, Taylor (1923) instead picked a curved version of the latter geometry, the flow between concentric rotating cylinders. In his landmark paper he demonstrated that by adding curvature to the Couette problem a linear instability arises and he moreover found excellent agreement between the theoretical prediction and experiments. In a subsequent study Taylor (1929) investigated curved rather than straight pipes and confirmed an earlier finding that in this case curvature delays the transition. Subsequent studies found that analogous to Couette flow, also in sufficiently curved pipes a supercritical instability arises. In this case a Hopf bifurcation occurs at Reynolds numbers significantly larger than those where instability is encountered in straight pipes. As shown in Figure 1 (figure adapted from Kühnen (2015)) depending on curvature the instability can hence be either sub- or supercritical. In the present talk we will show that unexpectedly in between these two cases, i.e. for intermediate curvature, yet another scenario is encountered. Here, rather than puffs, larger connected regions of turbulence are found. Instead of the familiar continuous transition that occurs in straight pipes, for this intermediate curvature case the transition tends towards a discontinuous case in the infinite pipe limit.

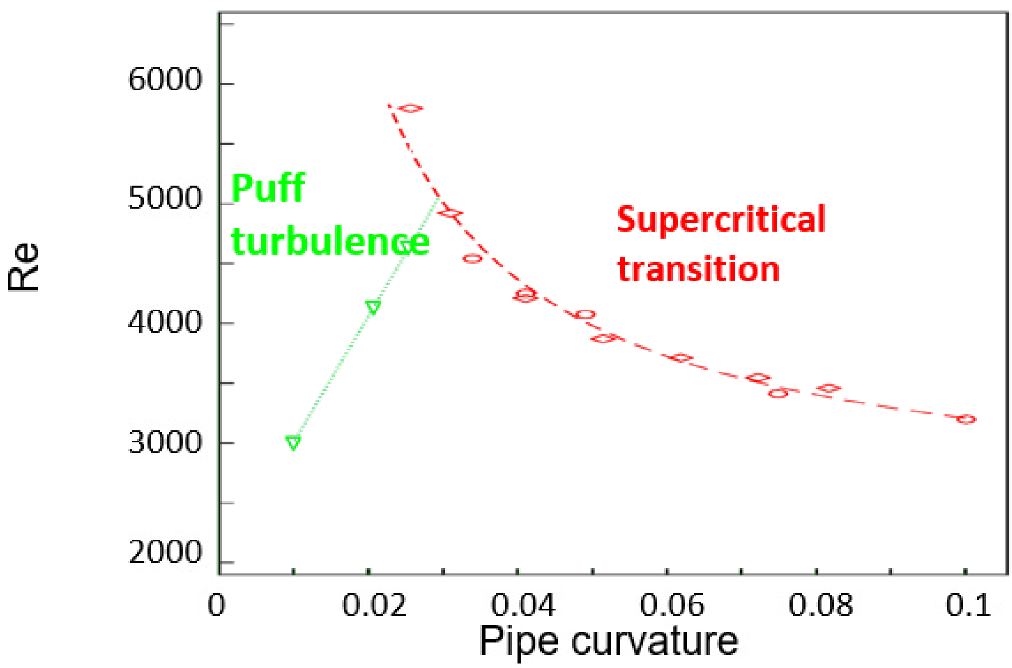

Figure 1: Transition in curved pipes. At low curvature the transition is subcritical and like in straight pipes the structures detected at onset are puffs. At high curvature however the first transition encountere is a superciritical Hopf bifurcation.

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The effects of salinity on bubbly drag reduction in turbulent Taylor–Couette flow

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Abstract

Bubbles in turbulent Taylor–Couette flow can greatly reduce the drag on the inner cylinder. An air volume fraction of only 4% can lead to a drag reduction of 40% van Gils et al. [2013]. This phenomena has very promising applications in the naval industry, where by injection of bubbles underneath the ship hull the drag, and with that the fuel consumption, can be reduced. The effects of water contamination on drag reduction has been given limited attention, although small amount of contaminants can drastically change the system's behaviour Verschoof et al. [2016]. Given the abundance of ions (salts) in the ocean, we want investigate the effects of these salts on bubbly drag reduction.

Using the Twente Turbulent Taylor–Couette setup van Gils et al. [2011] we investigate bubbly drag reduction in a highly turbulent flow ($\mathrm{Re}_i \approx 2 \times 10^6$). We investigate salinities from fresh water up to salt concentrations comparable to seawater. Using a variety of salts (NaCl, $MgCl_2$, Na_2SO_4, $NaCH_3COO$, and substitute ocean salt) we identify the effects of different salts on the drag reduction. High speed imaging is used to capture the bubble sizes and calculate the bubble Weber number, characterizing the bubble deformability. We connect the bubble deformability to the observed drag reduction.

