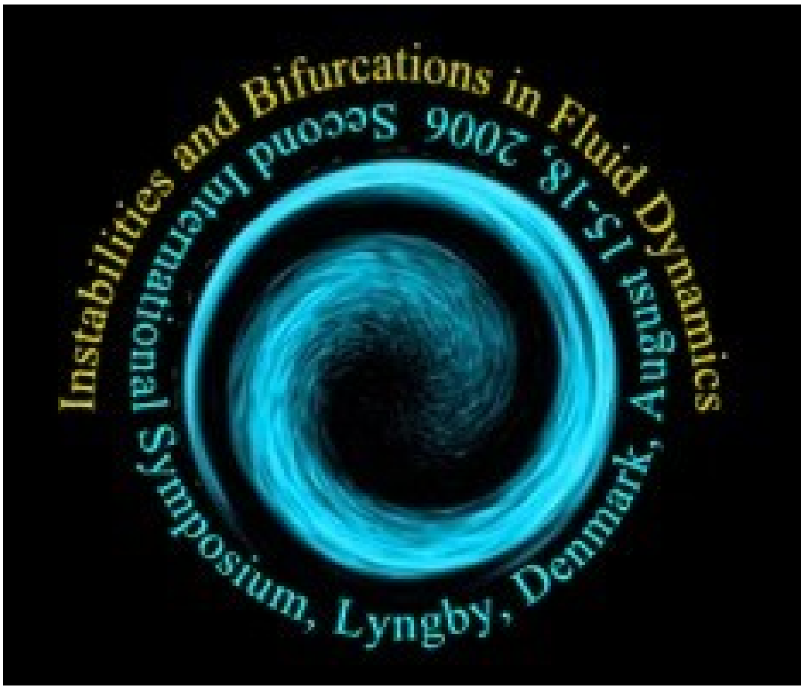

SECOND INTERNATIONAL SYMPOSIUM ON INSTABILITY AND BIFURCATIONS IN FLUID DYNAMICS

AUGUST 15 - 18 2006

TECHNICAL UNIVERSITY OF DENMARK
COPENHAGEN, DENMARK

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Program of the BIFD2006 Symposium

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Convective instabilities in complex systems with partly free surface

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Abstract. Experiments and observations and some selected theoretical studies of thermocapillary instabilities are reviewed. We start with simple idealized model systems of pure thermocapillarity and add to them more complex features like gravity forces, temperature gradients inclined to the free surface, static and dynamic surface deformations, solutocapillary effects and reacting or moving crystal boundaries (like during unidirectional solidification). Many effects and instabilities are demonstrated in video clips which can be downloaded from http://meyweb.physik.uni-giessen.de/1_Forschung/crystalgrowth/video/ homepage.html. We try to point out the relationship of thermocapillary instabilities in the more complex systems with those in theoretical studies where the name of these instabilities has been coined.

Double Diffusive Instabilities of Statically Stable Chemical Fronts

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[2]*Mechanical & Aerospace Engineering, Rutgers University*

Gravitational Hele-Shaw fingering of an autocatalytic reaction diffusion interface is investigated theoretically. Dimensional analysis based on reaction diffusion length, time, and velocity scales reveal the dependence on the Lewis number Le, and thermal and concentration Rayleigh numbers R_T and R_c. Linear stability analysis of a planar upward propagating (against the gravitational acceleration) interface results in an eigenvalue problem for each wavenumber k which we solve using a Chebyshev pseudospectral method. Novel light over heavy instabilities were found when $Le > 1$. One instability branch corresponds to an upward endothermic front that is equivalent to a downward propagating exothermic wave. Nonlinear second-order Crank-Nicolson, finite volume simulations are in agreement with linear theory and also show the docile nature of the interface breakup. A displaced particle argument confirms that this unexpected instability is local, that it is subdued by a region of local stability behind the front, and elucidates its dependence on the underlying reaction diffusion mechanism. A second branch of statically stable systems corresponds to an upward exothermic reaction. Displaced particle argument also explains this instability that takes place ahead of the front. This is confirmed by nonlinear computations with interface fingering much larger than that of the former branch.

Study of passive dye dispersion in convective hexagonal pattern

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The dispersion of a passive molecular dye in a convecting liquid has two physical origins: firstly the molecular diffusion from streamline to streamline, secondly, the transport of the tracer in the flow. So the goal of this work is to study this phenomenon in a hexagonal pattern of Bénard-Marangoni (BM) convection. Furthermore, it is also of interest to evaluate the effective (global) diffusion coefficient, which is strongly enhanced by the advection with respect to molecular diffusion coefficient alone. Moreover it is not straightforward to estimate it in such BM convection pattern, where the fluid flow is three-dimensional and periodical from cell to cell.

This study has been undertaken experimentally and numerically. In the experimental process, one first establishes a steady convective hexagonal pattern, where classically the fluid flow is upward at the cell centre and downward along the cell sides (Prandtl number ≈ 900). Then the dye is injected into the centre of a cell located in the middle of the pattern and dispersion takes place. This process has been numerically simulated by the means of a finite element model, previously validated in Bénard-Marangoni convection [1].

The computations have been undertaken for several Peclet numbers, but fluid flow characteristics being kept constant. One can distinguish two mechanisms of dispersion: inside a cell and from cell to cell. In the latter, only diffusion acts across the cell side in the horizontal direction, i.e. between symmetric facing streamlines with respect to the cell side. On the other hand, the dispersion inside a cell behaves streamwise depending on either the convective and diffusive fluxes add each other (low concentration gradient) or they oppose each other (high concentration gradient), while in the transversal direction by molecular diffusion. The global diffusion coefficient is enhanced by a factor from 10^2 to 10^5 depending on the Peclet number. Figure 1 illustrates the observed behaviour.

Reference:

M. Medale and P. Cerisier: Numerical Simulation of Bénard-Marangoni Convection in small aspect ratio containers, *Num. Heat Transf. A*, **42**, pp. 55-72 (2002).

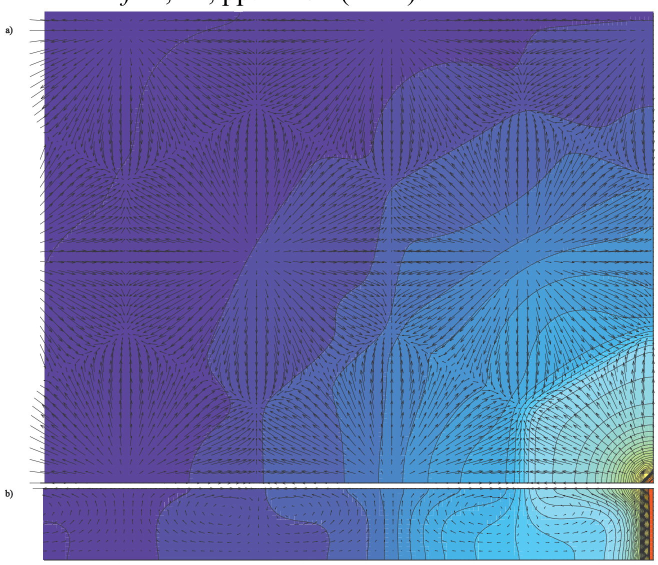

Figure 1: Computed velocity and concentration fields for Ma=85, Ra=0, Bi=0 and Pe=10, at t=7.2 s.
a) Top view of the free surface; b) Cross section in the (y, z) symmetry plane.

Instabilities due to a heating spike

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We study from the numerical point of view, instabilities developed in a fluid layer with a free surface, in a cylindrical container which at the bottom has a heating spike modelled by a parameter β. This localised heating approaches a boundary condition for a thermal plume. The partial differential equations that model this problem are discretized with a Chebyshev collocation method with appropiate conditions for the pressure field [1]. An axysimmetric basic state appears as soon as a non-zero lateral temperature gradient is imposed. A preconditioned Arnoldi method has been used to compute the eigenvalues for the linear stability analysis [2, 3]. The basic state may bifurcate to different solutions depending on vertical and lateral temperature gradients and on the shape of the heating. We find different kinds of instabilities: extended patterns growing on the whole domain which include those known as target and spiral waves [4]. Localised structures both at the origin and at the outer part of the cylinder may appear either as Hopf or stationary bifurcations.

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[4] M.C. Navarro, A.M. Mancho and H. Herrero, Spiral Instabilities in Rayleigh-Bénard Convection under Localised Heating, *Chaos*, submitted.

The influence of parametric forcing on the non-equilibrium dynamics of wave patterns

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We investigate analytically and numerically the effect of heterogeneities on the non-equilibrium dynamics of wave patterns in the framework of complex Ginzburg-Landau equation with parametric, non-resonant forcing periodic in space and time. The effect of modulations on the dispersion properties of traveling waves is analyzed, and wave solutions with essentially anharmonic spatial structure are found. We consider the influence of modulations on the development of an intermittent chaos and show that the parametric forcing may completely suppress the appearance of chaotic patterns. The results obtained are applied to describe the dynamics of thermal Rossby waves influenced by surface topography.

Draw Resonance Revisited

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We consider the problem of isothermal fiber spinning in a Newtonian fluid with no inertia. In particular, we focus on the effect of the downstream boundary condition. For prescribed velocity, it is well known that an instability known as draw resonance occurs at draw ratios in excess of about 20.2. We shall revisit this problem. Using the closed form solution of the differential equation, we shall show that an infinite family of eigenvalues exists and discuss its asymptotics. We also discuss other boundary conditions. If the force in the filament is prescribed, no eigenvalues exist, and the problem is stable at all draw ratios. If the area of the cross section is prescribed downstream, on the other hand, the problem is unstable at any draw ratio. Finally, we discuss the stability when the drawing speed is controlled in response to changes in cross section or force.

STREAMLINE TOPOLOGY IN VORTEX STREETS

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A standard approach to modeling the laminar wake of a bluff body is to consider point vortices in two-dimensional potential flow with periodic boundary conditions. When the vortex street is modeled as two oppositely signed vortices in a singly periodic strip, any choice of vortex positions gives a uniformly translating relative equilibrium. In the case of the staggered Kármán street, the wake translates along its length, and adjacent co-moving points (i.e., stagnation points in a frame moving with the vortices) are joined by streamlines. For small deviations from this ideal case, however, the wake translates obliquely, and the streamline structure can become quite intricate. Fluid entrained in the wake can be wrapped around many of the vortices before passing through to the other side. The bifurcations that occur in the streamline topology of obliquely translating vortex streets and the influence of this structure on mixing in wakes will be discussed.

