Book of Abstracts

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Contents

Thin Flow Over A Sphere

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Abstract

We present results on the isothermal laminar flow of a thin fluid layer over a sphere as it exits from a small hole at the top of the sphere as observed in a globe fountain shown below. These fountains are sold at garden centers for decorative purposes. Water is pumped out of the hole at a constant rate thus forming a pillbox at the top of the sphere. Although the fluid mechanics associated with the formation of the pillbox is very interesting, the focus in this study is in the subsequent thin layer flow following the pillbox. That is, we have modelled the flow as it spreads over the sphere. The fluid is taken to be viscous, incompressible and Newtonian while the flow is assumed to possess azimuthal symmetry. The governing Navier-Stokes equations are solved subject to no-slip and impermeability boundary conditions on the surface and the dynamic and kinematic conditions along the free surface. An approximate analytical solution for the steady-state flow has been derived by expanding the flow variables in powers of a small parameter, δ, which represents the shallowness parameter. The leading and first-order terms in the series have been determined and the findings demonstrate that for thin flows the difference between the leading and first-order approximations is indeed small. Various results and comparisons will be presented and discussed. For small Reynolds numbers the results predict that the flow separates from the surface before reaching the bottom of the sphere. Lastly, the analysis was also extended to solve the problem of thin flow over a cylinder and the fundamental differences between the flow over a sphere and that over a cylinder have been identified and explained. The technique and approach adopted here can be used to model and understand similar thin flows that occur in other settings.

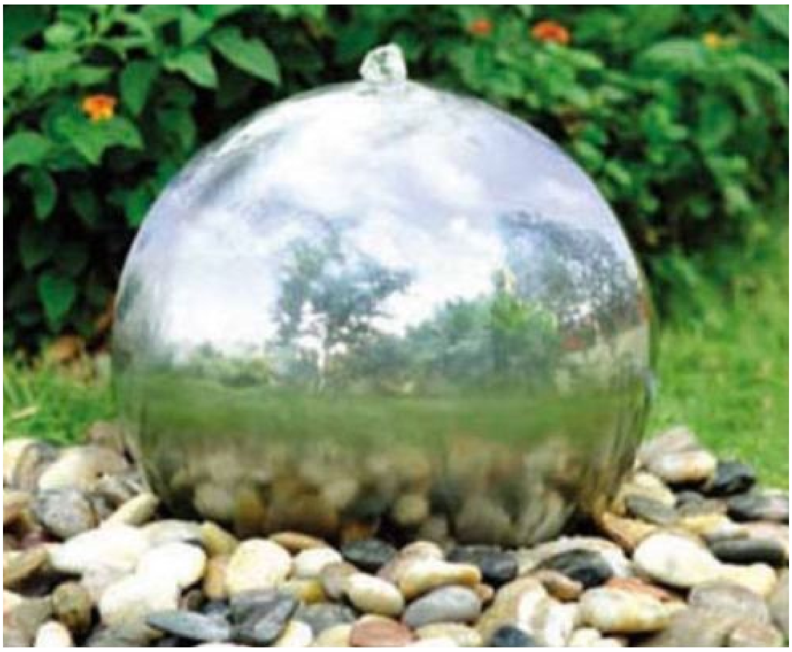

FIG. 1: A typical globe fountain.

Faraday instability in binary fluid systems

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The Faraday instability [1-4] arising in distinct immiscible and miscible fluid layers, when the parametric forcing is parallel to the gravity vector, is analyzed. The immiscible fluid system has been well studied in the literature but has dissimilarities with experiments for a rectangular geometry in previous theoretical approach [2]. For experimental studies a liquid set is chosen which can spontaneously glide across the wall container, with closest possible assumptions of the theory [2]. Experiments are conducted on low viscosity fluids and shows significant finite size effects which include viscous damping from the top and bottom wall as well as viscous damping from sidewalls.
For immiscible system a linear stability is been modeled through Navier Stokes equations in a Newtonian incompressible viscous fluid system through a Fourier Floquet method resulting into an eigenvalue problem and has been compared with experiments [see Fig 1a]. A correction in viscous damping is taken into account to understand increased effective viscosity in rectangular system suggested by Henderson [4].

The Faraday instability in miscible fluid layers is distinct from the immiscible fluid layer case, as it is triggered by the transverse variation of fluid density and is countered by the stabilizing viscous and diffusion processes. The mixing of fluids generated during the evolution of the instability gradually reduces the gradients of concentration in the layers and even results in the eventual "quenching" of the instability. Thus, the Faraday instability in miscible systems has a definite lifespan. A time-dependent density gradient is established from the moment the fluid layers are placed in contact with one another. However, consideration of a frozen-time approximation wherein the base concentration profile is assumed to remain frozen during the evolution of the instability allows the resulting linear stability analysis to become fully amenable to the Floquet theory (see details in [3]). First, the criticality is observed to occur at a sub-harmonic frequency (see Fig. 1b). Second, the large magnitude of the concentration gradient at early wait times is found to make the thin layers highly unstable. Third, the stability increases with forcing frequency, owing to the increased dissipation of the resulting choppy waves. All these observations qualitatively agree with experiments.

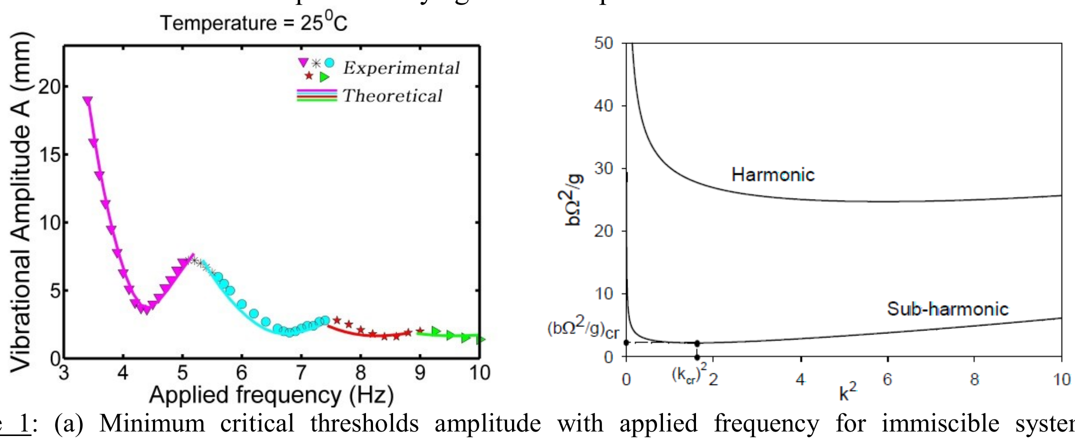

Figure 1: (a) Minimum critical thresholds amplitude with applied frequency for immiscible system; (b) Fundamental harmonic and sub-harmonic neutral curves for miscible system for some values of the different parameters.

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Partial wetting of porous substrates by blood droplets

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Dried blood spots (DBS) is a high potential blood collecting and sampling method which provides several advantages in blood sample collection, storage and transportation against conventional whole blood collection or plasma collection. The principle of DBS application is as follows: using a thin porous substrate, such as cotton fibres, cellulous fibres and polymer membrane etc., as an absorbent sponge where blood droplet from a fingertip or syringe is collected and the blood preserved as a dried spot sample. Therefore, the whole process of DBS sampling could be considered as spreading of non-Newtonian fluid (blood drop) over porous substrate (DBS card) with simultaneous spreading and penetration inside the porous substrate.

The spreading and wetting of porous substrate by blood are complex process depending on the physical and chemical properties of both a substrate and a liquid. This process has been investigated in the case of spreading/imbibition of Newtonian liquids [1, 2] and in the case of blood (non-Newtonian liquid) spreading/imbibition [3, 4] when liquid wets completely the porous substrate. Here the spreading behaviour of DBS sampling has been investigated in the case of partial wetting. Nitrocellulose membranes (NCM) with different pore size and silanized Whatman 903 blood saving card have been used as porous substrates. The spreading experiments have been applied to obtain the time evolution of spreading parameters, such as, radius of droplet base and wetted region, and dynamic contact angle.

The result of spreading on NCM showed that the spreading process was a partial wetting spreading with three subsequent stages as shown in Fig. 1: initial fast spreading, constant maximum droplet base and the shrinkage of the drop base. However, in spite of silanization of the Whatman 903 filter paper, the blood droplet showed a complete spreading behavior with two subsequent stages: initial fast spreading and the shrinkage of the drop base. A separation of red blood cells (RBCs) and blood plasma has been found in the case of the blood drop spreading over 0.2 and 3.0 μm NCMs in which the RBCs are mostly collected on the membrane surface and plasma is collected inside the membrane pores. Important that the RBCs were not damaged in this process. This opens a completely new opportunity to (1) investigate RBCs and plasma separately; (2) to use this method for non-destructive separation of living cells from aqueous solutions.

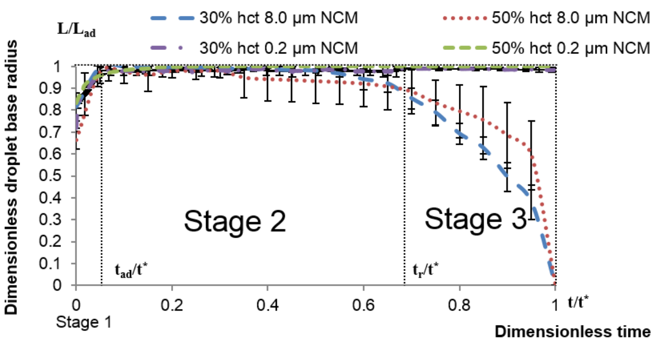

FIG. 1. Dimensionless radius of the droplet base in the case of spreading over NCM.

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Marangoni instability in a propagating autocatalytic reaction front under microgravity

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The oxidation of arsenous acid by iodate ions is an autocatalytic reaction in which the interplay between diffusion and the reaction itself leads to a propagating reaction front. In the course of the reaction the physical parameters of the fluid change. When the reaction is run in the presence of a gas-liquid interface, gradients in density and surface tension are generated which may lead to natural convection[1]. The role of Marangoni-related flow in the characteristics of this propagating autocatalytic front has been studied on board of the MASER-13 sounding rocket. The rocket mission has allowed approximately six minutes of microgravity (compared to 20 s in parabolic flights[2]) which is sufficient to examine the Marangoni effect alone by excluding any bouyancy related flows ever present in normal gravitational conditions.

The experiments have been performed in two different-sized quartz cells with a liquid–gas interface. The mixture has contained latex beads with a mean particle size of 6.4 μm for Particle Image Velocimetry (PIV). The geometry and the propagation of the front have been monitored using Fourier deflectometry, while three laser sheets in each cell have allowed the detection of the fluid flow field by PIV. Numerical simulations are also performed by solving the Navier-Stokes equation by applying the pressure implicit with splitting of operators algorithm using the OpenFOAM package. By modeling the reaction-diffusion-advection system driven by the Marangoni-flow, we are able to reproduce the flow conditions which have been observed during the experiments in microgravity.

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Convective formation of traveling waves on thin liquid films

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For thin liquid films on periodic domains, the instabilities which are driven by gravity, thermocapillarity, and van der Waals forces do not saturate and typically grow until the film ruptures. A few select works from the past decades have demonstrated that rupture is suppressed in favor of a saturated propagating wave when the film is advected by either a spatially uniform surface stress or body force of sufficient magnitude. Following the falling film notion that wavy propagating films are valuable in design of heat and mass transfer equipment, we investigate and provide unifying analysis of three mechanisms that generate propagating waves: (1) the Rayleigh-Taylor instability subject to slight substrate inclination, (2) the Rayleigh-Taylor instability subject to a weak substrate temperature gradient, and (3) the deformational Marangoni instability subject to a weak substrate temperature gradient. The film dynamics for each case are investigated on periodic domains via linear analysis, weakly nonlinear analysis, and numerical solution of the nonlinear evolutionary equations for the film thickness, derived via the long-wave approximation. Each of these equations is derived with scalings so as to represent the relative effect of destabilization to advection by either a single parameter, D, for cases (1) and (2), or two parameters, D and the Biot number, for case (3) . Discussion is provided to translate results of each case to characteristic values of dimensional parameters and film thicknesses, and the concluding discussion focuses on effects that must be considered in non periodic domains.

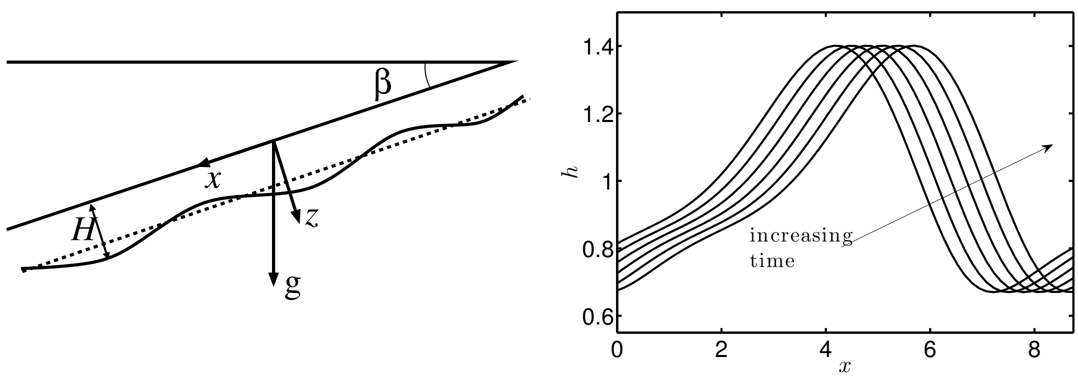

FIG. 1: Left: configuration of interest for case (1), that is, generation of traveling waves on hanging films via saturation of the Rayleigh-Taylor instability with substrate inclination. Right: numerical solutions of the saturated profile for case (1), with the destabilization parameter D_1=1 and the periodic domain width set to the fastest growing linear wavelength. For water, these profiles are expected in earth-based systems for mean film thicknesses of 0.1 mm and inclination angles of 2.3°.