Salts present in the working fluid inhibit the coalescence of bubbles, leading to a smaller bubble sizes in the flow. These smaller bubbles are found to be less effective to reduce the drag, and we see diminishing drag reduction for increasing salinity.

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The influence of rotation on heat and momentum transport in plane Couette and Taylor-Couette flow

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Abstract

Rotation has a strong impact on the transport processes and flow structures in plane Couette flow (PCF) and Taylor-Couette flow (TCF). Momentum transport in rotating PCF and TCF has been investigated by e.g. Brauckmann *et al.* (2016). However, rotation also affects the transport of scalars and heat in Couette flows, but this has been much less explored. Here, we present a study of the influence of rotation on both the heat and momentum transfer in PCF and TCF with a radius ratio $\eta = 0.71$ using DNS, see Brethouwer (2021) and Brethouwer (2023). Buoyancy effects are neglected, and the shear Reynolds number $Re = \Delta U d/\nu$ is varied from 240 to 40 000, where ΔU is the velocity difference and d the gap width between the walls/cylinders. We consider PCF and TCF in a reference frame rotating about the spanwise and axial directions, respectively, and define the rotation number as $R_\Omega = 2\Omega d/\Delta U$, as done in Brauckmann *et al.* (2016). Here, Ω is the frame rotation rate.

We observe that a small to moderate anticyclonic rotation rate leads to significant increase in both momentum and heat transport. However, anticyclonic rotation enhances heat transport more than momentum transport. As a results, the Reynolds analogy between heat and momentum transport breaks down in both PCF and TCF. This effect is particularly pronounced in PCF and TCF subject to fast anticyclonic rotation when the heat transport can be much faster than momentum transport. The turbulent Prandtl number then becomes much less than unity. Figure 1 shows that also the streamwise velocity and temperature field clearly differ when PCF is subject to fast anticyclonic rotation, with large-scale structures being absent in the velocity field but emerging in the temperature field. Further result are presented in Brethouwer (2021) and Brethouwer (2023) and discussed in the presentation.

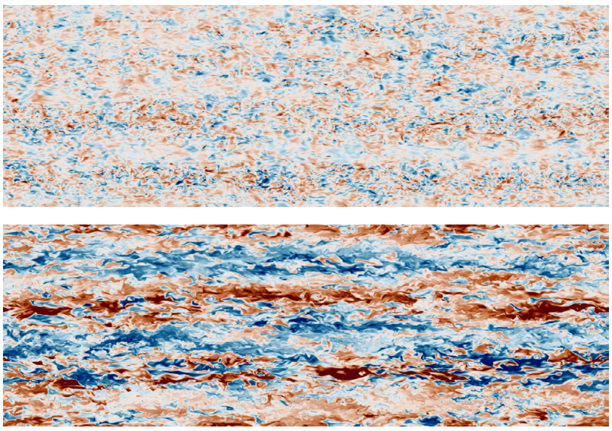

Figure 1: Visualization of the instantaneous streamwise velocity (top) and temperature field (bottom) at the centre plane in rotating plane Couette flow at $Re = 40\,000$ and $R_\Omega = 0.99$.

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The stratified Keplerian turbulence

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Abstract

Studies have revealed that Taylor-Couette flow within the Keplerian regime remains nonlinearly stable, even at high shear Reynolds numbers of up to 10^6. Both numerical simulations and experimental observations have failed to identify any turbulence that is not attributable to interaction with axial boundaries (end plates). Consequently, there is growing evidence that the purely radial shear, may not be the sole driver of turbulence in accretion discs. The most widely accepted explanation now is the magnetorotational instability (MRI), which posits that a conducting fluid in differential rotation subjected to a magnetic field can be destabilized. However, this mechanism cannot operate in some cold and poorly ionized discs. In such cases, thermal effects, in the form of stratification in both the vertical and radial directions, may also play a key role in driving turbulence. Here, through extensive direct numerical simulations of quasi-Keplerian flow with radial stratification, we investigate the generation of turbulence and delineate the various flow regimes concerning the scaling relations of heat and angular momentum as a function of Reynolds number and Richardson number. These findings offer fresh insights into the physical constraints of angular momentum and heat transport in Keplerian turbulence.