HYDRODYNAMIC INSTABILITY AND SPIRAL GROWTH OF BULK SINGLE CRYSTALS

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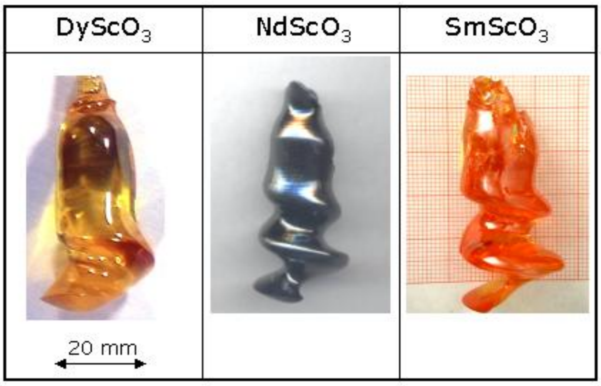
The growth of rare-earth scandates from the melt has become very important during the last few years. These crystals are excellent candidates for substrates of ferroelectric materials (e.g. non-volatile FRAMs). Unfortunately most scandates tend to produce an undesirable spiral structure during the growing process. Even in axisymmetric conditions with axisymmetric initial conditions, a spiral structure can arise via spontaneous symmetry breaking. The figure shows three examples grown at melting temperatures of about 2000°C using the Czochralski method. These high temperatures make internal measurements very difficult and a numerical simulation is required to understand what is happening..
The theoretical approach starts from a 2D axisymmetric solution and considers the stability of the solution with respect to 3D disturbances. This approach gives rise to a set of eigenvalue problems and is similar to that already published by an Israeli group [1]. The eigenvalue calculations can be used to estimate the approximate critical value of a parameter (such as crystal rotation rate) at which the symmetry breaking bifurcation occurs. The bifurcation points can be located exactly using an appropriate extended system of equations, and an effective numerical branch following technique used to compute paths of these bifurcation points as a second parameter is varied. This curve bounds the region in which no instability to spiral growth patterns occurs.



Numerical results in 2D and growth experiments already show the relative importance of several internal and external conditions that influence the flow pattern in the melt in a way to promote or avoid spiral growth. In our assumptions about the basic mechanism of spiral growth (corkscrew instability) the hydrodynamic interaction plays a significant role. It turns out that an analysis of the growth stability can be performed in terms of fluid flow behavior, i.e. a bifurcation study for the hydrodynamic parameters applied to the Navier-Stokes equations. Since the momentum equations are strongly coupled to the thermal conditions including radiation the problem becomes complex and therefore only the most significant parameters have been taken into account. This may happen directly by modifying the flow conditions (rotation rate, crucible shape) or via influencing the thermal environment (thermal absorption in the crystal, shape and location of a baffle). It can be shown that these modifications cause considerable changes of stable and unstable regions in a bifurcation diagram. The regions mark the border lines to be used for real crystal growth processes in order to avoid unstable growth conditions. However, this stability analysis only yields a solution for the limiting case determining the transition to a real 3D solution. The enormous computational requirements for solving sequences of eigenvalue calculations, 2D transient as well as the direct 3D computations can be met by applying a partly iterative solver combined with the fastest currently available direct solver MUMPS [2]. Moreover, recently IKZ became a privileged user of HLRN [3] allowing us to benefit from a total performance of about 5 TeraFlops

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J. Crystal Growth, **275**, e7-e13 (2005).
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Bifurcation of Streamline Patterns – Methods and Applications

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A qualitative (or topological) description of structures in fluid flows such as vortices and separated regions is of basic interest. We review some systematic methods to describe the creation and interaction of structures on the basis of bifurcation theory for low-dimensional dynamical systems, and how these topological bifurcations relate to dynamical bifurcations in the Navier-Stokes equations. We discuss the numerical implementation and some examples including vortex breakdown, the cylinder wake, and flow near walls with a Navier slip boundary condition.

Magnetic field effects on stability of convective flows

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Two model problems are considered to study the effect of an externally imposed magnetic field on buoyancy convective flows in rectangular or cylindrical cavities. The first problem is an extension of the benchmark [1], which we extend by adding the action of an external arbitrary directed magnetic field. Convection of a low-Prandtl-number fluid in a laterally heated two-dimensional horizontal cavity is studied. Fixed values of the aspect ratio (length/height=4) and Prandtl number (Pr = 0.015), which are associated with the horizontal Bridgman crystal growth process and are commonly used for benchmarking purposes, are considered. The effect of a uniform magnetic field with different magnitudes and orientations on the stability of the two distinct branches (with a single-cell or a two-cell pattern) of the steady state flows is investigated. Stability diagrams showing the dependence of the critical Grashof number on the Hartmann number are presented. It is shown that a vertical magnetic field provides the strongest stabilization effect, and also that multiplicity of steady states is suppressed by the electromagnetic effect, so that at a certain field level only the single-cell flows remain stable. Analysis of the most unstable flow perturbations shows that starting with a certain value of the Hartmann number, single-cell flows are destabilized inside thin Hartmann boundary layers. This can lead to destabilization of the flow with increase of the field magnitude, as is seen from the stability diagrams obtained. Contrary to the expected monotonicity of the stabilization process with increase of the field strength, the marginal stability curves show non-monotonic behavior and may contain hysteresis loops.

The second problem is a continuation of the study of three-dimensional instability of convection in a cylinder heated non-uniformly from its sidewall [2], which we extend by an addition of the electromagnetic force caused by an axial magnetic field. Convection in a vertical cylinder with a parabolic temperature profile on the sidewall is considered as a representative model. A parametric study of the dependence of the critical Grashof number Gr_{cr} on the Hartmann number Ha for fixed values of the Prandtl number (Pr = 0.015) and the aspect ratio of the cylinder (A = height/radius = 1, 2 and 3) is carried out. The stability diagram $Gr_{cr}(Ha)$ corresponding to the axisymmetric – three-dimensional transition for increasing values of the axial magnetic field is obtained. It is shown that at relatively small values of the Hartmann number the axisymmetric flow tends to be oscillatory unstable. After the magnitude of the magnetic field (the Hartmann number) exceeds a certain value the instability switches to a steady bifurcation caused by the Rayleigh-Bénard mechanism. More details on both problems considered can be found in [3,4].

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Experimental study of the suppression of Rayleigh–Bénard instability in a cylinder by combined rotating and static magnetic fields

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We consider experimentally transitions in a liquid metal cylinder heated from below and subject to superimposed rotating and static magnetic fields. Being itself unstable, a strong enough rotating magnetic field (RMF) driven flow suppresses considerably the temperature fluctuations due to the thermo-gravitational convection. The remaining fluctuations are caused by unsteady Taylor vortices generated near the side wall. This may be regarded as an 'embedded transition' between a large scale buoyancy driven and a small scale RMF driven turbulence. One of major keys to the RMF governed state is the additional unstable steady solutions disconnected from the basic flow and bifurcating well before the linear instability of a different type. Previous numerical studies have shown that the amplitude of these additional solutions is differently affected by different superimposed static fields. Main aim of our experiment was to verify if this difference is also reflected in the amplitude of temperature fluctuations.

Two types of static axisymmetric magnetic field were used: uniform axial and the so-called 'cusp' field. The experiment shows that the superimposed static 'cusp' field further reduces the amplitude and characteristic period of the remaining temperature fluctuations while a superimposed uniform axial field has no such effect. Moreover, the factor of fluctuation suppression agreed almost perfectly with the factor by which the amplitude of the additional steady solutions is reduced by the 'cusp' field. Thus, the observations of RMF driven turbulent state are consistent with description of a turbulent shear flow [1] as a trajectory wound irregularly on the skeleton of the additional unstable flow states. If this 'skeleton' is compressed by an external influence (the 'cusp' static field in our case), then also the averaged amplitude of turbulent fluctuations decreases by the same factor.

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On solitary vortices near the convection threshold in ferrocolloid

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Experimental studies and numerical simulations of stability of buoyancy-driven flows in a ferrocolloid for the cases of horizontal and inclined vertical orientation of a thin cylindrical cavity are performed. The ferrocolloid contains single domain magnetite particles suspended in kerosene carrier liquid and has the susceptibility thousand times higher then natural media. The influence of a homogeneous longitudinal magnetic field on convective instability and spatio-temporal patterns was also investigated. The results prove that a uniform longitudinal magnetic field allows to control the stability and the shape of secondary convection motions at inclined orientation of layer. The spirals, localized states and other travelling wave regimes were revealed.

In the case of ferrocolloids the gradients of magnetic permeability may arise due to both temperature and particle concentration gradients. The particle mass flux in a classical form is summarized from the translation diffusion coefficient and the thermal diffusion ratio. However, the explanation for the observed self-oscillation regimes in magnetic fluid for the cavities of sufficiently large thickness (several to tens of millimeters) is conditioned by the competition of density variations originating from the fluid thermal expansion and barometric sedimentation. So at the terrestrial conditions the heat and mass transfer is essentially complicated because of the uncontrollable gravitational sedimentation of magnetic particles and their aggregates.

As known, thermally driven shear flow in an inclined layer draws up convection rolls in the direction of inclination. In a ferrocolloid the repeated transients involving localized roll convection and pure shear flow took place. Under action of uniform longitudinal magnetic field orientated perpendicular to flux velocity of shear motion on such long-wave transients can lead to complicated types of chaotic localized states or solitary vortices.

Visualization of convection patterns was provided by means of liquid crystal sheet. The temperature oscillations were registered using thermocouples. Temporal evolution of the oscillations was analyzed using wavelets. The frequencies of temperature oscillations obtained under wavelet analysis were compared with results of Fourier analysis and visual observations with the help of video camera. Two main types of frequencies corresponding to multi-hour and minute periods were registered. They account for fast or slow (global) changes of patterns. To study the effect of sedimentation of large aggregates on convective instabilities, numerical simulations using both single phase assumption and two-phase mixture model were carried out for the same setup.

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SOLUTOCAPILLARY SPHERICAL CONVECTION

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Marangoni convection can be driven in spherical shells containing a solvent and a solute due to solvent evaporation at the outer surface. The viscosity is a function of the solvent concentration, the inner surface is assumed impermeable and stress free, while non-linear boundary conditions are derived and prescribed at the receding outer boundary due to evaporation with a prescribed mass transfer coefficient. A time-dependent diffusive state is possible and may lose stability because of surface tension dependence on solvent concentration. The Capillary number provides a measure of the deviation from sphericity and as it tends to zero the leading order outer surface evolves with time in a convective state as it does in the diffusive state. A frozen-time or quasi-steady state linear stability analysis is performed to compute the critical Reynolds number and degree of surface harmonics, as well as the maximum growth rate of perturbations at specified parameters. The development of maximum growth rates in time is also computed by solving the initial value problem with random initial conditions. Results from both approaches are in good agreement except at short times where there is dependence on initial conditions. We compute nonlinear, time-dependent, axisymmetric and three-dimensional supercritical motions and companion, compatible free surface deformations in this moving boundary problem subject to random initial conditions. The nonlinear results are compared with those from linear theory and microencapsulation experiments on laser targets used in inertial confinement fusion.

Oscillatory instability in a closed cylinder with rotating top and bottom

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A numerical investigation of oscillatory instability is presented for axisymmetric swirling flow in a closed cylinder with rotating top and bottom. The critical Reynolds number and frequency of the oscillations are evaluated as function of the ratio of angular velocities of the bottom and the top ($\xi = \Omega_{bottom} / \Omega_{top}$). Earlier Linear Stability Analysis (LSA) using the Galerkin spectral method by Gelfgat et al. [Phys. Fluids, **8**, 2614-2625 (1996)] revealed that the curve of the critical Reynolds number behaves like an "S" around $\xi = 0.54$ in the co-rotation branch and around $\xi = -0.63$ in the counter-rotation branch. Additional finite volume computations, however, did not show a clear "S" behaviour.