Thin Films with Time-Dependent Chemical Reactions

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Chemical reactions in thin liquid films can lead to Marangoni convection due to temperature or concentration gradients on the interface and therefore affect the film evolution [1]. The heat of reaction and changes in species concentration can also impose density and viscosity variations within the film, which affect film stability [2]. Using reactive surface active agents can influence the behavior in a desired manner [3].

In the present work we examine a thin liquid film, which is sheared by a turbulent gas flow and heated from below by a wall with constant temperature. A first-order chemical reaction is present in the film. This setup can be found in combustion engines, for example, where fuel films form on the cylinder walls and chemical reactions lead to deposit formation. Long-wave theory with a double pertubation analysis [1] is used to reduce the complexity of the problem and obtain an evolution equation for the film thickness. The chemical reaction is assumed to be slow compared to film evolution, which is the case for many industrial applications. However, available literature often assumes an unlimited amount of reactant available in the film. We examine the effect of time and temperature on the reaction rate and consequently the stability of the film, thus we are retaining those terms in the derivation of the evolution equation. A linear stability analysis is performed to identify the influence of material properties and environmental conditions on the stability of the film.

We show that exothermic reactions have a stabilizing effect on the film whereas endothermic reactions destabilize the film and can lead to film rupture. Gravity acts to increase the stability of the film. Figure 1 shows that initial disturbances in the film grow up to a certain point for an endothermic reaction and then begin to decline as the reaction rate decreases. Convective effects are present through the shearing of the liquid film by the external gas flow. Parameter studies are conducted identifying the influence of the external gas flow, reaction parameters, surface tension, and film height on film evolution and rupture, as well as the velocity and temperature field.

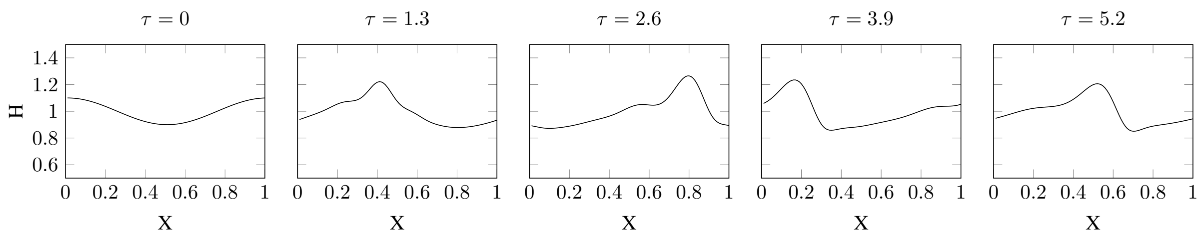

FIG. 1: Dynamics of the film evolution for an endothermic reaction

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A Thin Drop Sliding Down an Inclined Plate

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We examine two- and three-dimensional drops steadily sliding down an inclined plate. The drop's contact line is governed by a model based on the Navier-slip boundary condition and a prescribed value for the contact angle. The drop is thin, so the lubrication approximation can be used. In the three-dimensional case, we also assume that the drop is sufficiently small (its size is smaller than the capillary scale). These assumptions enable us to determine the drop's shape and derive an asymptotic expression for its velocity. For three-dimensional drops, this expression is matched to a qualitative estimate obtained in [1] for arbitrary drops, i.e. not necessarily thin and small. The matching fixes an undetermined coefficient in the estimate obtained in [1], turning it into a quantitative result.

Then we show that this theoretical result agrees with the experimental data obtained in [1] only for an unphysically small (subatomic) slip length l – which implies that the Navier-slip model does not hold for glycerine, glycerine/water mixture and ethylene glycol used in the experiments of [1]. Recalling also that the estimates derived in [2, 3] suggest subatomic values of l for water and mercury as well, one might wonder whether the list of exceptions has become long enough to cast doubt on the actual rule.

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Dancing drops over vibrating substrates

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We study the motion of a drop on a plate simultaneously submitted to horizontal and vertical harmonic vibrations. The investigation will be done via a phase field model earlier developed for describing static and dynamic contact angles [1–3]. The density field is nearly constant in every bulk region ($\rho = 1$ in the liquid phase, $\rho \approx 0$ in the vapor phase) and varies continuously from one phase to the other with a rapid but smooth variation across the interface. Complicated explicit boundary conditions along the interface are avoided and capturated implicitly by gradient terms of ρ in the hydrodynamic basic equations. The contact angle θ is controlled through the density at the solid substrate ρ_S, a free parameter varying between 0 and 1. We emphasize the swaying and the spreading modes, identified by Benilov *et al.* via a shallow–water model for drops climbing uphill along an inclined plane oscillating vertically [4]. For example, fig. 1 illustrates the swaying scenario of a hydrophobic droplet over a vibrating substrate. The numerical simulations will be completed by experiments. Some ways to prevent the flying into the gas atmosphere of the dancing drops will be also presented.

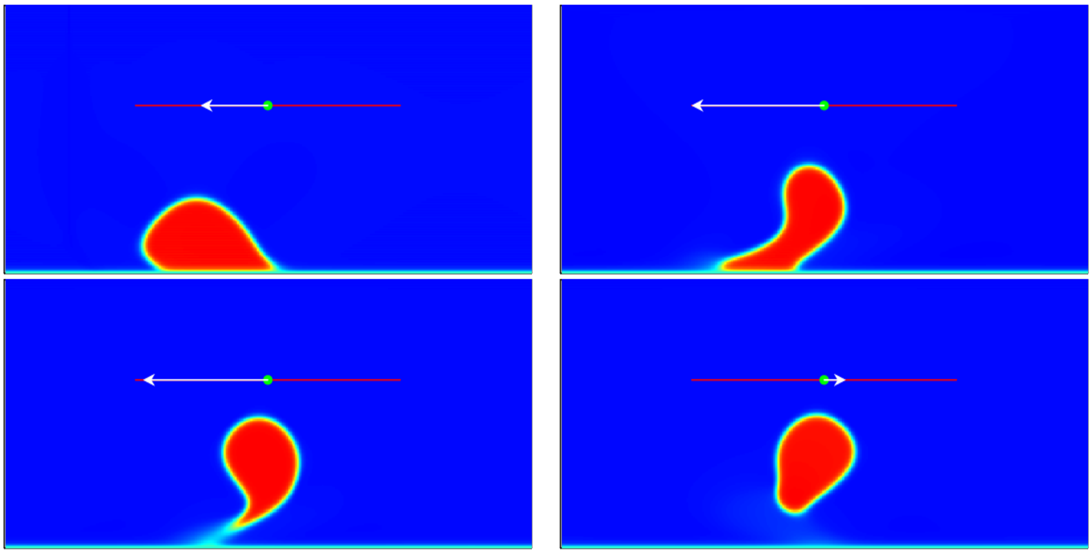

FIG. 1: Several snapshots illustrating a dancing droplet over a hydrophobic substrate subject to lateral and vertical harmonic oscillations. The arrows in the backgraound indicate the elongation of the triggering horizontal oscillatory motion at the solid substrate.

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3D Simulation of the Marangoni Effect on Transient Mass Transfer from a Single Moving Spherical Drop

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A three-dimensional numerical model was adopted for studying the Marangoni effect induced by the interphase mass transfer on the fixed interface of a single drop in an immiscible liquid. The numerical simulation was performed in the spherical coordinate system with the origin at the centre of the spherical drop. The continuity equation, Navier-Stokes equation and mass transfer equation were simultaneously solved for both phases and the corresponding interfacial boundary conditions were enforced. The negative value of drop terminal velocity, which was calculated via the force analysis of the drop, was assigned to the outer boundary of the continuous phase. A local grid refinement was implemented near the interface to improve the accuracy of mass transfer computing, and the minimum grid size was 10 μm for a drop size of approximately 1 mm. The algorithm was verified with a good comparison of the predicted mass transfer coefficient and drop velocity with the experimental data of the MIBK-acetic acid-water system. Even though this 3D simulation was simplified by working on a spherical drop, it is sufficiently powerful to illustrate the asymmetrical nature of the Marangoni effect and found a delay on the start of the 3D Marangoni effect. With the local flow field information revealed by the numerical simulation, this work analysed the enhancement mechanism of the Marangoni effect on the interphase mass transfer.

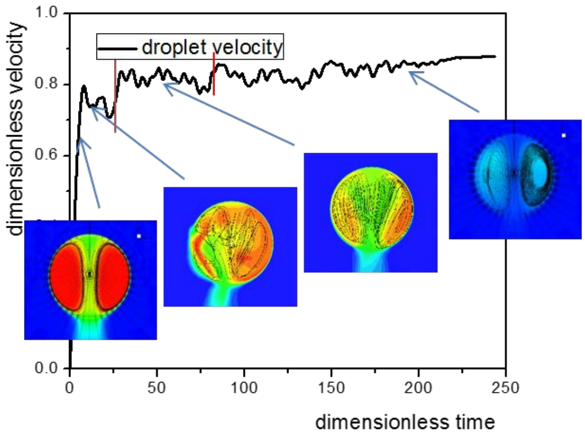

FIG. 1. The drop velocity and the interphase mass transfer process accompanied with the Marangoni effect.

Numerical Simulation of Solute-Induced Marangoni Effect of Two Coalescing Drops

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In liquid-liquid separation operation, the solute-induced Marangoni effect is frequently encountered. As a joint result of the inertia force, viscous force and the Marangoni effect, the drop behavior is very complex. It has been indicated that the drop coalescence behavior would be clearly different whether the Marangoni effect was present or not [1]. Therefore, this work is focused on the influence of the solute-induced Marangoni effect on the drop coalescence and the accordingly affected mass transfer rate. The rising drops driven by buoyancy in another continuous phase accompanied with the mass transfer process and the solute-induced Marangoni effect were modelled in a coupled scheme by the level set method. The semi-Lagrangian advection scheme was adopted to suppress the numerical diffusion occurring in the simulative interphase mass transfer process. The effects of relative position, drop size, and the Marangoni effect on the drop interaction and coalescence were analyzed.

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The Asymmetrical Capillary Channel Flow: Experiment Results and Theoretical Analysis

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I. BACKGROUD AND OBJECTIVES

The fluid transport process is very important to almost all industries. Especially for liquid management in space and lab-on-chip, which provide a condition that the gravity is negligible,the capillary effort dominatesthe behavior of the free surface. And the most challenging problem is how to preserveacontinuous,bubble-free flow. Once the flow rate within the channel has exceeded a certain value, the bent free surface is of no capacity to maintain a stable state, and the surface collapse and gas ingestion occur.There are many significant works[1,2], they use one dimensional model and three dimensional simulation method to get critical flow rate value and transition behaviour theoretically, meanwhile, experiment within drop tower, ballistic rocket and International Space Station also provide many useful result. But all of these works foucus on symmetricalcapillary channel geometries, for the real application , there are more asymmetrical ones, we choose a typical (a curved vane is perpendicular to a straight vane) asymmetrical channel to promote our experiment study. And an asym-metrical channel and an symmetrical one (two straight vanes are perpendicular to each other) as contrast, so we can figure out their capillary flow character and the differences.

II. EXPERIMENT RESULTS AND THEORETICAL ANALYSIS

The experiment setup of drop tower consists of two fluid containers in which there are two channels inside the different volumetric flow rates can be formed and measured by two flow meters. Two CCD cameras are used with two mirrors for flow observation. We choose HFE-7500 as test liquid andten drops in Beijing Drop Tower have been performed. The experimental results show in fig.1 that there exist two different kinds of the behavior of free surface flow such as the free surface collapse and gas ingestion or not. Due to the limit of microgravity time of 3.6s by using our drop tower, we can not judge all conditions that certainly. So we chose the location of the lowest point of the free surface in both flow and height direction, get the coordinates and plot them versus time. The critical flow rate of asymmetrical channel is 2.7±0.2ml/s, for symmetrical channel is 2.2±0.2ml/s. the cross-sectional geometries affect the capillary channel flow behavior.The capillary channel flow have three typical flow patterns: subcritical flow, supercritical flow and critical flow.

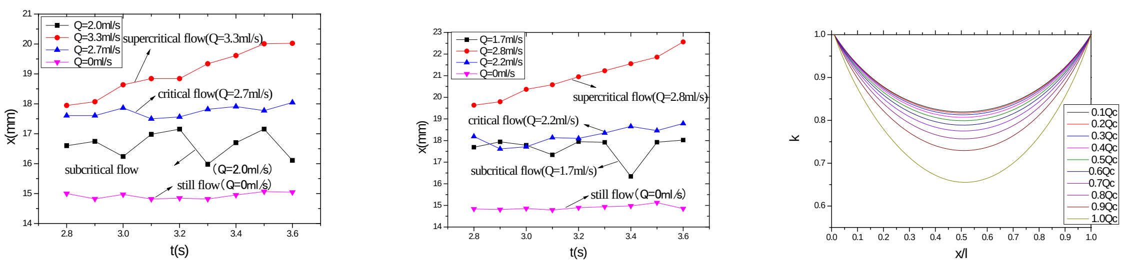

FIG.1. The locations of lowest point of free surface versus time t in x direction.
Left: asymmetrical channel; Middle: symmetrical channel;Right: theory result of asymmetrical channel with different flow rates(Q_c=4.3ml/s).