Thermomagnetic instability of a ferrofluid Couette flow under a magnetic field in Rayleigh-stable regimes

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Abstract

Ferrofluids are colloidal water- (or oil)-based suspensions of magnetic nanoparticles (1). They have many technological applications including vacuum rotary seals, moving coil loudspeakers, exclusion seal for hard disk drive, stepper motor, cooling of transformers and heat transfer (2; 3; 4). The magnetic particles under the magnetic field pertain a pondermotive force known as Kelvin force whcih contains a non-conservative term which plays the role of a centripetal buoyancy and can destabilize the flow. This magnetic centripetal buoyancy can be associated with an effective magnetic gravity $\mathbf{g}_m = -g_m \mathbf{e}_r$. The linear stability of a ferrofluid flow in a cylindrical annulus with an outward heating and imposed magnetic field is investigated in the case of stationary annulus and in Rayleigh-stable regimes of the circular Couete flows (Keplerian regime, solid-body rotation, sole rotation of the outer cylinder) in which the centrifugal force plays a stabilizing role. In the case of a stationary cylindrical annulus, it has been shown that thermomagnetic convection appears in form of helical stationary vortices when the magnetic Rayleigh number exceeds a critical value which depends on the curvature. The effects of rotation (differential (5) or solid-body) and of the Earth gravity are investigated. Solid-body rotation delays the onset of thermoconvection while Earth gravity dominates the thermal convection for weak magnetic field while magnetic gravity overwhelms for large itensities of the magnetic field.

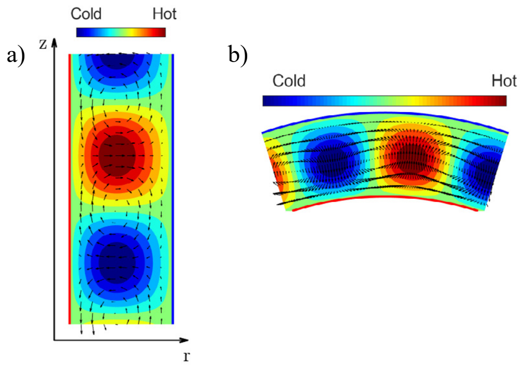

Figure 1: Velocity vectors and temperature fields of the perturbed state for (a) the Keplerian regime and (b) the solid body rotation regime. For the same configuration and the same intensity of the magnetic gravity, the Keplerian regime gives rise to stationary axisymmetric modes whereas the solid body rotation leads to oscillatory columnar modes.

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Transitions in Taylor-Couette flow of concentrated non-colloidal suspensions

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Abstract

Taylor-Couette flow of concentrated non-colloidal suspensions with a rotating inner cylinder and a stationary outer one is numerically investigated. We consider suspensions of the bulk particle volume fraction $\phi_b = 0.2, 0.3$ with the ratio of annular gap to the particle radius $\epsilon = 60$ confined in a cylindrical annulus of the radius ratio (i.e., ratio of inner and outer diameters) $\eta = 0.877$. Numerical simulations are performed by applying suspension-balance model and rheological constitutive laws. To observe flow patterns caused by suspended particles, the Reynolds number of the suspension, based on the bulk particle volume fraction and the rotating velocity of the inner cylinder, is varied up to 180. At high Reynold number, modulated patterns undiscovered in the flow of a semi-dilute suspension emerge beyond a wavy vortex flow. Thus, a transition occurs from the circular Couette flow (CCF) via ribbons (RIB), spiral vortex flow (SVF), wavy spiral vortex flow (WSVF), wavy vortex flow (WVF) and modulated wavy vortex flow (MWVF) for the concentrated suspensions. Moreover, friction and torque coefficients for suspensions are estimated. It turns out that suspended particles significantly enhance the torque on the inner cylinder while reducing friction coefficient and the pseudo Nusselt number. In particular, the coefficients are reduced in the flow of more dense suspensions (Kang et al. (2023)).

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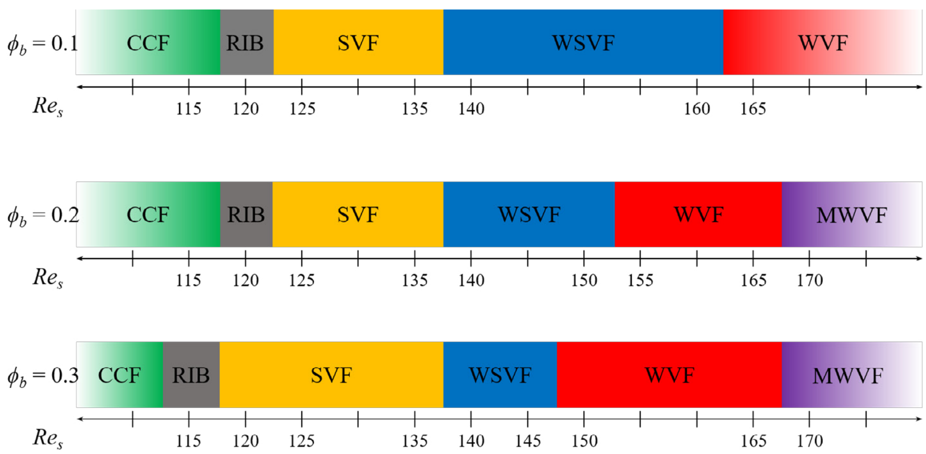

Figure 1: Phase diagrams of flow patterns for suspensions

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