In order to check the existence of the "S" shape, computations are performed using an axisymmetric finite volume Navier-Stokes code at aspect ratios ($\lambda = H / R$) 1.5 and 2.0. Comparisons with LSA at $\lambda = 1.5$ show that the "S" shape does exist. At an aspect ratio $\lambda = 2$, our results show that the critical Reynolds number curve has a "beak" shape in the counter-rotation region and a much wider "S" shape in the co-rotation region. This transformation of the "S" shape is caused by the change in aspect ratio from 1.5 to 2 and therefore the corresponding topological behaviour of the transition is different.

The bifurcation from a steady to an unsteady regime is governed by Hopf bifurcations in most of the counter and co-rotating regions. In a region close to the top of the "S" shape, however, a discontinuous bifurcation has been detected.

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Instabilities in magnetic spherical Couette flow

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I consider the flow of an electrically conducting fluid in a spherical shell, with the inner sphere rotating, and the outer sphere at rest. A uniform magnetic field is also imposed, parallel to the inner sphere's axis of rotation. I numerically compute both the axisymmetric basic state, and show how it varies with the Reynolds number Re (measuring the inner sphere's rotation rate) and the Hartmann number Ha (measuring the magnetic field strength), and then also compute the onset of non-axisymmetric instabilities. For weak fields the instabilities are equatorially antisymmetric; for strong fields they are equatorially symmetric. The transition from one regime to the other is mapped out in detail. Finally, I consider the nonlinear equilibration of some of these instabilities, and obtain further bifurcations and transitions between different states.

“Spatial limitation and gravity effects on the Taylor-Couette flow”

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Abstract

The problem studied here is the laminar – turbulent transition in two coaxial rotating cylinders under certain conditions such as height limitation H and inclination α of the system of the flow with the vertical axis. In that case the structure of the flow may be com unstable leading to, possibly, new instabilities and modifications regime. According to $\alpha = 0$ the type of instabilities is commonly known as the classical Taylor – Couette flow, and a large body of literature on this topic has developed over a century in both experimental and theoretical works. Yet surprisingly, this literature appears to be unknown for a given inclination α in the game $0 \leq \alpha \leq 90\,°$ as Taylor number Ta is increasing. Using visualisation techniques, observations indicate the existence of the three regimes (WVF, MWVF and Chaos) and consequently different modification on α. Of particular importance is the aspect ratio $\Gamma = \frac{H}{d}$ which is also discussed. When the system is completely filled $H = H_{\max}$, the angle of inclination α has no the effect on the flow. Otherwise, the most significant result concerns the relaminarization of the flow when Γ decreases and Ta number is increasing for a given value of α.

"Gravity effect on the flow between two coaxial rotating spheres"

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Abstract

With general acceptance that the flow between two coaxial rotating spheres or spherical Taylor–Couette flow is highly structured and has come a wealth of literature dealing with instabilities in laminar–turbulent regime. The present work regarding new measurements point out the possible effects of gravity and free surface on the onset of instabilities in spherical Taylor–Couette flow. The phenomena were described by visualization techniques in such a way as Taylor number *Ta* increases according to the appearance of instabilities induced by means of an inclination α (i.e. gravity effect) of the system of the flow and this constrained to move step by step on the angular range $0 \leq \alpha \leq 90°$ from the vertical axis ($\alpha = 0°$). It is observed that when the system is completely filled $H = H_{max}$ the angle of inclination has no effect. For a given height limitation of the flow $H < H_{max}$, the most significant result concerns the dependence on α of the onset wavy mode instability, say, $Tc_2 = Tc_2(\alpha)$ while Tc_1 characterize the appearance of the Taylor vortex flow remains unchanged as α is increasing. Another significant result concerns the relaminarization of the flow as both values of the Taylor number *Ta* and α are increasing.

Nonlinear stability of buoyant-thermocapillary flows in two-layer systems with a temperature gradient along the interface

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During the last decades, convective flows in systems with an interface have been a subject of an extensive investigation. Several classes of instabilities have been found by means of the linear stability theory for purely thermocapillary flows, and for buoyant-thermocapillary flows. The most of the investigations have been fulfilled for a sole liquid layer with a free surface, i.e., in the framework of the one-layer approach. Recently, Madruga et al. [1] studied the linear stability of two superposed horizontal liquid layers bounded by two solid planes and subjected to a horizontal temperature gradient. The analysis has revealed a variety of instability modes. Specifically, for the system 5cS silicone oil - HT70, the analysis predicts a change in the direction of the wave propagation with the growth of the ratio of the layers thicknesses.

In the present work, the nonlinear stability of two superposed horizontal liquid layers bounded by two solid planes and subjected to a horizontal temperature gradient, is investigated. The boundary value problem is solved by the finite-difference method. Two types of boundary conditions - periodic boundary conditions and heat - insulated lateral walls, are considered. The nonlinear simulations of the wavy convective regimes for the system 5cS silicone oil - HT70, are performed. It is found that the direction of the wave propagation depends on two factors, the ratio of the layers thicknesses (as it was predicted by the linear theory), and the Marangoni number. For sufficiently large values of the Grashof number values, the wave velocity is changed in a non-monotonic way. The general diagram of regimes is constructed. In long computational regions all types of traveling waves keep their perfect periodicity. Pulsating traveling waves changing their form and intensity, are observed.

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Pattern dynamics of the Bénard-Marangoni instability in a medium aspect ratio container

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This study is an experimental work devoted to Bénard-Marangoni instability in a medium vessel. The free surface deformation is visualised by interferometry (Fig. 1) and the free surface temperature field by infrared thermography (Fig. 2). These two techniques are complementary, since each method provides specific information, which may allow the detection of peculiar phenomena such as the spatial resonance, which is a situation in which the interfacial deformation does not conform to the flow pattern (Hadji, (1996)).

The influences of the aspect ratio, Rayleigh, Biot and Prandtl numbers, are considered. More dynamics are induced by increasing the Biot number. Conversely, increasing the Prandtl number reduces the dynamics. The deformation magnitude and the wavenumber increase as functions of the gradient of temperature. Two behaviours of the deformation, as a function of Prandtl and Biot numbers, were observed, depending on the value of the applied gradient of temperature.

The obtained results are discussed with previous experimental, theoretical and numerical studies. Results of other authors were confirmed concerning the evolution as functions of the gradient of temperature and the aspect ratio and new results were obtained concerning the behaviour of the pattern as functions of Pr and Biot numbers.

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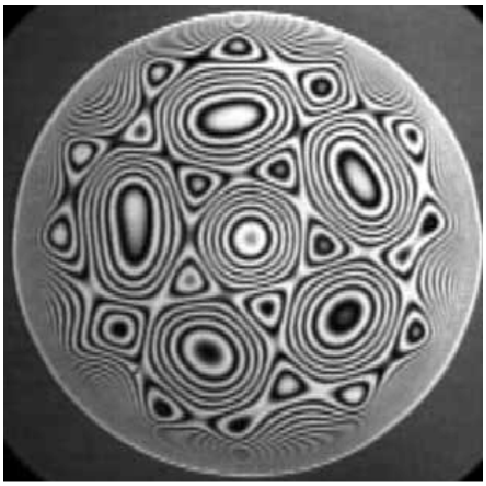

Figure 1: Free surface deformation obtained by interferometry.

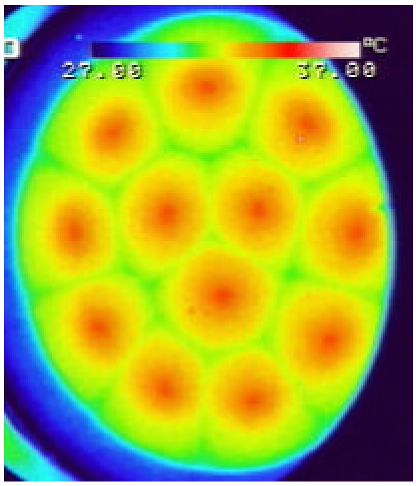

Figure 2: Temperature field visualised using infrared thermography.

Experiments on instability of thermocapillary convection in shallow annular liquid layers

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Abstract

Experimental study of thermocapillary convection of silicone oil (the Prandtl number Pr≈18) was conducted in a shallow annular cavity with outer radius R_o=55 mm and inner radius R_i=15 or 27.5 mm for liquid heights H in the range 1–3 mm. These heights correspond to aspect ratios $Ar=(R_o–R_i)/H$ in the range $9 \leq Ar \leq 40$. The liquid layer is heated from the outer cylindrical wall and cooled at the inner wall. The experiments were performed over a wide range of Marangoni numbers, 400<Ma<10000. The measurement of surface temperatures and observation of instability structures were made by using an infrared thermography technique. As Ma was exceeds a critical value, hydrothermal waves were observed for thin liquid layers, $H \leq$ 2.5 mm, of both the inner radii (Fig. 1). These waves are characterized by curved spoke patterns traveling in the azimuthal direction, owing to the surface basic flow toward the inner wall. For thicker layers, H>2.5 mm, oscillating longitudinal roll-type patterns were dominated (Fig. 2). For intermediate heights of layers, H≈2.5 mm, corresponding to the dynamic Bond number of Bo≈0.9, hydrothermal waves and longitudinal rolls coexisted. The transition map is presented in terms of Ma and Bo.

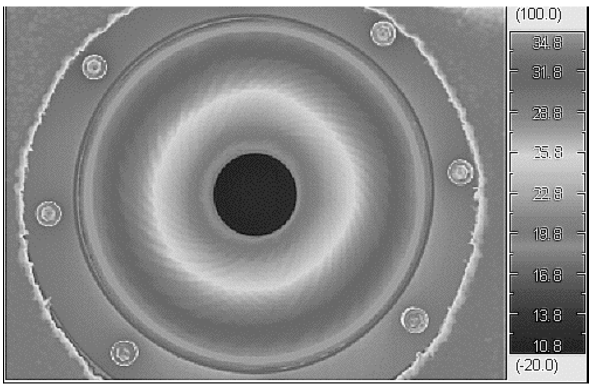

Fig. 1 Instantaneous thermograph of hydrothermal waves.

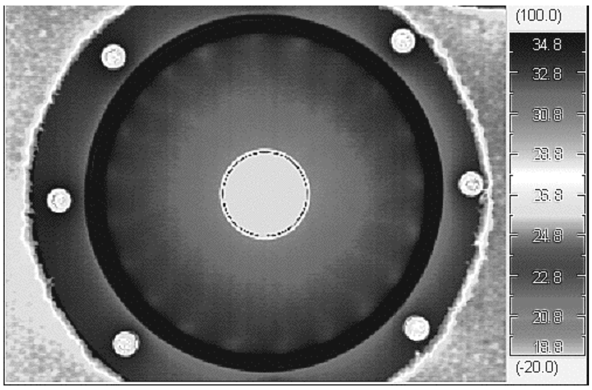

Fig. 2 Instantaneous thermograph of unsteady rolls.