Acknowledgements

The funding of drop twer experiment and the research project was supported by China National High-tech R&D Program (863 Program).

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Numerical Simulations of Sessile Droplet Evaporating on Heated Substrate

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I. Introduction

The EFILE (Space Experiment of Evaporation and Fluid Interfacial Effects, also a CAS/CNES joint project IMPACHT – InterfaceMicrogravity PhAse Change Heat Transfer) is one of the microgravity fluid physics experiments scheduled onboard Chinese scientific satellite of SJ-10 [1], the experiment is aimed to obtain the novel knowledge on the coupling mechanism of evaporation and convection in a system with phase-changed interface in microgravity environment, and also to understand the gravity effects on the heat and mass transfers of evaporation[2].In order to predict the whole evaporation process of the space experiment, numerical simulations of sessile droplet of millimeter size evaporating on a solid substrate, including the gas, liquid and solid phrase, are performed and reported here.

II. Numerical model

The numerical model is based on the conservative mass, momentum and energy equationsin three phases (gas-liquid-solid) and concentration equations in the gas phase, presentedin a two-dimensional (asymmetrical) systems as shown in Fig.1.The governing equations are solved numerically together with an advection/convection equation used to tackle the evaporation of a sessile droplet with a pinned contact line.In first approach, the evaporation can be considered as a quasi-steady-state process. Hence, the vapor concentration distribution above the droplet satisfies the Laplace equation but with a time-varying droplet surface. It is found both theoretically and experimentally that the net evaporation rate from the droplet remains almost constant with time for a small initial contact angle ($\theta < 40°$), even though the evaporation flux becomes more strongly singular at the edge of the droplet as the contact angle decreases during evaporation. We will report the influence of droplet size andof substrate temperature on the hydrodynamics of evaporation. The initial condition problem will be also assessed for droplets in order to investigate the effect of boundary conditions.

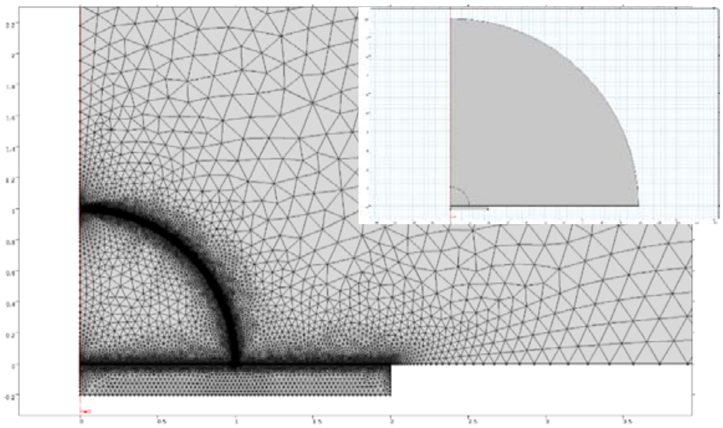

FIG. 1.Computational domain and an example of the mesh.

On the dynamical behaviour of anti-surfactants

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We analyse a recently developed model for the flow of a solution for which the surface tension depends on the surface excess of the dissolved solute. This model differs from classical models for surfactants in which surface tension is taken to depend solely on the surface concentration. By allowing surface tension to depend on the surface excess, the model captures not only the behaviour of surfactants (which decrease the surface tension of the fluid), but also the behaviour of so-called anti-surfactants (which increase the surface tension of the fluid). Performing a linear stability analysis of a quiescent layer of solution, the model predicts a novel instability for anti-surfactants which does not occur for surfactants, as shown in figure 1 (left), and we investigate the conditions for the onset of this instability. We also formulate the equations describing the flow of a thin film of such a solution, and perform fully non-linear numerical calculations to illustrate the wide range of dynamical behaviour that such solutions can exhibit. In particular, figure 1 (right) shows how the free surface of a thin film deforms when anti-surfactant is added to a small region on the surface of an otherwise pure solvent. Finally, we derive a novel semi-analytical similarity solution which describes the long-time behaviour of a thin film when anti-surfactant is added to a small region of the bulk of the fluid, and remains completely excluded from the free surface.

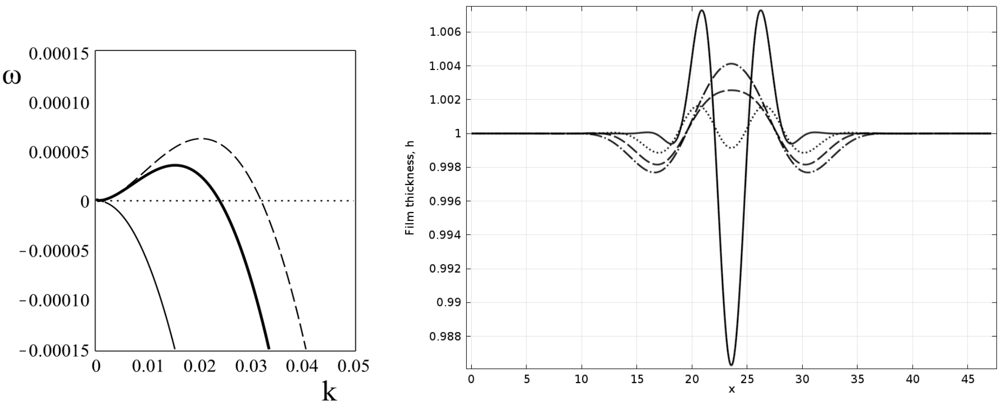

FIG. 1: Left: Growth rates of perturbations, ω, to a quiescent layer of an anti-surfactant solution, showing an unstable mode for a finite range of wavenumbers k. Right: Evolution of the free surface of a thin film due to the addition of anti-surfactant to a small region of the free surface.

Marangoni flows induced by atmospheric-pressure plasma jets

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Atmospheric-pressure plasma jets have generated significant interest for their versatile applications in material processing and surface modification. We studied the interaction of atmospheric-pressure plasma jets of Ar or air with liquid films of an aliphatic hydrocarbon on moving solid substrates. The hydrodynamic jet-liquid interaction induces a track of lower film thickness. The chemical plasma-surface interaction most likely oxidizes the liquid, leading to a local increase of the surface tension and a self-organized redistribution of the liquid film.

We used a commercial atmospheric-pressure plasma jet (KinPen 09, NeoPlas Tools), operated at a flowrate of approximately 1 l/min at normal incidence onto the substrate (Fig. 1). We used either Ar gas or purified air. We adjusted the electrical power input such that the visible length of the plasma jets was maintained at about 3 mm. The exit nozzle diameter is $D \approx 1$ mm. The substrates were rotated at a constant angular velocity Ω. The radial distance of the plasma jet from the (vertical) axis of rotation was approximately 1 cm, which implies that a value of $\Omega = 1$ rpm corresponds to a translation speed of $U \approx 1$ mm/s.

The stagnation pressure and wall shear stress of the gas flow induce a depression in the liquid film along the jet trajectory. Depending on the rotation rate, the remaining film thickness along the track centerline is in the range of approximately 0.1–1 µm. The grayscale fringes in Fig. 2 represent curves of constant film thickness. The most striking feature as a consequence of Ar plasma jet treatment is the formation of a pair of rims extending parallel to the centerline of the jet trajectory with initial separation $d_{rim} \approx 2$ mm, as indicated by the red arrows in Fig. 2. The rims move towards each other and merge within 5–9 min. Moreover, the rims tend to become unstable and break up into a series of droplets that grow and coarsen in time, as visualized e.g. in Fig. 2. We systematically studied the effect of the substrate rotation rate Ω. Moreover, we developed a numerical model that qualitatively reproduces the formation, instability and coarsening of the flow patterns observed in the experiments.

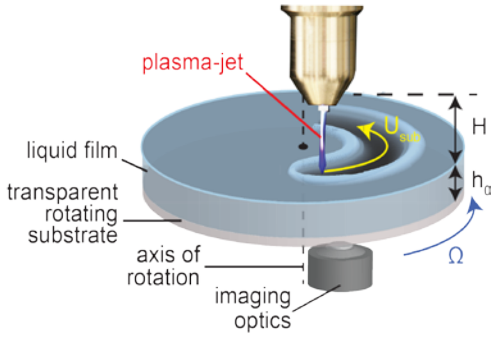

FIG. 1. Experimental setup [1].

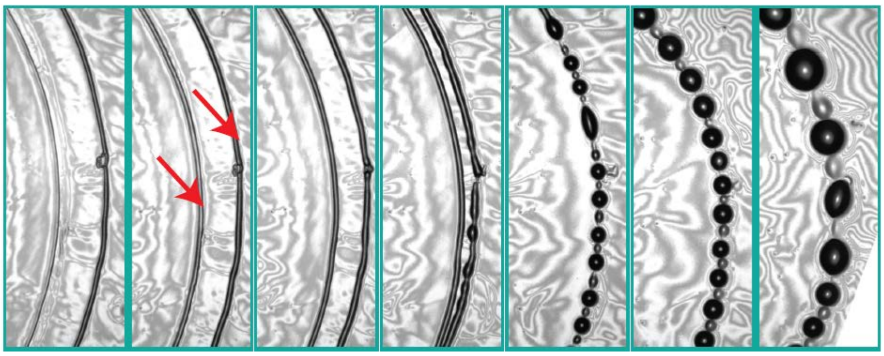

FIG. 2. Optical micrographs of an aliphatic thin liquid film on a rotating substrate ($\Omega = 1$ rpm) at 1, 2, 3, 5, 9, 17 and 33 minutes after interaction with an atmospheric Ar plasma jet [1]. Image widths 4 mm.

Monitoring the liquid flow has potential as an in-situ, spatially and temporally resolved, diagnostic tool for the plasma-liquid surface interaction. On the other hand, the plasma jets provide a versatile tool for inducing thickness- or composition modulations in a liquid coating prior to the drying or solidification stage.

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Dispersion and viscous attenuation of capillary waves with finite amplitude

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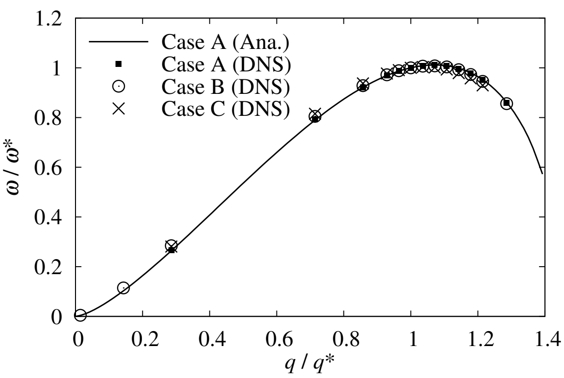
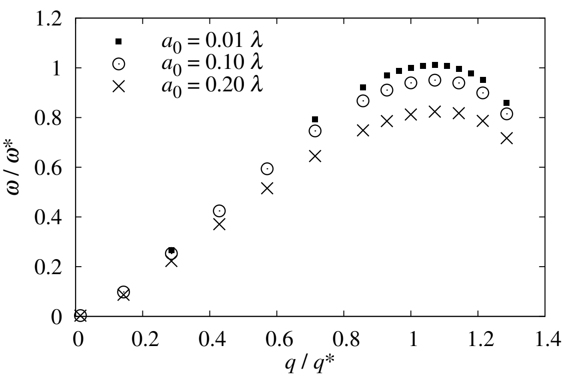
The dispersion and viscous attenuation of capillary waves is interesting for a wide range of fluid dynamics applications, such as interfacial flow through porous media or in microfluidics devices as well as for the stability of foams and capillary bridges. However, most research has focused on linear wave theory and capillary waves with infinitesimal amplitude and negligible viscous attenuation. For capillary waves in viscous fluids, similar to other damped oscillators, three damping regimes can be distinguished: the underdamped regime for $q < q_c$, critical damping for $q = q_c$ and the overdamped regime for $q > q_c$, where q is the wavenumber and ω is the frequency of capillary waves, with $\mathrm{Re}(\omega) = 0$ for $q \geq q_c$.

In this contribution we analyse and discuss the dispersion of capillary waves with finite amplitude, based on a detailed study using two different direct numerical simulation methods [1–3]. Our results reveal a self-similarity of the dispersion (i.e. frequency and phase velocity as a function of wavenumber) of capillary waves with small initial amplitude throughout the entire underdamped regime and independent of the fluid properties, as shown in Fig. 1a for three representative cases, where superscript $*$ denotes an appropriately chosen reference value. In addition, our results suggest that the widely adopted hydrodynamic theory for damped capillary waves, see e.g. Ref. [4], does not accurately describe the dispersion of capillary waves if viscous damping is significant. These observations are confirmed by analytical solutions for capillary waves with small amplitude [5]. With respect to the initial amplitude a_0 of capillary waves, we observe an increase of viscous attenuation with increasing initial amplitude, as seen in Fig. 1b. Interestingly, we show that the reported self-similarity of the dispersion also holds, to first approximation, for capillary waves with finite amplitude, i.e. outside the remit of linear wave theory.



(a) DNS results of three different two-phase systems with initial amplitude $a_0 = 0.01\lambda$, compared against the analytical solution ('Ana.') of Prosperetti [5].



(b) DNS results for a given two-phase system with different initial amplitudes a_0.

FIG. 1: Dimensionless frequency ω/ω^* as a function of dimensionless wavenumber q/q^*.

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Drying of colloidal dispersion in a blade coating configuration: from dilute dispersion to porous medium

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A numerical model is developed to investigate the drying of a colloidal dispersion in a blade-coating configuration, as depicted in fig. 1. The transition from the dispersed state up to the dense colloidal assembly is described through continuous models, in the framework of lubrication approximation. Beyond the evaporation length L_{ev}, air invades the porous medium and the film is dry. Meniscus profile and evaporation length L_{ev} are not imposed a priori but arise from the resolution of governing equations (momentum balance, total and particle mass balances) and from the estimation of the pressure in the film. We discuss the appropriate choice of boundary conditions at the solid/liquid interface.

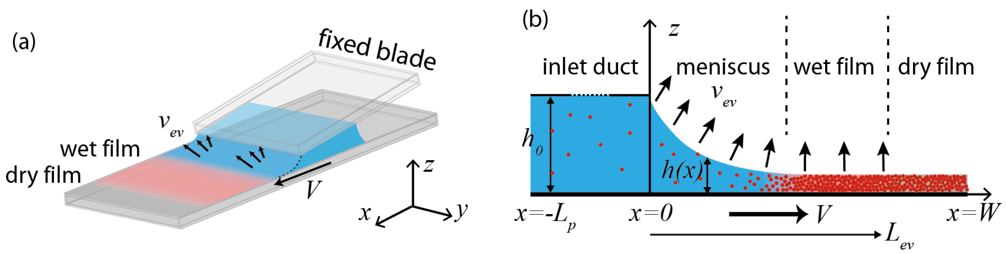

FIG. 1: Geometry

We consider "hard-spheres" colloids showing a divergence at the close packing transition for the mutual diffusion coefficient, the osmotic pressure, and the viscosity [1]. We investigate the dry deposit thickness as a function of the process parameters. It is now well documented that several regimes appear depending on the capillary number Ca. For sufficient capillary number, viscous forces are large enough to drag a film from the bath. This regime is known as the Landau-Levich regime, where the thickness of the dragged film is proportional to $Ca^{2/3}$. We focus on the evaporative regime encountered for smaller capillary numbers, for which the liquid flow into the meniscus is mainly driven by the evaporation. In contrast to the Landau-Levich regime, the dried film thickness in this evaporative regime is a decreasing function of the substrate velocity. Several experiments on various systems show that deposit thicknesses are proportional to V_{sub}^{-1} [2, 3]. However, for colloidal dispersion at very low velocity, we show that another regime appears, where the dry film thickness is no more proportional to V_{sub}^{-1} but show a V_{sub}^{-2} scaling. We analyze the apparition of this regime, which is induced by the specific properties of colloidal dispersions.

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Nonlinear dynamics and interfacial stabilities of Rayleigh-Taylor unstable condensing liquid layers: the effects convection and diffusion of the vapor

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ABSTRACT

The three-dimensional surface pattern and dynamics of condensing liquid layers lying on the underside of cooled horizontal substrates are investigated by an evolutionary system consisting of two coupled nonlinear partial differential equations. A vapor boundary layer is introduced above the condensing layer, to which the changes in gas composition and temperature are assumed to be confined. The present model extends that presented by Kanatani[1] by incorporating the effects of gravity accompanied by buoyancy and heat flux in the boundary layer. The influences of the mass-gain rate, vapor recoil, Marangoni effect, and the wavelength of the disturbance are examined. The results of traditional one-sided model are compared with those of the extended 1.5-dimensional model. The spontaneous rupture is found in all one-sided simulations and no continuous steady states exist that suggesting the localized vapor recoil and Rayleigh-Taylor instability (RTI)with mass-gain prevail over the stabilizing effects of thermocapillarity and surface tension variation. We also present the possible existence of stable stationary localized non-ruptured solutions without mass gain by analyzing the Liapunov functional. The results of the 1.5-dimensional model show that the RTI can be stabilized by the effects of thermocapillarity as well as the convection and diffusion of the vapor under the condensing conditions.

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Relaxation Oscillations of Solutal Marangoni convection

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Mass transfer of surface-active substances across fluidic interfaces is frequently accompanied by Marangoni instability [1]. This is of specific interest for extraction processes, as transfer rates are responsive to the magnitude of the resulting convection [2]. Marangoni convection can show a temporal periodicity in the form of relaxation oscillations (ROs) due to subsequent consumption and regeneration of its driving force. Contrary to the complex behavior of strong surfactants [3] or reactive mass transfer [4], a simple two-phase-system consisting of paraffin oil and water is employed in our study. Due to mass transfer of isopropanol as a weak surfactant, concentration gradients and, by implication, density gradients exist.
The focus of the present contribution is on combined experimental and numerical work on small droplets, placed in the concentration gradient. These droplets show about hundred periods of regular ROs over almost one hour, see Fig.1. By analyzing their characteristics, the underlying mechanism can be attributed to the interaction between the mixing by Marangoni convection and the restoring effects of diffusion and buoyant convection on the driving concentration gradients. The 2D numerical simulations are based on a diffusive-interface approach [5] and assume a linear concentration and density gradient. Furthermore, interfacial tension depends linearly on isopropanol concentration without accumulation of matter at the interface. As shown in Fig.1, this simplified model is capable of reproducing the ROs observed experimentally.

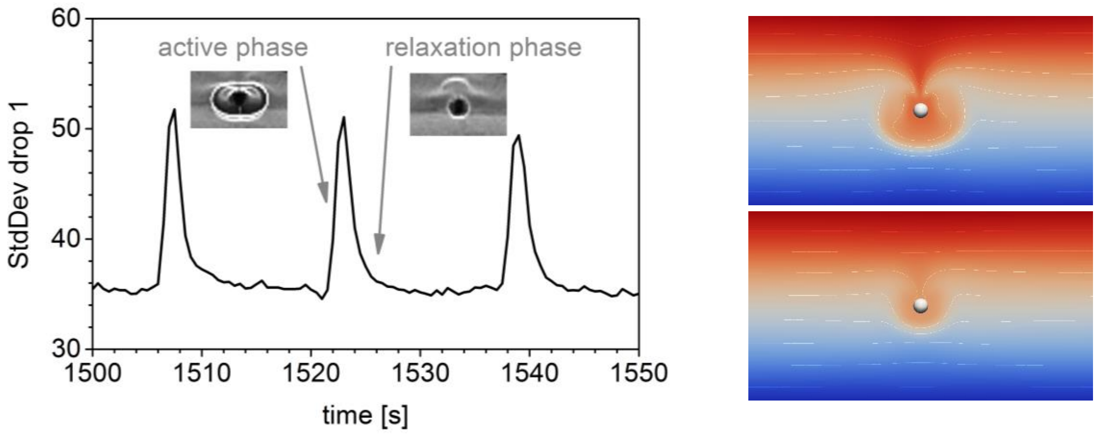

Fig.1: Relaxation oscillations at droplets: experiment (left) and simulation (right).

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Nonlinear Evolution of the Interface between Immiscible Fluids in a Microchannel subject to an Electric Field

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The interface between two immiscible, leaky-dielectric, incompressible Newtonian fluids can be destabilized in the presence of an externally applied electric field. In this work, once the critical voltage for the instability is found out, the nonlinear evolution of the interface is studied. Analyzing this dynamic behavior is a step to determine if micro droplets will be formed as the interface might flap one of the walls and between two flaps a droplet would form. As the microchannel length is much longer than the interface deflection, the nonlinear equations are simplified using the lubrication theory. The resulting coupled nonlinear differential equations for the interface position and the interface charge distribution are solved with a Chebyshev spectral method. The results will be qualitatively compared to experimental work. The important parameters that are analyzed are capillary number, ratio of flow rates, and ratios of the viscosities and the electrical properties of the liquids.

Linear stability analysis of the vibration influence on Marangoni waves in two-layer film

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We consider influence of vibration on the dynamics of a heated from above two-layer liquid system with deformable interface and upper free surface. The surface tension at both surfaces depends linearly on the temperature. The lower boundary is rigid and its thermal conductivity is higher than that of both liquids. The heat flux from the free surface is governed by Newton's law of cooling. The reduction of the three-dimensional problem to a two-dimensional one in the framework of the lubrication approximation and the derivation of the set of two amplitude equations have been carried out recently [1, 2]. In [1], it was shown that without vibration, both monotonic and oscillatory modes are possible. In [2] only numerical analysis for the evolution of perturbations was done. In the present work we apply the Floquet theory to study vibration influence on the both monotonic and oscillatory modes found in [1]. For the details of the Floquet theory application we refer to work [3]. After introducing normal perturbations into the linearized amplitude equations we obtained system of two ordinary differential equations. That system was integrated with different initial conditions and according to the Floquet theory monodromy matrix was constructed and Floquet multipliers were found. These multipliers allow us to classify the perturbations. The oscillatory boundary becomes quasiperiodic with subharmonic zones of instability, starting from some value of the vibration amplitude the subharmonic mode becomes critical. Monotonic mode becomes synchronous mode. The neutral curves in wide parameter interval were obtained and stability maps were built.

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Pattern selection on square and hexagonal lattices in a problem of Marangoni instability in ultrathin two-layer film

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Weakly nonlinear analysis is carried out for the longwave Marangoni instability. Under consideration is a heated from above two-layer liquid system with deformable interface and upper free surface. The surface tension at both surfaces depends linearly on the temperature. The lower boundary is rigid and its thermal conductivity is higher than that of both liquids. The heat flux from the free surface is governed by Newton's law of cooling. The reduction of the three-dimensional problem to a two-dimensional one in the framework of the lubrication approximation and the derivation of the set of two amplitude equations have been carried out recently [1]. It was shown that both monotonic and oscillatory modes are possible and only numerical analysis for the evolution of perturbations was done.

In the present work we consider nonlinear evolution of small-amplitude oscillatory perturbations. We aim at the nonlinear analysis of small-amplitude perturbations and the comparison of the results with the direct numerical simulations within nonlinear amplitude equations [1], and the extention of the results of the mentioned paper. In what follows, we deal with pattern selection on a square and hexagonal lattices. According to the weakly nonlinear analysis we present local heights of the lower and upper layers, and Marangoni number as a power series in small δ, where δ is a measure of the supercriticality, and introduce two timescales. The fast one, $\tau^{(0)}$, corresponds to the oscillations, whereas the amplitudes evolve in the slow one, $\tau^{(2)}$. Substituting this ansatz into the nonlinear amplitude equations, and collecting the terms of equal powers in δ, we obtain in each order a stability problem. The problem at the third order contains nonhomogeneous terms. The solvability conditions provide the set of ordinary differential equations for the complex amplitudes. The coefficients of nonlinear interaction were calculated. Detailed explanation of the method application could be found elsewhere [2]. The set of the ordinary differential equations for the complex amplitudes represents a standard set of Landau equations, such systems were obtained on a square lattice and on a hexagonal lattice. Following [1], we deal with fluorinet FC70 as a lower liquid and silicon oil 10 as an upper one. Applying the stability conditions from [3], one can analyze pattern selection near the stability threshold on a square lattice. Pattern selection on the square lattice shows that there is a competition between three structures: traveling and standing rolls, and alternating rolls. Stability maps of the mentioned regimes have been built. It was shown that in the parameter region where oscillatory instability exists in wide parameter region 1-dimensional structures (traveling and standing rolls) were observed. Alternating rolls have been found in a narrow parameter region. Note, that the areas of the traveling and standing rolls do not cross over, because the stability conditions for these structures exclude one another. From the other side stability regions for 1-dimensional and 2-dimensional structures overlap each other. In the narrow parameter region alternating rolls are stable.

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Development of Thermocapillary Convection Induced by Nonuniform Heating of a Free Boundary in the Presence of Insoluble Surfactant

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We consider a 2D problem of a free convection in a horizontal rectangular cavity. The horizontal size of the cavity l is much larger than vertical one h ($l/h \sim 5$). The origin of the y axis directed upward is on the lower plane. The upper layer boundary $y = h$ is heated by radiation, whose power varies linearly with the horizontal coordinate x: $N = A(l - x)$. The source is powered on at time $t = 0$. The radiation is absorbed by a thin liquid layer with the thickness of $d \ll h$. Initially, the fluid is at rest and has the same temperature everywhere. We assume that the surface tension on the free boundary depends linearly on temperature T and surfactant concentration $\Gamma(x, t)$ of a surface-active agent (surfactant) $\sigma = \sigma_0 - \sigma_T(T - T_0) - \sigma_\Gamma(\Gamma - \Gamma_0)$. The inhomogeneity of surface tension in such system causes the Marangoni convection. In addition a gravitational convection is developed due to the dependence of fluid density on temperature $\rho = \rho_0(1 - \beta(T - T_0))$ in the gravity field.

In the initial phase, the upper boundary of liquid is covered by a uniform film of insoluble surfactant with the Bingham rheology. At low shear stress the film keeps the surface of liquid, and the liquid moves in the same way as near a solid surface. When the heating of liquid and the development of convective motion take place, a tensile strength on the film rupture increases. When at some point the force P exceeds the tensile strength of the film (i.e., $P > P_0$), the surfactant film is ruptured, a ”polynya” of pure liquid arises, and the fluid surface begins to move. The liquid motion is described in the Boussinesq approximation. The thermal source term is added to the heat equation. The heat exchange with the environment on the solid boundaries takes place from Newton’s law.