Bifurcation to chaos in the Bénard-Marangoni instability in a confined geometry.

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An experimental study of dynamical regimes in Bénard - Marangoni convection, for various Prandt and Marangoni numbers, has been carried out in a confined geometry. Indeed, a small hexagonal vessel allowing the formation of only one convective cell, for a large extent of the Marangoni number, has been used (Fig. 1). Fourrier spectra (Fig. 2) and a correlation function have been used to recognize the various dynamical regimes. For fixed values of the Prantl number and aspect ratio; an oscillatory, a quasi-periodic and chaotic states were successively observed, as the Marangoni number was increased. The correlation dimensions of strange attractors corresponding to the chaotic regimes were calculated [1]. The dimensions were found to be larger then those calculated by other authors for the Rayleigh-Bénard convection in small aspect ratio geometries [2]. The transition from temporal chaos to spatio - temporal chaos has also been observed. Indeed for higher values of the Marangoni number, spatial dynamics are observed.

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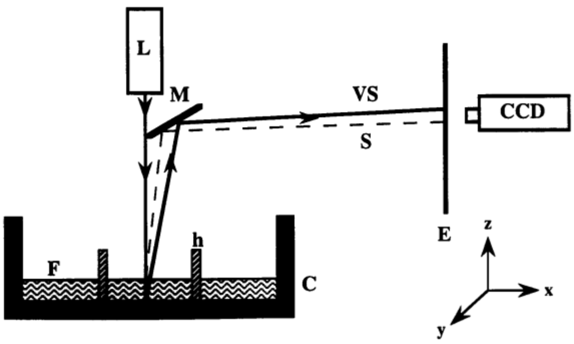

Fig. 1: Experimental set - up. C: Container, h: hexagonal vessel, F: Fluid, M: Mirror, L: Laser, E: Screen, CCD: Camera.

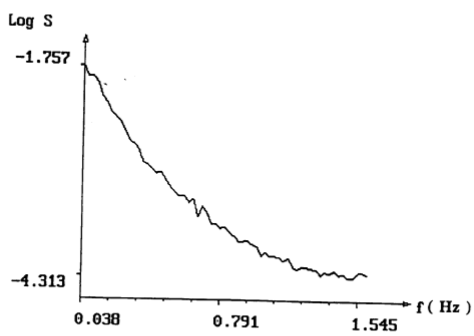

Fig. 2: Power Fourier spectrum of a chaotic regime.

Pattern formation in the longwave Marangoni instability of a binary liquid with the Soret effect

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The longwave Marangoni instability in a binary-liquid (mixture of two species) film with the Soret effect (thermodiffusion) is discussed.
Both monotonic and oscillatory instabilities attributed solely to the presence of the Soret effect are found in the case of a finite heat transfer rate at the liquid-gas interface. A set of nonlinear partial differential equations of evolution type describing the spatiotemporal dynamics of the film thickness and the solute concentration in the oscillatory regime is derived. Weakly nonlinear analysis in the case of the oscillatory instability based on these evolution equations shows the emergence of several kinds of stable supercritical standing and traveling waves along with superposition of two traveling waves propagating at a certain angle in various parameter domains.

Bifurcations of a weighted-residual integral boundary-layer model for nonlinear dynamics of modulated falling liquid films

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We have carried out a numerical investigation of the nonlinear dynamics of thin modulated and non-modulated falling films on a vertical solid plate in the context of the first-order weighted-residual boundary-layer (WRIBL) equations that extend those derived by Ruyer-Quil and Manneville [1]

$$h_t + q_x = 0, \tag{1a}$$

$$q_t = \frac{5}{6}h + \frac{5}{6}\kappa h h_{xxx} - \frac{5}{2}\frac{q}{h^2} - \frac{17}{7}\frac{q q_x}{h} + \frac{9}{7}\frac{q^2 h_x}{h^2} + \mathcal{F}(t, h, q; \delta, \Omega), \tag{1b}$$

where $h = h(x,t), q = q(x,t)$ are, respectively, the local film thickness and the leading-order approximation of the volumetric flow rate

$$q = \int_0^h u \, dy, \tag{2}$$

and δ, Ω are, respectively, dimensionless amplitude and frequency of in-plane harmonic oscillations of the plate. We have found that in the case of a stationary plate, these equations, augmented with periodic boundary conditions have been shown to admit solutions of various kinds, among which one finds traveling waves (TW) and several types of aperiodic non-stationary waves (NSW). We note that while TW solutions were documented previously by [1,2], the existence of NSW solutions for Eqs.(1) is first determined in this paper. Furthermore, we found the coexistence of stable TW flows in several parametric regions. Additional coexisting forms of TW and NSW have also been observed. We have found that the first-order WRIBL equations investigated reveal a local loss of positivity of the volumetric flow rate that suggests the emergence of flow reversal. To our knowledge, this phenomenon has not been documented for vertically falling films neither experimentally nor numerically. while we cannot rule out the emergence of this local phenomenon, we conclude that positivity loss of the flow rate is a special feature of the first-order WRIBL and may be spurious.

The bifurcation structures of various cases in the non-modulated regime investigated have several common features: (i) traveling waves of the γ_1-type (depression-type) bifurcate from the stability threshold of the system; (ii) slightly before the parameter range, where the second mode becomes linearly unstable, a coexistence between the traveling waves of γ_1- and γ_2 (hump) -types arises; (iii) traveling waves of the γ_2-type then become dominant; (iv) the γ_2-type waves then lose stability to a non-stationary flow regime; (v) when more unstable modes become involved in the film dynamics, an increase in complexity of the spatiotemporal film dynamics occurs.

Harmonic modulation of TW and various NSW solutions retains their fundamental non-modulated spatial form but evolve to temporal quasiperiodic and chaotic solutions respecively.

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Using Singular Vectors and Rossby Waves Interaction to Understand Optimal Growth in Shear Flows

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Shear flows are inherently non-normal dynamical systems in the sense that their linearized eigen functions are not orthonormal. As a result, a superposition of the eigenfunctions might yield transient growth even if all their eigenvalues are negative. Hence, although the linearized system is asymptotically stable it can exhibit large growth in final time and become nonlinearly unstable.Consequently, the linearized stable asymptotic limit becomes irrelevant.

Furthermore, in non-normal unstable linear systems, the maximal possible growth is always larger than the growth given by the largest eigenvalue (the most unstable normal mode).Thus, in order to obtain the optimal growth, that is the largest possible growth the system extracts for a given target time, one needs to apply a Singular Value Decomposition (SVD) of the propagator matrix, rather than an eigen value decomposition. The first singular value gives the maximal growth where the structure of the optimally growing perturbation is given by the singular vectors.

Here, we will present the SVD formulation and its application for non-normal dynamical systems. Next we will use the Rossby Wave perspective to find the vorticity perturbation building blocks and will describe the optimal evolution in terms of constructive interaction between those waves.

Bifurcations and properties of stochastic regimes of double-diffusive convection.

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Transition to turbulence and its development is under consideration for double-diffusive convection in plain layer. For calculations we are using Bubnov-Galerkin method. During the computation the relative residual was calculated, so proximity to the genuine solution could be estimated. For moderate supercriticalities 20 space harmonics are sufficient for relative residual to be less than 0.001. Sequence of bifurcations leading to the formation of the attracting manifold, which has a structure of Mebius band, and its reverse bifurcation cascade is investigated. Existence of periodic solutions after the reverse cascade of bifurcations is shown. Qualitative changes in the structure of Poincare mapping with the growth of supercriticality after the transition of the system through periodic solutions are explored. Application of coherent structures and modified chain of momentum equations is discussed.

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Vortex Dynamics of Wakes

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One of the most spectacular, significant and well studied fluid instabilities is the formation of a vortex wake behind a bluff body. The Kármán-Bénard vortex street will be well known. The presentation will highlight recent work on (i) a physical rationale for the Strouhal-Reynolds number relation for vortex shedding; (ii) the phenomenology of vortex wakes behind an oscillating cylinder and a theory of the Williamson-Roshko bifurcation diagram for such wakes; (iii) some ideas on the vortex structure of "exotic wakes" involving more than two vortices shed per period from the body. Although there are also very interesting three-dimensional effects, we will restrict attention to purely two-dimensional flows where the opportunities for analysis and modeling are greater, and numerical simulations can be done with relative ease.

Low Reynolds Number Instabilities and Transitions in Bluff Body Wakes

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In recent years, we have undertaken extensive studies on the instabilities and transitions that occur in the wakes of bluff bodies at low Reynolds numbers, using both computational and experimental techniques. Of particular interest has been the different types of instabilities and transitions and their order of appearance in the flow around fully immersed fixed bluff bodies (2,3,5,6,7,9,13,18,19,22,23), bluff bodies close to surfaces (1,8,11,12,14,20), oscillating bluff bodies (natural or forced flow) (4,10,15,16,17,21,24). The types of mechanisms, such as elliptical or centrifugal, leading to the three-dimensional instabilities has been determined in a number of cases and a variety of geometries has been considered.

At BIFD2006, the latest results of the continuing studies on the instabilities/transitions in the flows around bluff bodies will be presented plus an overview of the richness of transitions that have been found.

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Spatial versus temporal instabilities in a parametrically forced stratified mixing layer

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The present study compares the temporal and spatial instabilities of parametrically excited stratified mixing layer flows. For this purpose a relatively simple iteration procedure yielding solutions of both temporal and spatial problems is proposed. This procedure can be easily extended to other plane-parallel shear flows with the parametric excitation of instability. Using this procedure the parametric analysis of the temporal and spatial Kelvin-Helmholtz and Holmboe instabilities is performed and characteristic features of the instabilities are compared. Both inviscid and viscous models are considered. The parametric dependences on the mixing layer thickness and on the Richardson and Reynolds numbers are studied. It is shown that in the framework of this study the Gaster transformation is valid for the Kelvin-Helmholtz instability, but cannot be applied to the Holmboe one. The neutral stability curves are calculated for the viscous flow case. It is found that the transition between Kelvin-Helmholtz and Holmboe instabilities is continuous in the spatial case and in the temporal case occurs via the codimension two Takens-Bogdanov bifurcation at which a complex pair of the leading eigenvalues merges into a multiple real eigenvalue (Fig.1). It is found also that for the same governing parameters the spatial upstream and downstream Holmboe waves have different amplification rates and different absolute phase velocities, with larger difference observed at larger Richardson numbers. It is also found that at large Richardson and small Reynolds numbers the primary temporal and spatial instabilities set in as a three-dimensional oblique Holmboe wave (Fig. 2).

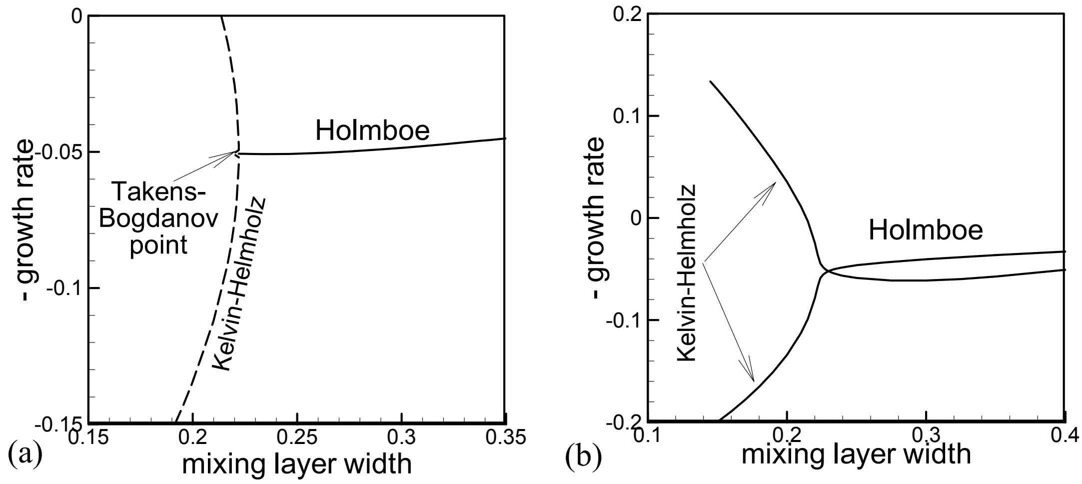

Fig.1. Transition between Kelvin-Helmholz and Holmboe modes for temporal (a) and spatial (b) instabilities.

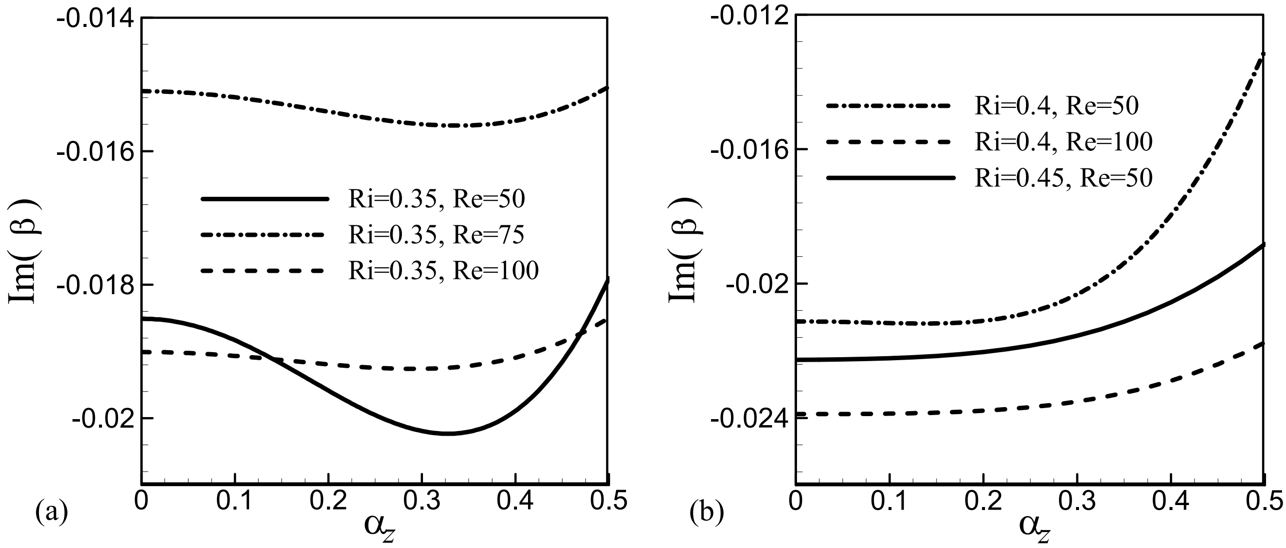

Fig. 2. Dependence of spatial amplification rates on spanwise wavenumber. Second Holmboe mode.

Transition of flow past a couple of cylinders placed in a uniform flow

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1. Introduction Flow past a pair of circular cylinders in side-by-side arrangement has been investigated as a typical model of simple wake interaction. It has been revealed that wakes behind the two cylinders interact in a complex manner, which yields various flow patterns[1]. Among many experimental works, we note the observation by Thomas and Kraus[2] that vortex shedding from a pair of cylinders is synchronized in-phase or antiphase. Such synchronization was reproduced in numerical simulation by Kang[3]. He classified the flow patterns into six categories: antiphase- and in-phase-synchronized, flip-flopping, deflected, single bluff-body and steady wake patterns, whose origins are the major objective to be explored in the present paper.

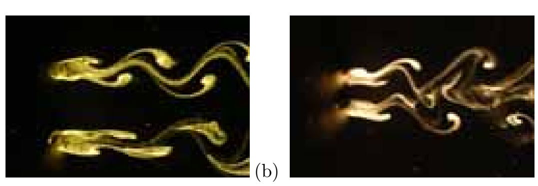
2. Problem description Consider a flow past a pair of circular cylinders placed, side-by-side, perpendicularly to the stream. The flow is assumed to be uniform with velocity U^* far upstream. The diameters of the two cylinders are the same with each other and taken to be d^* and the gap distance between them to be s^*. Then, we have two nondimensional parameters characterizing the flow, i.e. the Reynolds number $Re \equiv U^* d^*/\nu^*$ and the gap ratio $\sigma \equiv s^*/d^*$, where ν^* is the coefficient of kinematic viscosity of the fluid.

3. Numerical and experimental methods Three different methods are employed to investigate the route of transition of the flow to an oscillatory state. One is the time marching method of the time dependent equation and another the iteration method for the steady state equation by the S. O. R. method. The third method is the linear stability analysis of the steady state solution, where the linear growth rate is evaluated numerically by using the S. O. R. method. In all numerical calculations, temporal and spatial derivatives are approximated by finite differences in a curvilinear numerical grid generated to fit the circular cylinders. In order to generate the numerical grid, solutions of the Poisson equations are adopted following the technique proposed by Steger and Sorensen[4]. Visualization of flow pattern is the major objective in our experiment and resultant flow patterns are compared with numerical results.

4. Results and discussion Our numerical simulation was performed in the range of $Re \leq 100$ for $0.3 \leq \sigma \leq 5.0$, and showed that the flow pattern is categorized into five kinds of flow, i.e. steady symmetric flow, antiphase and in-phase oscillatory flows, oscillatory and steady deflected flows. The existence of the last flow, deflected steady flow, is our new finding, which may be the origin of deflected single bluff-body and steady wake patterns reported by Kang.

We confirmed that antiphase flow appears for $\sigma > \sigma_c = 2.34$ (Fig. 1(a)), while in-phase flow is the preferred flow patten for $\sigma < \sigma_c$ (Fig. 1(b)), which agrees well with observations in experimentals. In a very narrow region near $\sigma \sim 0.6$, steady deflected flow is found to be a unique stable solution which originates due to a pitchfork bifurcation from the steady symmetric flow. For $\sigma = 0.6$, the flow is steady but asymmetric at $Re = 60$ and then becomes oscillatory being deflected, which is the flow pattern classified as deflected single bluff-body wake by Kang. However, for a little smaller gap ratio of $\sigma = 0.5$, it is in-phase oscillatory flow that appears from the instability of the steady symmetric flow. The transition is found to be caused by a Hopf bifurcation with a critical Reynolds number $Re_c = 44.4$. At $Re = 60$ the oscillatory flow becomes deflected to one side. The origin of the deflected oscillation is shown to come from a pitchfork bifurcation with $Re_c = 54.6$ although the steady symmetric flow is already unstable to oscillatory disturbance. This complicated bifurcation structure is clarified and the classification of the flow by Kang is well explained by the bifurcation diagrams obtained.

The transition of flow past two tandem circular cylinders is also investigated by the present authors, whose results will be also presented at the symposium.



(a) (b)

Fig. 1 Two modes of synchronous oscillation. (a) antiphase, (b) in-phase oscillations.

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Experiments regarding transition in a subcritical air channel flow

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In this experimental study we report on some aspects associated with the possible route to transition in a subcritical plane Poiseuille air flow, which involves the artificial generation of streamwise vortices and their secondary instability leading to the nonlinear formation of hairpin vortices. For this purpose hot-wire technique and 2D flow visualization are used as a first step to determine the generation conditions and dimensions of the coherent structures (streaks and hairpins), their shedding frequency, trajectory and convection velocity. Then a Holographic Particle Image Velocimetry (HPIV) system is employed to obtain the instantaneous topology of the hairpin vortex and its associated 3D distribution of the two (streamwise and spanwise) velocity components as well as the corresponding wall normal vorticity. The experimental data is compared with results of related experimental, numerical and theoretical studies.

The present experimental results support the view that the generation of hairpins under various base flow conditions is governed by a basic mechanism, the important common elements of which are the shear of the base flow and an initial disturbance having sufficient large amplitude. Furthermore, it is demonstrated that the onset of hairpin vortices as function of the initial streamwise-independent vertical disturbance varies as the Reynolds number to the power of -1.5. This finding agrees with a recent theoretical prediction (Chapman, S. J."Subcritical transition in channel flows", Journal of Fluid Mech. vol. 451 pp. 35-97, 2002) and illustrates the fact that the domain of attraction for the laminar state shrinks for large Reynolds number so that small but finite amplitude perturbations lead to transition.

Pattern formation and instability of flow between two corotating disks in a fixed enclosure

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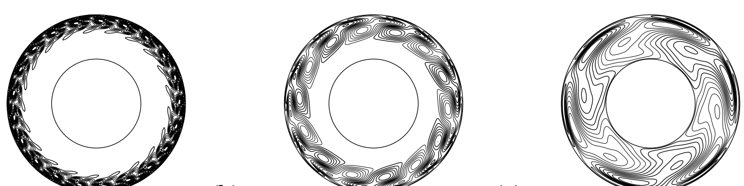
1. Introduction Appearance of fascinating polygonal shapes has attracted researchers to flow between two corotating disks enclosed in a stationary outer cylinder, whose research was initiated as a simplified model of flow in computer disk storages by Lenneman[1] and has been a subject of numerical and experimental studies[2–5]. In the present paper we seek the origin of polygonal shape in instability of steady axisymmetric flow which remains a solution, irrespective of Reynolds number, and clarify the underlying physics of the appearance of polygonal flow patterns.

2. Problem description Consider a flow between corotating disks in an enclosure. The outer cylinder of radius r_2 is fixed and the inner cylinder of radius r_1 rotates together with the two disks with angular velocity Ω. The spacing between the two disks is taken to be ℓ. Then, we have two nondimensional parameters characterizing the flow, i.e. the Reynolds number $Re \equiv r_2\Omega d/\nu$ and the length ratio $\Gamma \equiv \ell/d$, where $d = r_2 - r_1$ and ν is the coefficient of kinematic viscosity of the fluid. Another parameter, the radius ratio $\eta \equiv r_1/r_2$, is taken to be 0.5 in the present paper.