In this formulation, at $P_0 = 0$ the problem corresponds to traditional formulation of the problem of developing the combined gravitational and Marangoni convection. At $P_0 \neq 0$, the delay of the Marangoni convection onset is observed in [1, 2]. At large P_0 the development of capillary convection is impossible.

In this paper, the solution of time-dependent problem for the model with the Bingham properties of the fluid surface is obtained by using a difference method. The problem parameters, at which the surface is cleaned from the surfactants, are defined. The changing the dimension of the ”polynya” with time is also studied.

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Ratchet flow on a substrate with an asymmetric topography sustained by the thermocapillary effect

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We investigate the flow of liquid in a thin film over a thick, asymmetric corrugated surface in a gas-liquid bi-layer system. The substrate is uniformly heated from below, while the gas layer is bounded from above by a solid plate, held at a fixed temperature. Using long-wave approximation, we derive an evolution equation for the spatiotemporal nonlinear dynamics of the liquid-gas interface, driven by thermocapillarity over the corrugated topography. We show analytically that for a non-flat topography of the solid substrate, the average volumetric flow-rate through the system can be non-zero. We demonstrate the existence of a non-zero ratchet flow by numerical investigation of the evolution equation mentioned above, and proceed to study the stability of the interface with respect to topographical variations, gravitational effects and different values of the Marangoni number. Furthermore, we show that the average flow-rate through the system can be controlled and amplified through manipulation of the temperature difference across the system, and demonstrate that the described mechanism can be applied to the liquid in order to create travelling droplets, which can act as microscopic flasks and serve as means of transport for micro- and nano-particles. The simplicity of this mechanism has many advantages over other flow inducing methods, and and commends its application to various problems in the context of fluid transport in enclosed microfluidic systems with an interface between liquid and gas.

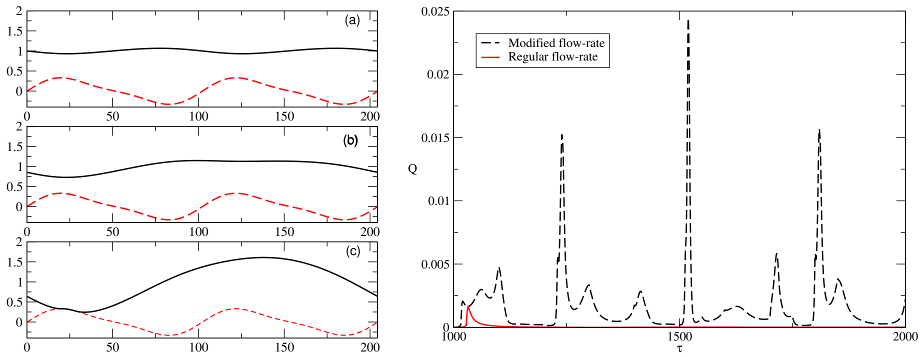

FIG. 1: Left: Temporal evolution of the film interface over an asymmetric corrugated surface. (a) a metastable state at $\tau = 100$ which persists for a relatively long time τ before it loses its symmetry and proceeds toward rupture; (b) the state corresponding to the largest positive averaged flow rate at $\tau = 330$; (c) the state slightly before rupture at $\tau = 400$. Red dashed curve represents the substrate;
Right: (a) Red solid curve represents the time variation of the average flow rate Q for a sufficiently large Marangoni number with rupture taking place around $\tau = 1100$. Dashed grey curve displays the time variation of the average flow rate Q with the control that consists of the Marangoni number varying in time as shown in panel (b). In the latter case rupture is prevented and flow reverts from negative (to the left) to the predominantly positive (to the right) direction.

Interfacial instability in miscible liquids induced by vibrations

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The stability of the system under periodic vibrations with the direction along the interface has attracted large research interest in different problems studied under microgravity and normal gravity conditions. Liquid-liquid interfaces may become unstable if a shear stress is applied and a well-known example is the Kelvin-Helmholtz instability. Horizontal vibration of the flat liquid-liquid interface produces an instability in the form of frozen waves caused by a shear-driven mechanism similar to the Kelvin-Helmholtz instability. The distinction is that, as a result of a harmonic change in the flow direction, the wave remains on average in the same place, as its profile is frozen in the reference frame of a vibrating container.

Our recent experiments [1 , 2] demonstrated that an interfacial instability may occur between two miscible liquids of similar (but non-identical) viscosities and densities under horizontal periodic excitations. In a gravity field, a spatially periodic saw-tooth frozen structure is generated on the interface under horizontal vibrations somewhat similar to immiscible liquids. Under the low gravity conditions of a parabolic flight, the crests widen and the final and long-lived pattern consists of a series of vertical columns of alternating liquids.

The target of present study is to identify the influence of gravity on instability of the interface between two miscible liquids and to examine the evolution of the interfacial wave shape for parameter ranges that are out of reach experimentally, i.e., when gravity changes within the range from zero up to the Earth's gravity. This study is related to space experiment VIPIL (Vibrational Phenomena in Liquids) which is planned to be performed on ISS.

The considered system has two layers of binary mixtures of the same constituents (water–alcohol mixtures of different percentage): 90% (mass) of water in isopropanol and a 50% (mass) of water in isopropanol. The imposed vibrations have been chosen for frequency (f) and amplitude (A) within the ranges 2–24Hz and 1.5–16mm, respectively. The both liquids are placed into the cell (15.0mm×7.5mm×5.0mm).

We present results of numerical simulations in the geometry which corresponds to the experimental cell for the nonlinear evolution of waves at the interface between two miscible liquids subjected to horizontal oscillations at different gravity levels (see Fig.1). A detailed comparison between simulations and recent experimental observations in normal and low gravity showed an excellent agreement. The obtained results delineate parameter space where gravity affects differently interfacial instability. Based on qualitative observation of a large number of snapshot sequences and an extensive quantitative analysis, three distinctive regimes of instability were identified depending on the gravity level.

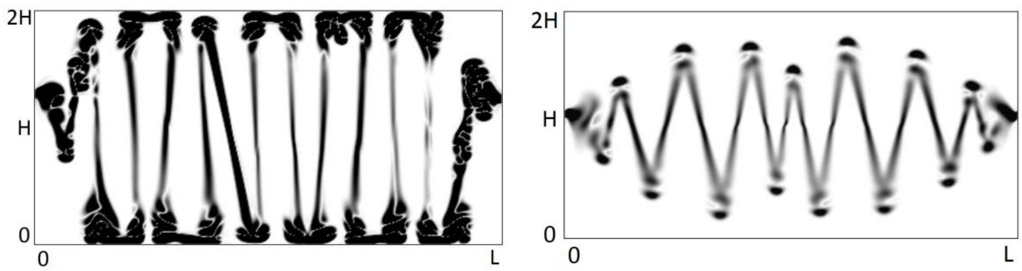

FIG. 1. Interfacial patterns in a vibrating cell at A=5mm, f=20Hz for different level of gravity. Left: gravity is absent; Right:g/g_0 = 0.25.

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Interfacial Waves in Inviscid Two-Layer Liquid System Subject to Longitudinal Vibrations

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We study the waves at the interface between two thin horizontal layers of immiscible fluids subject to high-frequency horizontal vibrations. Previously, the variational principle for energy functional, which can be adopted for treatment of quasistationary states of free interface in fluid dynamical systems subject to vibrations, revealed the existence of standing periodic waves and solitons in this system. However, this approach does not provide regular means for dealing with evolutionary problems: neither stability problems nor ones associated with propagating waves. In this work [1], we rigorously derive the evolution equations for long waves in the system, which turn out to be identical to the plus (or good) Boussinesq equation. With these equations one can find all the time-independent-profile solitary waves (standing solitons are a specific case of these propagating waves), which exist below the linear instability threshold; the standing and slow solitons are always unstable while fast solitons are stable [1, 2]. Depending on initial perturbations, unstable solitons either grow in an explosive manner, which means layer rupture in a finite time, or falls apart into stable solitons. Scenarios of two-soliton collisions were also studied; collision of a pair of relatively slow counterpropagating solitons leads to formation of singularity ("explosion"), while collisions of copropagating solitons are always elastic.

The results are derived within the long-wave approximation as the linear stability analysis for the flat-interface state [3] reveals the instabilities of thin layers to be long wavelength.

The work has been financially supported by the Russian Science Foundation (grant No. 14-21-00090).

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Self-Stirring of a Two-Liquid System with Vapour Generation on the Liquid-Liquid Interface

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For a well-stirred multiphase fluid systems the mean interface area per unit volume *or* “specific interface area”, $(\delta S/\delta V)$, is an important characteristic of the state. It becomes even more significant for the systems where this interface is active chemically or in some other way. The systems of immiscible liquids experiencing interfacial boiling are an example of the systems where parameter $(\delta S/\delta V)$ becomes especially important (e.g., see [1, 2]). The problem of calculation of $(\delta S/\delta V)$ cannot be addressed rigourously and any direct numerical simulation, being extremely challenging and CPU-time consuming, will provide results pertaining to a quite specific system set-ups. Some generale assessments on $(\delta S/\delta V)$ can be highly beneficial. We perform these assessments for the process of direct contact boiling in a system of two immiscible liquids.

At the direct contact interface, a vapour layer grows and produces bubbles which breakaway of the interface and rise. The presence of vapour bubbles change the fluid buoyancy and perform a “stirring” of the system. This stirring enforces increase of the contact area S, while surface tension and gravitational segregation of two liquids counteract the increase of the contact area. Assuming for the flow near the contact interface statistical properties known for turbulent boundary layers (validity of this assumption can be supported by a subtle analysis of the system), one can establish relation between the characteristic macroscopic current velocity and the fluxes of heat and kinetic current energy to the interface. Assuming the processes in the system to be statistically stationary, one can establish conditions for the kinetic energy balance and (separately) the heat balance. These conditions provide transcendent equations for $(\delta S/\delta V)$ with various macroscopic quantities (average system overheat, heat influx per the unit volume of the system, etc.) in the role of control parameters.

The work has been financially supported by the Russian Science Foundation (grant No. 14-21-00090).

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Modeling of the Two-Layer Fluid Flows with Evaporation at Interface on the Basis of the Exact Solutions

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The exact solution of the convection equations is constructed analytically to describe the joint flows of an evaporating viscous heat-conducting liquid and gas-vapor mixture in the horizontal channel. The governing equations in gas-vapor phase and the interface conditions include additionally terms responsible for the effects of thermodiffusion and diffusive heat conductivity. The constructed solution has a group nature and describes the different classes of the fluid flows. Influence of the physical effects on the properties of the exact solution and, consequently, on the characteristics of the two-layer flows are investigated analytically. Classification of the possible flow types is carried out with respect to types of the boundary conditions for the vapor concentration function on the upper solid wall of the channel. Variety of the flow types is also explained taking into account the Soret and Dufour effects in the upper layer of the liquid-gas system. Experimental and analytical results are compared; qualitative and even quantitative agreement between results is demonstrated (see [1 , 2]).

Stability of the two-layer flows of the liquid and gas-vapor phase is investigated for equal and different values of the longitudinal temperature gradients on the channel walls. The exact solution describes three classes of flows: pure thermocapillary, mixed and Poiseuille flows according to a dominant force. In the case of equal thermal loads on the solid boundaries the perturbations of the basic flow can lead to formation of the vortex (fig.1a) and thermocapillary structures (fig.1b). The method developed for investigation of stability of the flows with evaporation in the case of different thermal loads is presented. Influence of the intensity of the thermal load, gas flow rate and initial disturbances on the type of arising instability is studied. The small values of these quantities guarantee stability of basic flows. The results of numerical investigations of the evolution of perturbations show the existence of different types of instability.

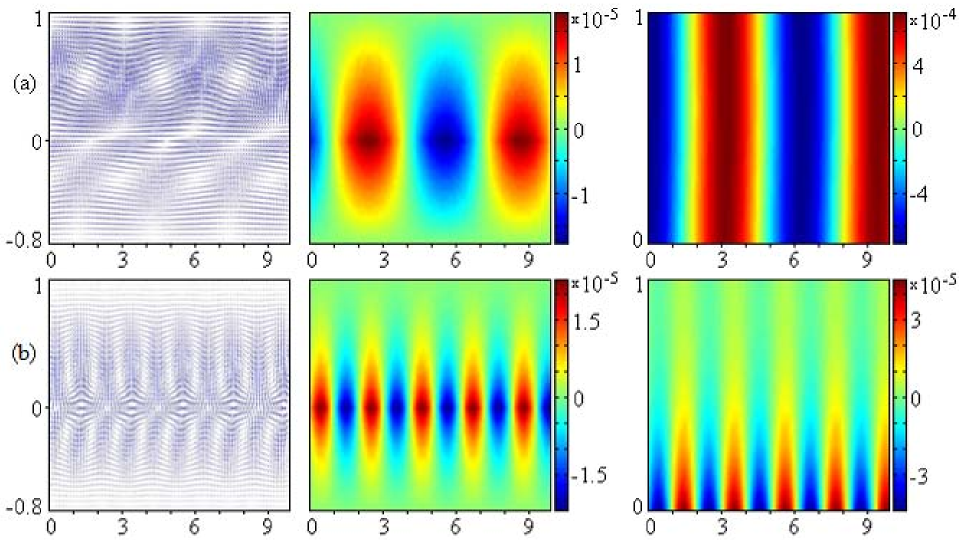

FIG. 1. Example of types of disturbances of velocity, temperature and concentration (HFE 7100 – nitrogen): a) large-scale vortex structures, thermal spots and concentration rolls; b) thermocapillary structures, thermal and concentration spots.