3. Numerical and experimental methods Linear stability of steady axisymmetric flow, the unique solution at small Reynolds numbers, is investigated by numerically solving linearized equation for disturbance added to the steady flow. The steady flow is obtained with a time marching method of the time dependent equation assuming axisymmetry of the flow field, where temporal and spatial derivatives are approximated by finite differences and the fractional time step method is utilized. The disturbance is decomposed into a Fourier series in the azimuthal variable and each Fourier mode of disturbance is analyzed separately. The linearized time dependent equation for the disturbance with a single Fourier mode is solved numerically similarly to the steady flow. Visualization of flow field is performed in experiment.

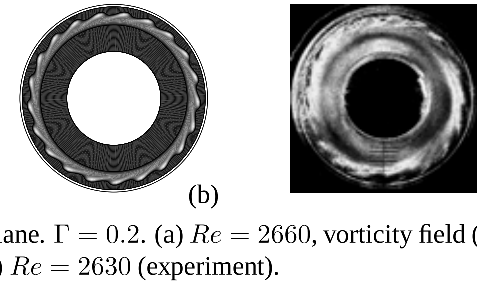
4. Results and discussion Linear stability of steady axisymmetric flow, say the basic flow, was analysed for a range of length ratio $0.2 \leq \Gamma \leq 0.6$, and the critical Reynolds number and wavenumber were determined for each length ratio. For example, the basic flow becomes unstable to a disturbance with a wavenumber $k_c = 21$ at $Re_c = 2660$ (Fig. 1(a)), which results in an appearance of 21-polygonal flow field (Fig. 2(a)). The resultant flow field is composed by adding the disturbance to the basic flow, where an approriate multiplier to the disturbance is assumed by estimating the magnitude of disturbance. Comparison of the flow field with a visualized one obtained in experiment (Fig. 2(b)) shows good agreement with each other. The disturbance has large magnitude in a narrow region adjacent to the outer cylinder in Figs. 1(a), 2(a) and 2(b).

For larger length ratios, the critical Reynolds number decreases together with the critical wavenumber. The most unstable disturbance has a wavenumber of $k_c = 7$ for $\Gamma = 0.4$ (Fig. 1(b)), which grows above $Re_c = 1200$. Square and trigonal polygons appear due to the instability of the basic flow at $Re_c = 970$ and 800 for $\Gamma = 0.5$ and 0.6, respectively (see Fig. 1(c) for $\Gamma = 0.6$). Figures 1(a)–1(c) show that disturbance invades inner region of the flow field for larger length ratio Γ, and occupies the whole field at $\Gamma = 0.6$. This invasion of the disturbance is easily understood if we consider that the region near the inner cylinder undergoes rigid rotation and rejects the invasion of disturbance for smaller length ratio and that the region of rigid rotation shrinks as the length ratio increases.



(a) (b) (c)

Figure 1: Flow pattern of disturbance in the horizontal plane (azimuthal component). (a) $\Gamma = 0.2$, $Re = 2660$. (b) $\Gamma = 0.4$, $Re = 1200$. (c) $\Gamma = 0.6$, $Re = 800$.



(a) (b)

Figure 2: Flow pattern in the horizontal plane. $\Gamma = 0.2$. (a) $Re = 2660$, vorticity field (numerical result, the whole flow composed of the basic flow and the disturbance). (b) $Re = 2630$ (experiment).

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Polygons on a Rotating Fluid Surface

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We report a novel and spectacular instability of a fluid surface in a rotating system. In a flow driven by rotating the bottom plate of a partially filled, stationary cylindrical container, the shape of the free surface can spontaneously break the axial symmetry and assume the form of a polygon rotating rigidly with a speed different from that of the plate. With water we have observed polygons with up to 6 corners. It has been known for many years that such flows are prone to symmetry breaking, but apparently the polygonal surface shapes have never been observed. The creation of rotating internal waves in a similar setup was observed for much lower rotation rates, where the free surface remains essentially flat. We speculate that the instability is caused by the strong azimuthal shear due to the stationary walls and that it is triggered by minute wobbling of the rotating plate. The slight asymmetry induces a tendency for mode-locking between the plate and the polygon, where the polygon rotates by one corner for each complete rotation of the plate.

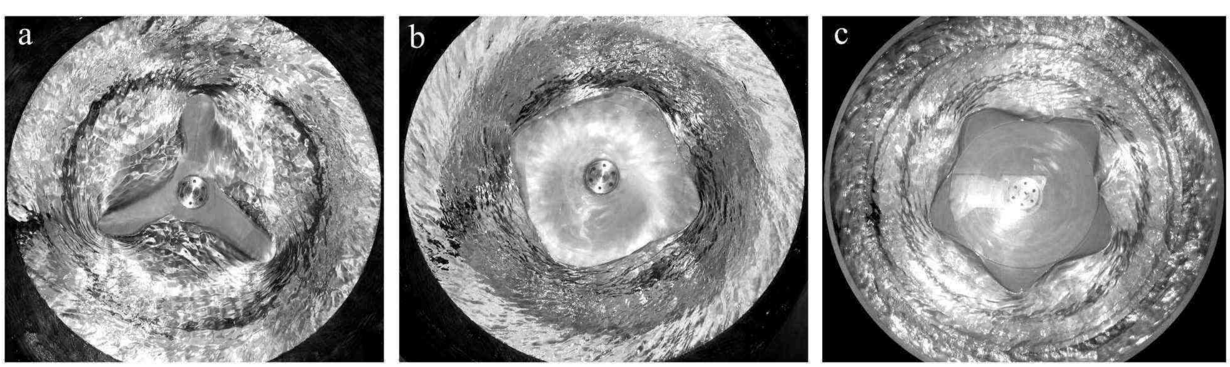

Figure 1: Setup consisting of a stationary plexiglass cylinder of radius 19.4 cm with a circular plate that is rotated by a motor. Water or ethylene glycol is filled to the level H above the plate. At sufficiently large rotation frequencies f the axially symmetric surface becomes unstable and assumes the shape of a regular, rigidly rotating polygon.

HYDRODYNAMIC INSTABILITY IN CZOCHRALSKI PROCESS OF CRYSTAL GROWTH

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ABSTRACT

Numerical linear stability analysis was performed on Czochralski's process of crystal growth ([1]). The governing equations are the Navier-Stokes equations coupled with the equation of energy through the Boussinesq appoximation. The hydrodynamics and heat transport in this process are fairly complex, thus most published works perform full 3D time dependent analysis which is very CPU consuming. In the present work the basic solution is steady axisymmetric and is solved first using, the spectral element method ([1]). Penalty method is applied to eliminate pressure terms and finally preconditioned GMRES is employed to solve the resulting system of algebraic equations. In the linear stability analysis 3D perturbations, decomposed into Fourier series in the azimuthal direction, are considered ([2], [3]). Stability diagrams are presented for parameter ranges of Prandtl number (Pr) between 0.005 and 0.02 and for aspect ratios between 0.4 and 1.0. The dependence of dominant wave numbers and critical Grashof numbers on geometry was studied. Results show that dominant modes are the first 5 Fourier wave numbers (0 ... 4). Dependence of modes on aspect ratios was studied for Pr=0.01 (Silicone melt). It was found through analysis of dispersion relation of the critical frequencies as functions of modes and geometry that for aspect ratios lower than 0.85 convective heat transfer dominates the instability mechanism while for aspect ratios greater or equal to 0.85 rotational effect take over. Many mode transitions were observed at different aspect ratios. Some modes were observed approaching each other closely in some ranges of the aspect ratio parameter. Further analysis was carried out for the case where heat convection is absent (Pr=0). This analysis strengthens the conclusions about the role of convective heat transfer in the instability mechanism.

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Experiments on Three-dimensional Instabilities in a Confined Flow Generated by a Rotating Lid

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Abstract

The swirling flow between a rotating lid and a stationary cylinder is studied experimentally. The flow is governed by two parameters: The ratio of container height to disk radius *h*, and the Reynolds number *Re*, based on the disk angular velocity, cylinder radius and kinematic viscosity of the working liquid. For the first time the onset of three-dimensional flow behavior is measured by combining the high spatial resolution of Particle Image Velocimetry (PIV) and the temporal accuracy of Laser Doppler Anemometry (LDA). A detailed mapping of the transition scenario from steady and axisymmetric flow to unsteady and non-axisymmetric flow is investigated for $1 \leq h \leq 3.5$. The flow is characterized by the generation of azimuthal modes of different wave numbers. A range of different modes is detected and critical Reynolds numbers and associated frequencies are identified. The results are compared to the numerical stability analysis of Gelfgat et al. [J. Fluid. Mech. 438, (2001)]. In most cases the measured onset of three-dimensionality is in good agreement with the numerical results and disagreements can be explained by bifurcations not accounted for by the stability analysis. In the range $3.3 < h < 3.5$ the experiment revealed the existence of a stable triplet that may explain the steady behaviour of the $k = 3$ mode. If this is correct it is the first time that a steady three-dimensional structure has been observed in the lid-driven rotating cavity. However, this is still being investigated and will be reported later.

Keywords: Confined swirling flow, transition, non-intrusive measurements, onset of three-dimensionality, unsteady.

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Development of helical vortex theory

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Recent progress in the theory of helical vortices is addressed. New ideas for studying the classical helical vortex problem were due to by Hardin[1] who introduced Biot-Savart law in the form of Kapteyn series from twisted products of the modified cylindrical functions to describe velocity field induced by a helical filament of infinitesimal thickness. Ricca[2] later employed numerical simulations of the Kaptayn series to determine the influence of the helix torsion on the self-induced motion of thick helical vortices. The representation via Kapteyn series for a helical filament bounded on a circular cylinder has been considered by Okulov[3] who developed an efficient analytical technique for a singularity separation the series (see also Kuibin & Okulov[4]). Boersma & Wood[5] used an integral representation of the Kapteyn series and from that made an asymptotic as well as numerical analyses of the velocity. In addition to this, Wood & Boersma[6] expanded the same technique to describe the motion of a system of N helical vortices.

Using the singularity-separation technique, the algebraic approximations for the velocity of self-induced motion of a single helical vortex and the total velocity field of an array consisting of N helical vortices was obtained[7,8] for the first time. Furher, a linear stability analysis of a regular N-gon of point vortices from equilibrium was generalized to be valid for an array of N helical vortices placed in free space[7] as well as for an array embedded in an axisymmetric helical vortex field[8]. The influence of finite-core thickness on the velocity field around a helical vortex tube was investigated by Fukumoto & Okulov[9].

The purpose of the present work is partly to review and summarize the last achievements in the theory of helical vortices and partly to report on some new important mathematical aspects. Exact solutions of the motion of multiple helical vortices are compared to the approximate formulas of Boersma & Wood[5] and Okulov[7] to estimate the domaine of applicability of both approximations. The influence of different types of assigned flows and the question of right or left-handed helical symmetry of the vortices on the stability properties are also discussed.