Acknowledgments. The research has been supported by the Russian Foundation for Basic Research (14-08-00163).

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Stochastic spatially correlated noise effects on the stability of thin films

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The thermal fluctuations effects on the instability of the free surface of a flat liquid metallic film upon a solid substrate are considered within the long wave approximation. Unlike the case of polymeric films, we find that this stochastic noise, while remaining white in time, must be colored in space at least in some regimes. The noise term has a nonzero correlation length, ℓ_c, which combined with the size of the system, leads to a dimensionless parameter β that accounts for the relative importance of the spatial correlation ($\beta \sim \ell_c^{-1}$). The linear stability analysis (LSA) of the film shows that the wavelength of the peak of the spectrum is larger than that corresponding to the deterministic case when ℓ_c is larger than a critical value that depends on the system size while, for all ℓ_c's, the peak approaches the deterministic one for larger times (Fig. 1). The numerical simulations of the complete non-linear problem are in good agreement with the LSA power spectra for early times at different values of β. For late times, the stochastic LSA predicts well the position of the dominant wavelength, showing that nonlinear interactions do not modify substantially the trends of the early linear stages.

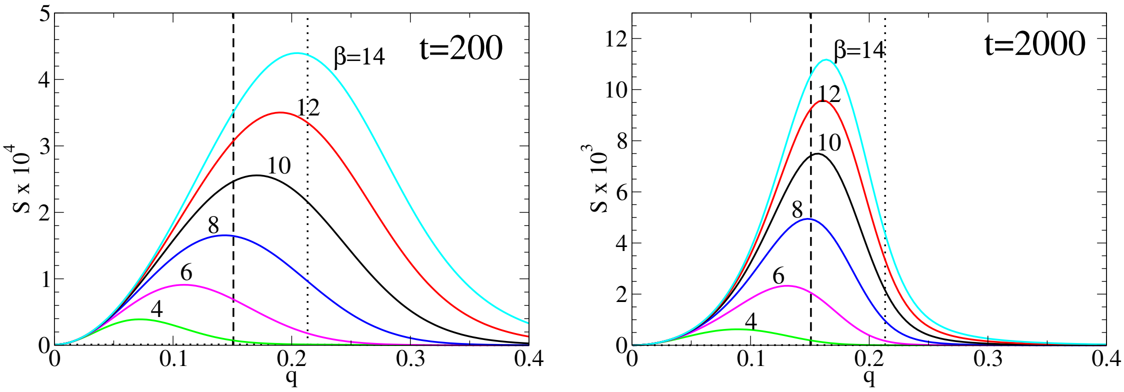

FIG. 1: Power spectrum for $\sigma = 5\times10^{-5}$ as a function of the dimensionless wavenumber, q, for different times and values of β as given by the LSA. The vertical dashed and dotted lines correspond to the wavenumbers of maximum growth rate, q_m, and marginal stability, q_c, respectively, of the deterministic case. For $\beta \lesssim 9$, q_m is approached from the left as time increases, and viceversa. Time is measured in units of $3\mu h_0/\gamma$, and $\sigma = k_B T/(\gamma h_0^2)$ estimates the relative importance of the stochastic term with respect to the deterministic part, where T is the temperature, γ is the surface tension, μ is the viscosity, k_B is the Boltzman constant, and h_0 is the thickness of the film.

We compared LSA predictions with the experimental data from the instability of laser-melted copper nanometric films on a silicon oxide substrate. As a result, we found that the early stages of the experiment evolved with an almost white noise in space, while a strong spatial correlation appeared in the spectra for later times. Thus, correlated noise seems to be an important factor in the central regions of the laser spot, i.e. those with larger liquid lifetimes. Taken together, our results provide a clear indication that the stochastic differential framework for metallic thin-film phenomena at the nanometric scale requires the inclusion of thermal noise with extended spatial correlations [1].

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Dynamics of water condensation over arrays of hydrophilic patches, and in the presence of humidity sinks

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We report experiments [1] of Breath Figures [2] on two different surfaces under different conditions. The first one consists in two salty drops on an ITO coated glass. Salty water acts as a humidity sink [3]. In our experiment, we observe the interaction between the regions created by both drops, where condensation is inhibited. Their simple presence will modify the law of growing of condensed water droplets $\langle r\rangle \sim t^{\beta}$. The region of condensation is divided and put as function of the perimeters of the two salty drops to understand the diffusion of water vapor on the surrounding atmosphere. 2) The second one is a 2-d array of lecithin patches on a modified glass surface. Here, there is not a relevant humidity sink. However, the lecithin patches are highly hydrophilic while the remaining surface is hydrophobic. This, together with the geometry of the array produces a very different Breath Figure pattern without the existence of inhibited condensation regions-

In all the cases, to produce the heterogeneous condensation on the substrate, we direct filtered air with saturated water vapor at room temperature towards a chamber where the substrate is cooled by a Peltier cell.

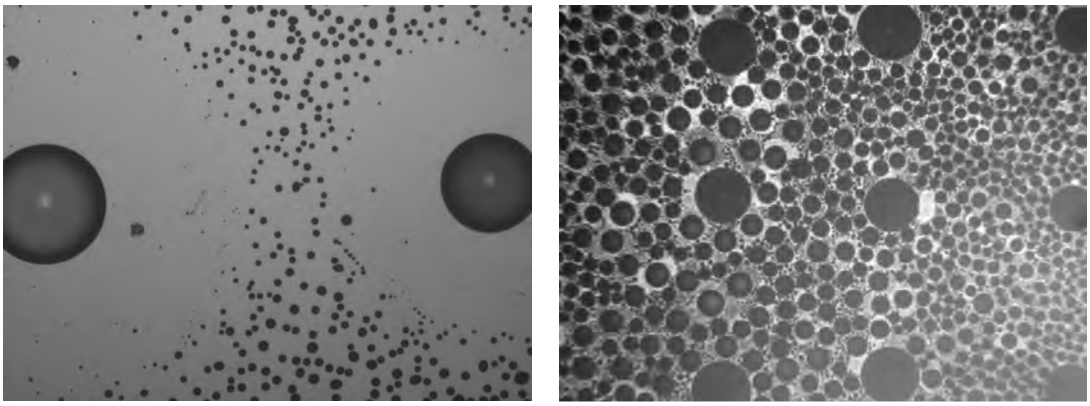

FIG. 1: Breath figures. Left: in the presence of two salty drops, without much coalescence; Right: in the presence of an array of lecithin patches, where coalescence has taken place and more than one generation of droplets can be seen.

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Numerical simulation of an evaporating thin film of polar liquid in presence of a surfactant

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I. INTRODUCTION

Experimental studies[1,2] shown that a droplet of polydimethylsiloxane (polar polymer liquid) forms a bilayer dynamic system when spreading on a smooth silicon substrate. There are two parts in this system, a "thin" film of the order of 10 Å, and "thick" molecular layer with a thickness of about 100 Å. The first part features a precursor of the spreading droplets, and its thickness doesn't change in time, while thickness of the second part eventually tends to precursor thickness.

In a theoretical paper[3], it was found that complexive nature of intermolecular interaction shall be taken into account to describe the spreading of thin layers of polar liquid. Theoretical and experimental studies on the evaporation of thin water films are presented in papers[4,5].

This paper is dedicated to investigation of a thin layer of the polar liquid (water) put on a solid substrate and having a free deformable gas-liquid interface, in presence of a soluble surfactant.

II. INVESTIGATION

Considering that the surface tension is a linear function of the surface concentration of the surfactant, authors numerically studied the thin film of polar liquid using a long-wave approximation of Navier-Stokes equations. At various values of dimensionless parameter of evaporation Ω and Marangoni number Ma_c presenting the effect of surface concentration of surfactant, authors received various film profiles and examined stability of the system.

The stability of the system is investigated considering the base state as frozen in time, when the value of the layer thickness and volume concentration have constant values. Perturbation are assumed in the "normal" form $\exp(\lambda t+ikx)$, where λ is a decrement of disturbances and describes the behavior of the perturbations with time, k is the wave number along the x axis. Solving the system of equations with respect to λ gives two independent modes, presenting effects of the surface concentration and evaporation on the film, correspondingly.

III. RESULTS

It was found that a surface structure of the film in the presence of the surfactant is quite different from the case without the surfactant. Clean film withoud surfactant saves its shape, "thick" part of the film keeps its thickness, volume of the film decreases by moving of the front between "thick" and "thin" parts and decreasing of "thick" part's area. But if the one puts some surfactant on gas-liquid interface, the situation dramatically changes: entire surface of the "thick" part becomes unstable and cavitates. The film in cavities grows thinner until the "thin" film thickness will be reached, and the entire surface assumes a peaked shape. Then every peak reduces, and the entire film has one thickness. This difference between behavior of polar liquid film with or without surfactant could be used as an indicator of contaminants for various technological applications.

The stability of the system has been investigated as well. It was found that Marangoni effect born by surfactant decreases stability of the system, that is, after reaching some critical value Ma_c^{crit}, the perturbation grows independetly of the wave number. Evaporation has inverse effect and increases stability of the system, so that the faster the evaporation is, the more stable the system.

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1D periodic microstructure Prepared by Co-assembly of Binary Colloidal Particles

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Assembling micro/nanoscopic particles into one dimensional (1D) structures has been extensively studied, among which assembly by binary colloidal particles has great potential for fabricating complex architectures and devices[1]. However，it is still a challenge to implement well control of diverse 1D periodic structures by co-assembly of binary colloidal particles.

Here we demonstrate an effective method to precisely assemble binary colloidal particles into different 1D periodic structures. In our system, binary collidal suspensions are sandwiched between a specific flat substrate and a pillar-structured silicon template. With evaporation of solvent, arrays of liquid bridge are formed between two adjacent pillars[2]. After the liquid bridge is dried, a variety of 1D ordered microstructures are formed, such as small particles situating at periphery of adjoining larger ones or cluster of close-packed small particles and a larger one alternately arranging. These distinctive structures can be well controlled by regulating interaction between particles and interface through controlling temperature and width of the liquid bridge, as well as particle-particle interaction by adjusting size ratios and quantity of particles. The results can be ascribed to particle dynamics in capillary flow[3] and Marangoni effect[4] and thermodynamics in the interfacial confinement. This work extends methods for preparing 1D ordered structures by binary colloidal particles co-assembly, and inspires research into seperation of colloidal particles, which will open new opportunity in fabricating intergrated functional devices.

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Thermocapillary flow instabilities in pools of medium Pr fluids
-- effect of curvature on the critical condition--

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Hydrothermal wave instabilities in liquid layers of finite extent have been studied[1,2,3]. However still there remain some unknowns, i.e., hydrothermal waves in deep pools under μG, difference and similarity between the instabilities in annular pool and rectangular pools, etc. In this work, a series of linear stability analysis of buoyant-thermocapillary flows in annular cavities is conducted over a wide range of aspect ratio for medium Pr fluids ($Pr=\nu/\alpha$=6.7 and 10) under 0G and 1G conditions. The cavity is composed of a heated outer wall (radius: *Ro*), a cooled inner wall (*Ri*), an adiabatic bottom and liquid layer. The aspect ratio of the pool $\Gamma=(Ro-Ri)/d$ ranges from 1 to 50. To see the effect of the curvature of pool, $\Gamma_R=Ro/Ri$ is varied from 1.01 to 21 while $\Delta R=Ro-Ri$ is kept at a constant value. We use following non-dimensional parameters; $Re=\gamma_T\Delta Td^2/\mu\nu\Delta R$, $Gr=g\rho_T\Delta Td^4/\nu^2\Delta R$, $Bo_d= g\rho_T d^2/\gamma_T$.

Present LSA results with energy budget analysis clarify the feature of the hydrothermal waves in deep annular pools under μG. Present results with various *Ri* values elucidate that the critical Reynolds number (Re_c) in deep annular pools show significant *Ri* dependence (see Fig. 1) but Re_c values for large *Ri* (small curvature) asymptotically approach to the results for rectangular pools[3] (solid lines in Fig. 2). This indicates that the annular pool with small curvature is equivalent to the rectangular pool. However, the present result with Ri=1000mm shows one more stability curve in small *d* region (black dotted line in Fig. 2). Surface temperature patterns in Fig. 3 indicate that this new curve correspond to the HTW1 (d≤0.9mm) and HTW2 (d>1mm) type oscillatory flows.

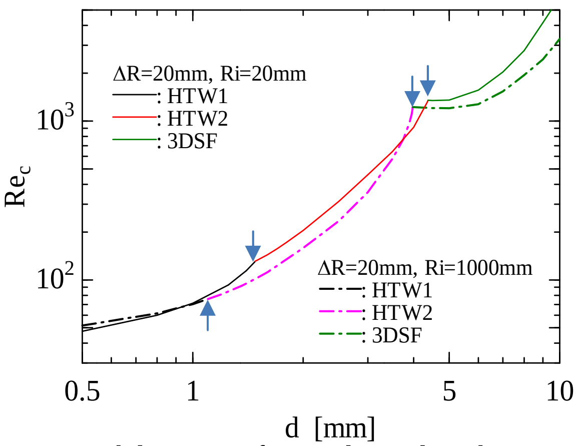

FIG. 1. Stability curves for annular pools with *Ri*=20mm and 1000mm (Pr=6.7, 1G)

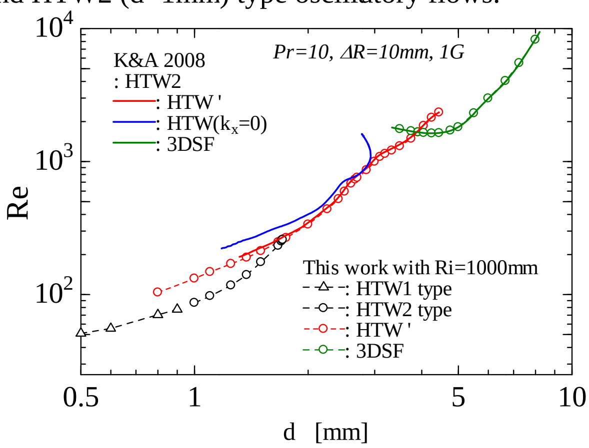

FIG. 2. Stability curve for the onset of perturbation Pr=10, ΔR=10mm, Ri=1000mm, 1G.

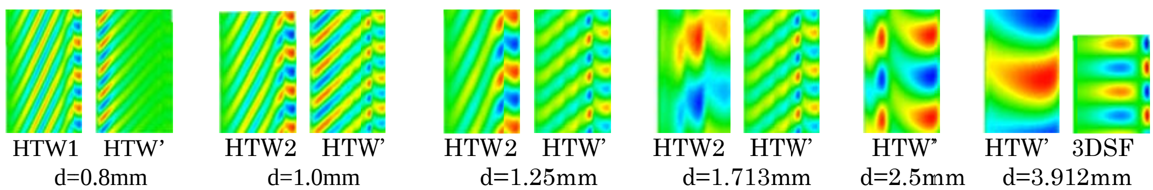

Fig. 3 Surface temperature patterns at 6 critical and neutral states on the stability curves in Fig. 2.

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Formation of interfacial patterns due to micro-particles presence

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Since the work of Saffman-Taylor [1] on the instability of an interface between two immiscible fluids, there has been an unprecedented growth of literature in this field. Developing viscous fingering as an instability occurs whenever a low viscosity fluid displaces a high viscosity fluid. Beside the beauty of the structures and the experiments, this great deal of attention is explained by the daily life applications, such as, flow in porous media[2], the flame propagation[3], and growth of bacterial colonies[4].

On the other hand, no instability occurs when we inject a highly viscous fluid in a low viscous one. We experimentally study this case in presence of micro-particles. A radial Hele Shaw cell is used for this investigation. This cell is made of two circular glass plates placed on top of each other, separated by a narrow gap, typically between 0.1 and 1mm. We lye a bed of roughly shaped Rilsan (Polyamide 11) particles of 15m radius, on the surfaces. DI Water is injected to the cell by a syringe pump at constant flow rate, through a hole drilled in the center of the top plate.

This study examines the influence of the micro-particles on the stability of the water-air interface. We show that the particles clings to the liquid interface, leading to a non-linear interfacial pattern formation. We focus on two aspects of the instability. (i) The critical radius where the instability appears. (ii) The characteristic lengths obtained from these patterns. These two aspects depends to a large extent on the concentration of the particles and the distance between the plates. It was found that the emerging patterns develop fingers and labyrinths. Therefore we can predict the conditions of the stability of the interface.

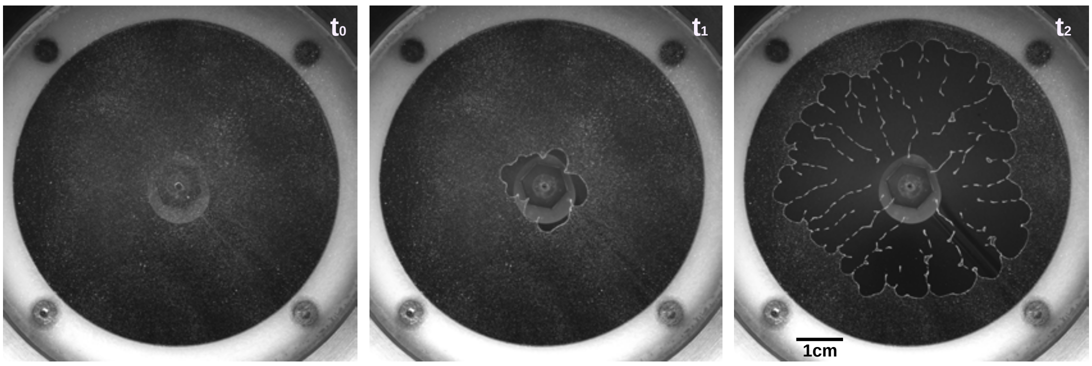

FIG. 1: Images showing a time sequence of the interfacial instability in a radial Hele-Shaw cell with a plate spacing of 150 μm, $C = 0.45$, flow rate $Q = 2000\ ml/h$ and $[t_0, t_1, t_2 = 0, 5, 31s]$.

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Direct numerical simulation of dynamic behavior of liquid-gas interface after interaction with particle.

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Impact of a solid matter on a liquid is a common phenomenon widely seen in industrial processes as well as nature. This phenomena seems quite simple, but involves complex combinations of physical mechanism such as deformation of the free surface, accompanying flow around the solid matter, effect of the boundaries in the system and wetting around the solid matter. We pay our special attention to the effect of the wettability of the solid matter on the phenomenon. It is of great importance to comprehend the behavior of the macroscopic contact line, that is, the boundary line among the solid-liquid-gas phases, in the wetting processes in multiphase flow. We conduct a series of three-dimensional direct numerical simulation (DNS) to elucidate this phenomenon by considering the contact angle of the liquid on the impacting solid matter.

The target system is a falling spherical solid particle onto a pool of a liquid settled in a rectangle reservoir[1]. Consideration for particle-liquid interaction only enables us to simplify this analysis. We employed volume of fluid (VOF), the continuum surface force (CSF) and immersed boundary (IB) to analyze this model with accuracy. VOF is the part of reconstructing interface, we can take into account wettability by CSF. We can solve the flow field associated with the motion of the immersed body which can be flexible or rigid nature in IB.

From the results of extracting the pressure around the particle, we found that when the "pocket" is formed, the pressure on top of the particle increased (Fig. 1). It is caused by the curvature of the pocket. Additionally, as the contact angle changed, the pressure distribution around the particle and the maximum value of the pressure on the particle summit changed. Furthermore, when the pocket is formed, the liquid velocity behind the particle increased (Fig. 2). The pressure difference in the liquid leads the fluid to re-cover the particle. This force drove the liquid and caused the acceleration of the liquid. We will discuss the correlation between the behaviors of the particle and the liquid as a function of the wettability.

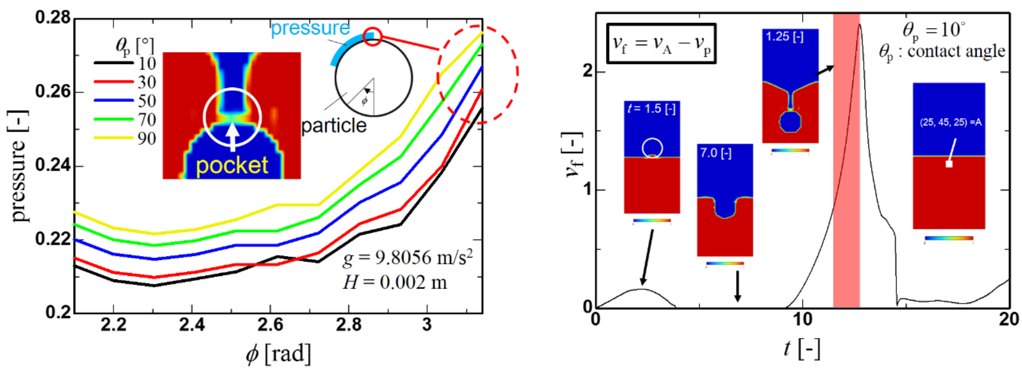

FIG. 1. Left: Pressure around the particle at each contact angle when pocket is made. Right: Acceleration of the relative velocity between the particle and the liquid behind the particle. Red region indicates the increasing point of the pressure.

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Experimental study on the finite-size particle behavior in a steady flow in a thermocapillary liquid bridge

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It is known that the particle accumulation structure (PAS)[1] emerges in a certain condition in a half-zone liquid bridge with thermocapillary-driven convection. It is not easy to comprehend mechanism of its occurrence with a numerical simulation or theoretical models, because we cannot avoid interactions between fluids and particles or particles and particles. Romanò and Kuhlmann[2] indicated that the Maxey-Riley equation alone cannot describe the particle motion as a real phenomenon in systems with boundaries and we must consider the interaction between the free surface of the liquid bridge and the particle. We focus on a single particle behavior in steady flow and investigate the correlation between the particle behavior and its size.

In our experiment, a liquid bridge is formed between two coaxial cylindrical rods. The radius (R) and height (H) of the liquid bridge are 2.5 mm and 1.65 mm, respectively. And the aspect ratio ($\Gamma = H/R$) of the liquid bridge is fixed 0.66. The top rod is heated by an electric heater and the bottom rod is cooled by a coolant through a cooling channel. The temperature difference between both rods is kept at $\Delta T = 10$ K. We employ 2-cSt silicone oil as a test fluid. We check the liquid volume every 5 minutes and inject or remove silicone oil to keep the volume ratio, at $V/V_0 = 1.00\pm0.02$ for 60 minutes or more ($V_0 = \pi R^2 H$). Gold-coated acrylic particles are used in the experiments. The radius of particles can range from 7.5 to 25 μm. Accurate measurement of the particle size is important to confirm the correlation between the particle behaviors and its size, so we measure the radius of each particle which is used in the experiment. We use a microscope and can get an image with resolution of 1/6.28 μm/pixel. We pick up the measured particle with a needle and put it in the liquid bridge. We record the particle's behavior with two high-speed cameras from the top and the side. We can track the particle trajectories from the top view images. Figures 1(a) and (b) are typical top views of steady flow at Ma = 9.3×10^3 in the cases of putting (a) many particles and (b) single particle. Figures 1(a) and (b) are obtained by averaging 600 and 320 image frames, respectively. There are many kind of length of trajectories which particles passed through shown in Figure 1(a). These difference might be caused by the interaction between particles, or an inaccurate particle size. Figure 1(b) is the enlarged top view with a single particle. We trace its motion and investigate the difference between particle sizes. We found the smaller particle to move into the liquid bridge deeply.

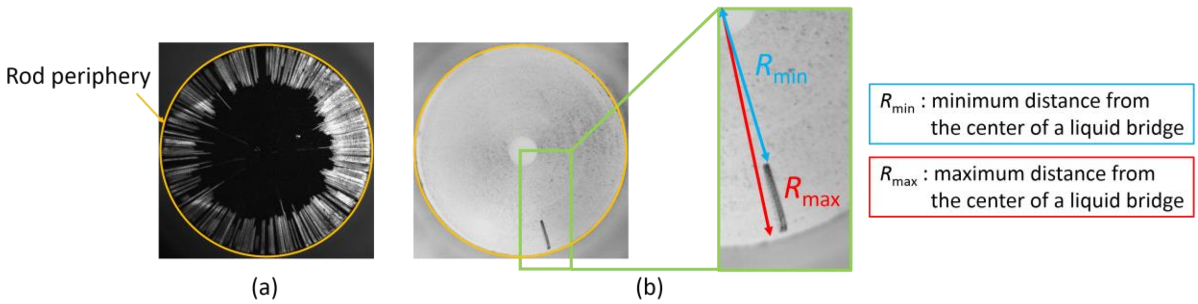

FIG. 1 Experimental region. (a) The top view of the liquid bridge with a steady flow with many particles. (b) The partial enlarged view of top view with a single particle. These images are reversed black and white.

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Droplet growth caused by laser-induced solutocapillary flows in films of binary liquid mixtures

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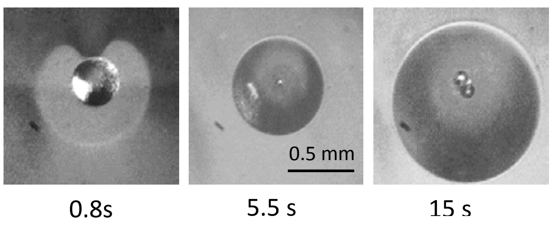
Droplet microfluidics technology isof great importance in biological and chemical micro-analytical systems, lab on chips and optofluidics systems [1, 2].This technology enables on-demand generation and manipulation of small volumes of liquid samples with a precise control over the experimental parameters. In this work, the process of droplet formation in thin layers of mixtures of positive tensioactive substances (water and ethylene glycol) and isopropyl alcohol under the heating by the laser beam was studied (fig.1: left). The droplet growth is controlled by solutocapillary flows directed from the periphery to the center of heated area [3, 4]. Theseflows arise due to a decrease of concentration of volatile alcohol in the heated zone, which has the lower surface tension than positive tensioactive substances. Experimental results have shown that the increase in initial concentration of water and ethylene glycol in mixtures gives rise to the increase of the droplet growth rate. The higher surface tension of positive tensioactive component in comparison with volatile alcohol, the faster droplet growth rate(fig. 1: right). A one-dimensional model of the droplet growth was proposed. The model involves a dependency of surface tension on both temperature and concentration of components in liquid mixture as well as evaporation of volatile component. The experimental results were compared with those obtained using numerical simulations. A reasonable agreement between experimental and numerical results was found.