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Paradox of inductionless magnetorotational instability

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The magnetorotational instability (MRI) is thought to be responsible for the fast formation of stars and entire galaxies in accretion disks. The velocity distribution in accretion disks is apparently hydrodynamically stable by the Rayleigh criterion while the viscosity alone is not sufficient to account for the observable accretion rates. However, a hydrodynamically stable velocity profile in the cylindrical Taylor-Couette flow can become unstable in the presence of magnetic field (Velikhov, Sov. Phys. JETP 36, 995, 1959; Balbus and Hawley, Astrophys. J. 376, 214, 1991). In this case, an axial magnetic field provides an additional mechanism of energy exchange between the base flow and perturbations that, however, requires the magnetic Reynolds number to be at least $Rm \sim 10$. Note that for a liquid metal with the magnetic Prandtl number $Pm \sim 10^{-5}$ this corresponds to a hydrodynamic Reynolds number $Re = Rm/Pm \sim 10^6$. Thus, this instability is hardly observable in the laboratory because any conceivable flow at such Reynolds number would be turbulent. However, it was shown recently (Hollerbach and Rüdiger, Phys. Rev. Lett. 95, 124501, 2005) that MRI can take place in the cylindrical Taylor-Couette flow at $Re \sim 10^3$ when the imposed magnetic field is helical. The most surprising fact is that this type of MRI works even in the inductionless limit of $Pm = 0$ where the critical Reynolds number of the conventional MRI with axial magnetic field diverges as $\sim 1/Pm$. The induced currents are so weak in this limit that their magnetic field is negligible with respect to the imposed field. Thus, on one hand, the imposed magnetic field does not affect the base flow, which is the only source of energy for the perturbation growth. But on the other hand, flow perturbations are subject to additional damping due to the Ohmic dissipation caused by the induced currents. We show rigorously that, in the limit of $Pm = 0$, the imposed magnetic field increases the energy decay rate of any particular perturbation. On one hand, this means that the energy of any perturbation, which is growing in the presence of magnetic field, grows even faster without the field and vice versa. On the other hand, the flow which is found to be unstable in the presence of magnetic field is certainly known to be stable without the field. This apparent contradiction constitutes the paradox of the inductionless MRI which we address in this study. We consider MRI in the inductionless approximation at $Pm = 0$ that allows us to eliminate the magnetic field and, thus, leads to a considerable simplification of the problem containing only hydrodynamic variables as in the classical Taylor-Couette problem. First, we use a Chebyshev collocation method to calculate the eigenvalue spectrum of the linearised problem. In this way, we confirm that MRI with helical magnetic field indeed works in the inductionless limit. Second, we integrate the linearised equations in time to study the transient behaviour of small amplitude perturbations. In this way, we show that the energy arguments are correct as well – the energy of an unstable perturbation indeed starts to grow faster when the magnetic field is switched off. However, there is no real contradiction between both facts. The energy grows only for a limited time and then turns to decay in accordance to the linear stability predictions. It is important to stress that the linear stability theory predicts the asymptotic development of an arbitrary small-amplitude perturbation, while the energy stability theory yields the instant growth rate of any particular perturbation but it does not account for the evolution of this perturbation. Thus, although switching off the magnetic field instantly increases the energy growth rate of the most unstable as well as that of any other perturbation, in the same time the critical perturbation ceases to be an eigenmode without the magnetic field. Consequently, this perturbation is transformed with time and so looses its ability to extract energy from the base flow necessary for the growth. Analogously, switching on the magnetic field causes an instant decrease of the growth rate of any particular perturbation because of Ohmic dissipation, while the magnetic field transforms the perturbation so that it becomes able to extract more energy from the base flow and so eventually grows. The helical magnetic field, in contrast to pure axial or azimuthal fields, provides an additional coupling between the azimuthal and meridional perturbations. In case of an axial external field, the helicity of the field is caused only by the azimuthal advection of the base field that requires $Pm > 0$ and, respectively, $Re \sim 1/Pm$.

Instabilities in the flow past localized magnetic fields

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The flow in a shallow layer of an electrically conducting fluid past a localized magnetic field is analyzed numerically. The field occupies only a small fraction of the total flow domain and resemblances the magnetic field created by a permanent magnet located close to the fluid layer. It is shown that the Lorentz force created by the interaction of the induced electric currents with the non-uniform magnetic field acts as an obstacle for the flow and creates different flow patterns that remind those observed in the flow past bluff bodies. A quasi-two-dimensional model that takes into account the existence of the bottom wall through a linear friction term is considered. This term models the magnetic (Hartmann) friction in the zone of high magnetic field strength or the viscous (Rayleigh) friction in zones where the magnetic field is negligible. When viscous effects dominate over inertial ones, steady vortical structures are formed in the magnetic field zone when the strength of the field is strong enough. For inertial dominated regimes a wake is formed behind the zone of high magnetic field. In the fringing zones of the magnetic field, shear layers parallel to the main flow direction are formed. When the magnetic force is sufficiently strong, the wake is destabilized and a periodic vortex shedding similar to the classical von Kármán street is found. The case of a flow under the field of two permanent magnets is also analyzed. A preliminary characterization of the flow stability in terms of the Reynolds and Hartmann numbers and the layer depth is presented and a comparision with some available experimental results is carried out.

MHD Kelvin-Helmholtz instability in non-hydrostatic equilibrium

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Abstract

The present work dealt with the linear stability of a magnetohydrodynamic shear flow so that a stratified inviscid fluid subject to a thermal wind is rotating about a vertical axis when a uniform magnetic field is applied in the direction of the streaming or zonal flow.

In geophysical flow, the stability of the flow is determined by taking into account the non- hydrostatic condition depending on Richardson number R_i and the deviation δ from hydrostatic equilibrium. According to P.H.STONE [1] it is shown that such deviation δ decreases the growth rates of three kinds of instability which can appear as geostrophic (G), symetric (S) and Kelvin-Helmholtz (K-H) instabilities.

To be specific, the evolution of the flow is therefore considered in the light of the influence of magnetic field, particularly, on K-H instability. Results are discussed and compared to previous works as S.CHANDRASEKHAR [2].

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On the saturation of the magnetorotational intability near threshold

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Abstract:

We explore by means of a weakly nonlinear analysis near threshold of the magnetorotational instability for two-dimensional disturbances. We find that amplitude of saturation of the unstable mode goes as the square root of the magnetic Prandtl number (Pm) in the small Pm limit. We further demonstrate that in the small Pm limit, the shearwise transport of momentum scales as the 1/R where R is the hydrodynamic Reynolds number. We discuss the implications of these results for astrophysical accretion disc systems, numerical simulations and earth-bound laboratory experiments.

Computation of periodic orbits for the Navier-Stokes equations

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We present a new method for computing periodic orbits of the Navier-Stokes equations that combines a finite-element discretisation in space with a spectral discretization in time. We illustrate our technique with calculations of the two-dimensional flow past a cylinder that is confined between the walls of a channel. Results for both rotating and non rotating cylinders will be presented.

When the Navier-Stokes equations are discretised in space using a finite-elment method (our technique would also work for a finite-difference or finite-volume method), we get a large system of ordinary differential equations

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{f}(\boldsymbol{x};\lambda); \quad \boldsymbol{f} : \mathrm{R}^N \times \mathrm{R} \mapsto \mathrm{R}^N. \tag{1}$$

where $\boldsymbol{x}$ is the vector of all the spatial degrees of freedom for the velocity and pressure. The velocity and pressure degrees of freedom are expanded in a Fourier series in time

$$\boldsymbol{x}(t) = \sum_{k=-K}^{K} \boldsymbol{x}_k \exp(i\omega t) \tag{2}$$

and the Galerkin method is applied to obtain a set of equations for the $\boldsymbol{x}_k$. A phase condition is added and this determines the period, $2\pi/\omega$, of the orbit. The method has two particularly attractive features: it preserves the circle group symmetry of the orbit; and it has an exponential rate of convergence as the number of Fourier modes is increased.

The steady laminar flow past the cylinder loses stability to a time-dependent flow at a supercritical Hopf bifurcation point. We compute the path of periodic orbits that emerge from this bifurcation point using our new method. When the cylinder does not rotate, the problem is symmetric about the mid-plane of the channel. Although the flows along the periodic orbit are not symmetric about channel mid-plane, it is still possible to exploit the symmetry to carry out the computation on the upper (or lower) half of the domain, thus reducing the cost significantly.

The periodic orbit that arises at the Hopf bifurcation point can disappear at a second Hopf bifurcation point at a higher value of the Reynolds number: the range of Reynolds numbers for which the orbit exists depends on the blockage ratio, i.e. the ratio of the channel width to the diameter of the cylinder. For sufficiently large blockage ratios (approximately greater than 0.85), there is no Hopf bifurcation from the symmetric steady flow. At these large values of the blockage ratio the flow first undergoes a steady symmetry-breaking bifurcation. There is then a pair of Hopf bifurcations, one on each of the asymmetric flows. The periodic orbits that emerge from these Hopf bifurcations have also been computed, but in this case it is no longer possible to exploit the reflectional symmetry to reduce the cost.

When the cylinder rotates, the reflectional symmetry of the problem is destroyed. If the cylinder rotation rate is high enough the flow is again stabilised and no Hopf bifurcation points are found for the steady flow, at least within the parameter ranges investigated here.

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Algorithms and Software for Bifurcation Analysis of Incompressible Flows on Massively-Parallel Computers

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A library of bifurcation analysis algorithms has been developed to perform stability analysis of large-scale applications on massively-parallel computers. Incompressible flow problems have been used to drive the development of these general-purpose analysis tools. We will present some results for 2D and 3D buoyancy-driven flow stability problems with finite element discretizations of over 10 Million unknowns.

The CFD code is an unstructured-grid stabilized finite element code with equal-order linear interpolation that uses domain decomposition to partition the finite element mesh for distributed-memory computations. In addition to incompressible flow, the code solves for heat transfer and species transport and reaction. An analytic Jacobian is calculated for Newton-based solution algorithms.

The continuation and bifurcation analysis library (LOCA) has been incorporated into a large framework (Trilinos[1]) of solution and analysis algorithms for parallel computations. To scale to large problem sizes, it is imperative to develop algorithms that work with approximate iterative linear solvers. We will discuss or efforts to develop stable and general-purpose algorithms. The effort to develop algorithms within a larger software framework has allowed a large set of solution algorithms to impact the flow problems. These include:

- Linear Solvers: Krylov algorithms preconditioned with ILU and Multilevel methods.
- Nonlinear Solver: Newton's method with globalizations.
- Eigensolver: Arnoldi iteration with Cayley transformation.
- Continuation Algorithms: Natural and arclength continuation.
- Bifurcation Algorithms: Tracking of turning point, pitchfork, and Hopf points.
- Space-Time Formulation (under development): Period orbit tracking with parallelization of time domain.

[1]Available for download at: http://software.sandia.gov/Trilinos

AN EFFICIENT PARALLEL IMPLEMENTATION OF A CONTINUATION ALGORITHM BASED ON AN ASYMPTOTIC NUMERICAL METHOD

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This presentation aims to give an idea about the efficiency of continuation algorithms based on Asymptotic Numerical Method in comparison with classical ones in the framework of Rayleigh-Benard-Marangoni instabilities. Indeed, as many others instabilities problems, mixed buoyancy and surface-tension-driven convection are well known to be computationally time consuming, owing to strong non-linearities and multiple secondary bifurcations. Therefore, special attention has to been paid to look for the best compromise between the finite element formulation, the solution algorithm and the computer to be run, particularly if one intend to achieve high performance computations.

One assumes the problem is governed by the coupled incompressible Navier-Stokes and energy equations, in the Boussinesq approximation. However, to search for high performance computing, we have implemented separated finite element formulations and solution algorithms, depending on steady states or transient solutions are to be computed. The finite element model used in the computation of steady-state bifurcating branches of solution is built on a fully coupled primary variable approximation using a penalized formulation to address the incompressible constraint. The solution algorithm implements a refitting of the basic asymptotic numerical method [1-2], for coupled fluid flow and heat transfer problems in a high performance framework. It enables us to get both the threshold value and its associated pattern, or steady supercritical solutions together with subsequent bifurcations, in containers of various shapes. As an illustration, we compare several solution algorithms (Newton-Raphson + arc length control, standard and improved asymptotic numerical methods) and parameterizations for the computation of Rayleigh-Benard-Marangoni convection in a silicon oil layer (Pr = 880 at 25°C) of infinite horizontal extent. As far as multiple bifurcations have to be undertaken in the problem, Lopez 's parameterization [2] outperforms standard ones. Figure 1a presents the steady state branches of solution and the associated dominant patterns (hexagonal, mainly pentagonal and square), whereas in figure 2 the computation times are plotted for different solution algorithms versus the control parameter.

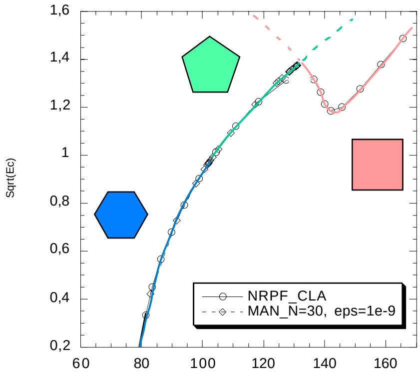

Figure 1: Steady-state branches of solutions

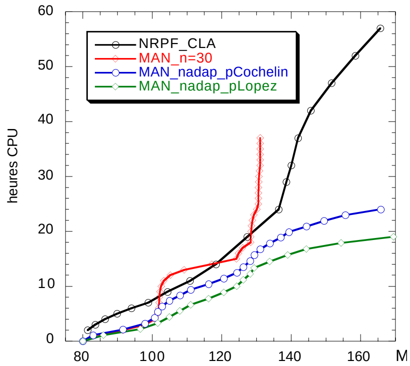

Figure 2: computing time of several solution algorithms

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Solution of stability problems by a low-order finite volume method

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The present study is devoted to analysis of stability of steady buoyancy convection flows by a low-order finite volume method. We consider several benchmark problems, part of which are widely known, and another part is added here to complete the study. The motivation for this work is the necessity to perform the stability analysis for many applied problems, which cannot be treated by spectral of pseudospectral methods.

It is well-known that spectral and pseudospectral methods yield the most accurate solutions for benchmark problems considering flows in rectangular cavities, and especially instabilities of these flows. However, these methods are restricted to simple geometries and because of this cannot be applied to many practically important problems. As an example one can mention problems of melt instabilities in bulk crystal growth processes, which was the motivation for one of the most well-known convective benchmarks [1].

Here we apply the second-order finite volume method to several problems of buoyancy and thermocapillary convection in rectangular cavities. It is emphasized that the numerical technique briefly described below is not restricted to a certain class of problems and already was applied for stability studies in Czochralski [2] and floating zone [3] crystal growth configurations. The studies of this kind usually have two main bottlenecks. The first one is connected with the calculation of steady state flows, whose stability is to be studied. The Jacobian-free or other inexact Newton methods combined with a Krylov-subspace-based iterative linear solver usually are applied for this purpose. These solvers are very effective when relatively simple benchmark problems are considered, however fail to converge in more complicated cases. There were also some reports about possible loss of accuracy when Jacobian-free approach is applied. Therefore in the present study we calculate the Jacobian matrix using the corresponding analytical evaluations, which follow from the discretized equations. We also argue that when very fine grids are used and due to the high level of the sparseness of the Jacobian matrix it can be more effective to replace iterative solvers by direct ones.

The second bottleneck is connected with the eigenvalue problem of very large dimension, which must be solved for the study of linear stability of a steady flow. The usual approach here is the Arnoldi iteration method, which allows one to calculate only necessary part of the whole spectrum. The Arnoldi iteration also needs computation of the Krylov-subspace basis. An additional difficulty here is connected with the incompressible continuity equation, which does not contain the time derivative. The latter requires considering the eigenvalue problem in the shift-and-invert mode. Consequently, the Krylov basis vectors are to be computed as solutions of a system of linear algebraic equations. Again, we argue here that instead of iterative solvers, which can diverge and be CPU-time consuming, it is more effective to built an **LU**-decomposition of the matrix, so that the necessary amount of the Krylov basis vectors will be computed by the back substitution.

The effectiveness of the application of the direct sparse matrix solvers described here is the consequence of the matrix sparseness, which follows from the low-order discretization method applied. As reported below, we are able to perform calculations of steady states and stability analysis on the grids consisting of 450^2 nodes. Apparently, time-stepping algorithms can handle much finer grids. To the best of our knowledge, however, the direct stability analysis of numerically calculated flows was never performed on the grids of this size. The only restriction for the further grid refinement is the computer memory consumed by a direct sparse matrix solver. The results reported here are obtained on an Itanium-2 workstation with 16 Gbytes memory.

The convergence studies reported below show that correct critical parameters can be calculated only on rather fine grids having more than 100 nodes in the shortest direction. We show that use of uniform grids combined, where possible, with the Richardson extrapolation can significantly improve results. We show also that the mesh stretching can significantly speed up the convergence, but there can be also a certain loss of accuracy.

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Relating between the Counter-Propagating Rossby Wave and the Over-Reflection perspectives – toward a deeper understanding of shear instability

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Shear instability is a central mechanism in fluid dynamics in general, and in atmospheric dynamics in particular. Yet, a full mechanistic understanding, of the kind we have for the onset of buoyant convection, is still lacking. Some understanding has been gained using the framework of Counter–Propagating Rossby Waves (CRW), which describes the instability as an interaction between two Rossby waves which are phase locked in a reinforcing configuration. So far, this approach has only been used to explain the discrete spectrum set of solutions, including modal and non modal evolution, and has not been extended to the continuous spectrum. Hence, it can not fully explain optimal growth, which is thought to be central to cyclone growth in the atmosphere. In addition, the role of the critical surface, which is where the perturbations interact with the mean flow most strongly, is obscure.

A different approach to shear instability describes the perturbation growth as resulting from an overreflection of waves, which propagate across the shear and are then reflected back so that the reflected and overreflected waves interfere constructively to form a growing mode. The main limitation of this approach is the lack of a mechanistic understanding of the overreflection process itself, although the conditions necessary for it to happen are known. While both the overreflection and the CRW perspectives illuminate different fundamental aspects of shear instability they have not been unified into a coherent basic theory.

We propose to generalize the CRW approach to include also the continuous spectrum, using a Hamiltonian framework, and to apply this framework to understand overreflection and its role in shear instability as well as optimal growth in various physical norms. This will lead to a deeper, mechanistic understanding of shear instability and the necessary conditions for modal and non modal growth.

Application of the Proper Orthogonal Decomposition to Turbulent Czochralski Convective Flows

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The aim of this work is to study the general aspects of the convective flow instabilities in a simulated Czochralski system. We considered the influence of the crystal rotation and buoyancy. Velocity fields, obtained by an ultrasonic technique (Fig. 1), the corresponding 2D Fourier spectra and a correlation function, have been used. Steady, quasi-periodic and turbulent flows, are successively recognised, as the Reynolds number was increased, for a fixed Rayleigh number. The orthogonal decomposition method was applied and the numbers of modes, involved in the dynamics of turbulent flows, calculated. As far as we know, this method has been used for the first time to study the Cz convective flows. This method provides also information on the most important modes and allows simple theoretical models to be established. The large rotation rates of the crystal were found to stabilize the flow, and conversely the temperature gradients destabilize the flow. Indeed, the increase of the rotation effects reduces the number of involved modes and oscillations, and conversely, as expected, the increase of the buoyancy effects induces more modes to be involved in the dynamics (Fig. 2). Thus, the flow oscillations can be reduced either by increasing the crystal rotation rate to the adequate value, as shown in this study and in [1] or by imposing a magnetic field [2].

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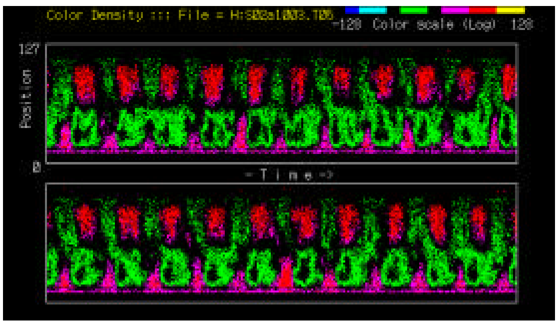

Figure 1: Example of a velocity field obtained by ultrasound.

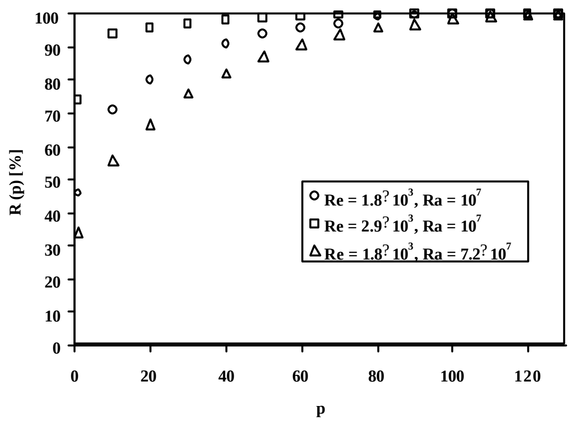

Figure 2: The cumulative energy R (p) versus p for various Re and Ra numbers.

Stability of flow and kinetic energy dissipation in 2D annular shear flows of inelastic hard disk assemblies

Abstract

We have used simulations of inelastic hard disks in two-dimensional shear flows to investigate the stability conditions of kinetic energy upon shearing through different circumstances. We varied some influential properties of system such as the restitution coefficient, shear rate and packing density to determine the limits where the difference between incoming kinetic energy (from shearing) and dissipating kinetic energy (due to collisions) becomes divergent. We study the differences between stable and unstable flows in the profiles of velocity, density, kinetic energy dissipation and average velocity fluctuation. Our results reveal how different models for the phenomenological coefficient of restitution can change the stability of the system. Moreover, we determine the conditions which lead to inelastic collapse where a large number of particles agglomerate and form clusters or crystals with nearly zero fluctuation energy. The current results assist us in finding proper modeling ways in simulation of suspension flows, colloids and magnetic fluids.

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