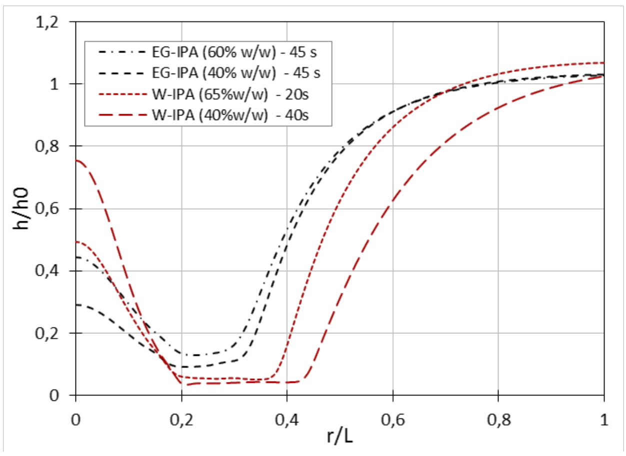


FIG. 1. Left: Time sequence of images of the droplet growing in EG-IPA mixture (50%w/w/) under the laser beam heating (15 mW). Right: Numerical profiles of the droplet shapes in the irradiated area for both EG-IPA and water-IPA mixtures. The initial depth of the mixture layer - h_0 =100 microns, the radius of the layer 20 mm.

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Festoon instabilities of volatile liquids during spreading on another liquid under evaporation cooling conditions

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We have investigated a festoon instability for a volatile insoluble liquiddrop placing on the surface of another liquid [1](fig. 1: left). Isooctane, o-xylene and n-heptane were usedas volatile liquids, andthick (4 cm) layer of hot distilled waterwas as a liquid substrate.The experimentswere fulfilled in a ceramicbowl with a flat bottom. A 50μlsingledrop was placed on the surface of hot water using the micropipette.The drop shadow projectedonto the bowel bottom was recorded by a video camera.The water was kept at a constant temperature during the experiment.

After the deposition of the drop of the volatile liquid on the water surface, the festoon structures in the form of hillocks appear at the drop periphery and growth until a critical diameter (~ 1mm)is reached. Then, the festoons started to travel toward the centerof drop with the constant velocity depending on the temperature of the water substrate, (fig. 1: right). The higher temperature of water the higher the velocity of festoons.It was also observed that the festoon diameter increases linearly with time in the course of the centripetal motion and, finally the festoon disappears near the center of drop. Moreover, an increase of viscosity of the volatile liquid reduces the velocity of festoons as a power law.

The growth of festoons is caused by thermocapillary flows, while their ejection is related to the capillary forces, which tend to decrease the free surface. This kind of instability substantially differs from the other known thermocapillary instabilities, since the ejection of festoons prevents the drop from spreading and thus increases its lifetime.

Moreover, we found that during the lifetime of drops, its volume would have time to mix by festoons several times, which can be useful for micromixing[2].

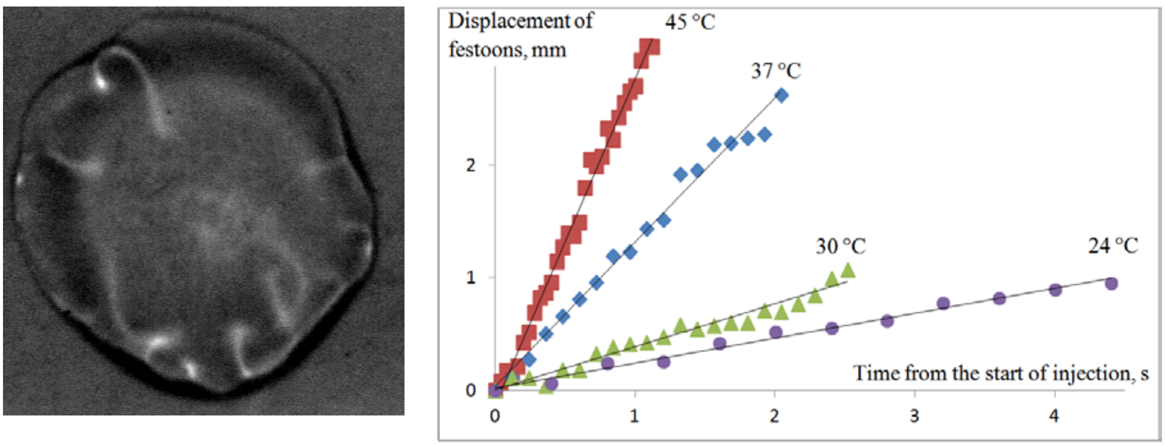

FIG. 1. Left: Festoon instability of isooctane drop on water at its temperature 45 °C; Right: Displacement of festoons in isooctane drop from the moment of start injection till the moment of festoon disappearance at water temperature in the range from 24 to 45 °C.

Acknowledgements: Authors are grateful to the Royal Society, UK and RFBR, Russia(Grant no. 14-01-92602 KO_a); European Space Agency; The Ministry of Education and Science of the Russian Federation, grant no. 1019.

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Removal of micrometer particles from solid surfaces using the laser-induced thermocapillary effect

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Removal of particle contaminations from solid and delicate surfaces is of great importance in many industries dealing with critical surfaces [1]. A new non-destructive method based on the laser-induced thermocapillary effect [2] for the removal of micron size particles from surfaces is proposed. The cleaning mechanism is related to the surface-tension-driven flows [2] produced by the laser heating in thin layer of a cleaning liquid deposited onto a surface contaminated with particles and the capillary forces arising at the moving three-phase contact line [3]. Focusing the laser irradiation into the line laser beam allowed for a large-scale cleaning of surfaces, fig.1(a). Hexadecane was used as a cleaning liquid to remove the micron-sized polyethylene (PE), PTFE, talc and Al_2O_3 particles from surfaces of welding glass, carbolite and soft magnetic disc using the line beam of the IR laser. A high cleaning efficiency was achieved for olephobic PE and PTFE particles on all substrates used, fig. 1(b). In this case, both the thermocapillary flows and the capillary force at the contact line acting on particles are responsible for the cleaning. For the oleophilic talc and Al_2O_3 particles, the effectiveness of the method depends on the intensity of thermocapillary flow of the cleaning liquid that in its turn determined by thermal properties of surfaces. The thermal influence of the laser irradiation on substrates during the long-time heating increases insignificantly and cannot cause any damage of the substrate.

The thermocapillary flow induced by the line laser beam is very promising tool for large-scale cleaning of solid substrates at low cleaning temperatures. The proper combination of such parameters as wetting properties of particles and/or substrates and the surface tension gradients induced by the laser heating enables to improve the cleaning effectivness of the laser-induced thermocapillary method.

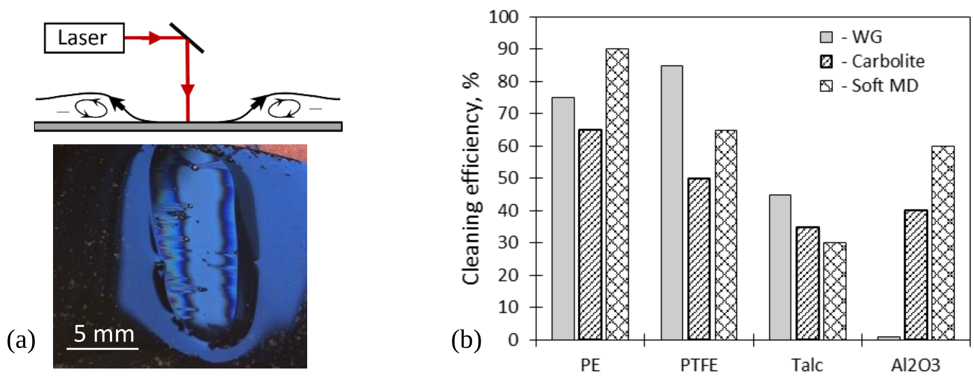

FIG. 1. (a) Schematic diagram of the laser-induced thermocapillary displacement of liquid and an image of the thermocapillary rupture of hexadecane layer on a magnetic disc under the irradiation by laser beam. (b) The cleaning efficiency of the laser induced thermocapillary method for all combinations of particles and solid surfaces.

Acknowledgements: Authors are grateful to the Royal Society, UK and RFBR, Russia (Grant no. 14-01-92602 KO_a); European Space Agency; The Ministry of Education and Science of the Russian Federation.

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Forced sliding of volatile drops: formation of a microrivulet

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The motion of droplets on solid surfaces is fundamental to many technological processes and applications, such as painting, coating, cleaning, printing and others. The previous studies focused mostly on sliding nonvolatile viscous droplets. In this research, we investigate the various flow regimes and deposition patterns observed in volatile droplets moving over inclined solid substrates. Two types of volatile droplets are investigated: pure component droplets and binary solution droplets. Binary solution droplets are characterized either by inward or outward solute-capillary Marangoni flow, with particular attention to binary solution droplets characterized by solute-capillary Marangoni flow, which are relevant for a new printing method via deposition of a micro-rivulet (μ-R) pattern [1].

Single component droplets exhibit a spreading regime only at any Capillary number (Ca). When a component with *lower* surface tension evaporates faster, *outward* Marangoni flow leads, at low Ca to spreading regime and at sufficiently high Ca, to a long rivulet. When a rapidly evaporating component has a *higher* surface tension, which causes *inward* Marangoni flow leading to the μ-R formation at the receding end (see Fig.1). Further increase of Ca leads to the formation of a wider rivulet similar to cusps observed in nonvolatile droplets [2].

We carried out a detailed experimental study of the μ-R formation in different binary solutions. The directionality and intensity of the Marangoni flow was controlled by vapor composition in a sealed chamber enclosing the sliding binary droplets. We show that the μ-R formation in a certain range of Ca is a universal phenomenon subject to the occurrence of inward Marangoni flow. We propose a simplified mathematical model for the shape of μ-R based on the lubrication approximation. The resulting μ-R profile shows a good agreement with the experimental results.

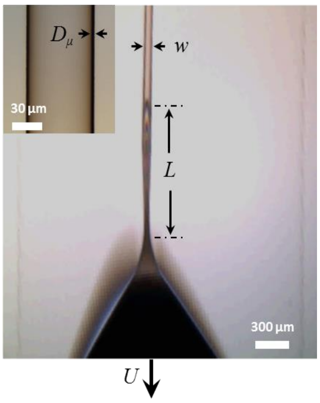

FIG 1 A drop of 80/20 volume fraction of Toluene/ Nonane sliding on a silicon oxide substrate at 25° inclination angle. A μ-R of length L emerges from the cornered droplet leaving a strip of deposited nanoparticles of width *w* behind it.

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DNS study of a small droplet driven by the thermal Marangoni effect

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Non-contact manipulation of micro droplets in liquid has received a lot of attention in the fields of medical and biological engineering. The photothermal manipulation is known as a microfluidics technology of using the temperature dependence of surface tension, so-called the Marangoni effect. Since the effect of interfacial phenomena become dominant with decrease of the length scale in microfluidics, the local control of surface tension can be effective for the droplet manipulation. Muto & Motosuke [1] experimentally demonstrated the phenomenon of a droplet driven by temperature difference and measured the driving velocity and acting force. In this study, we carried out the numerical analysis by means of DNS (direct numerical simulation) to investigate quantitatively the photothermal droplet manipulation. In our simulation, the liquid-liquid interface is captured by the VOF (Volume of Fluid) method, and the surface tension and Marangoni effect are treated by the CSF (Continuous Surface Force) model [2] with considering temperature dependence. We have validated the present code by simulation of a square drop.

Figure 1 shows the analysis object, which is an oil droplet in water pool. We set a spherical droplet with a diameter D in a rectangle reservoir of water without touching the wall. A linear temperature distribution in the x-direction was given as an initial field. The momentum and heat transports were calculated by Navier-Stokes and energy equations, respectively, assuming the constant properties. The heat conduction is actually dominant in the present configuration, although the convective transport was considered in our DNS. The dimensions of the computational domain are $4D \times 2.4D \times 2.4D$ with Cartesian grid of $70 \times 42 \times 42$. We tested various conditions in terms of the droplet diameter (D = 40–1000 μm) and the temperature difference between both ends of the droplet (see Fig. 1: $\Delta T = D\mathrm{d}T/\mathrm{d}x$ = 2–6°C). The physical properties including the temperature coefficient of surface tension ($\partial\sigma/\partial T > 0$) were same as those used in the previous experimental study [1].

We have successfully demonstrated the droplet moved toward the cold side, which is low surface tension side, as theoretically predicted. The dependence of the driving velocity on the droplet diameter is shown in Fig. 2. The driving velocity of the droplet manipulation is the order of millimeter per second, and agrees well with the experimental results [1]. With fixed ΔT, the driving velocity is constant independently of the droplet size, as shown in the figure. This result is consistent with YGB theoretical equation [3]. However, the driving velocity is expected to be non-constant for larger-sized droplets. Then, we are performing further DNS to examine a limitation of the scale-independency of the driving velocity.

In the full paper, we will discuss the phenomenon and the limit of the manipulation with using the Marangoni effects. Results of other cases in terms of D and ΔT will be also presented.

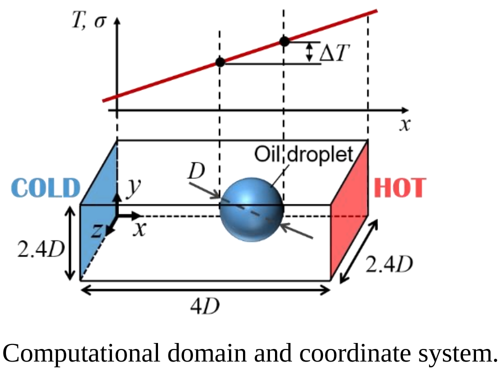

Fig. 1. Computational domain and coordinate system.

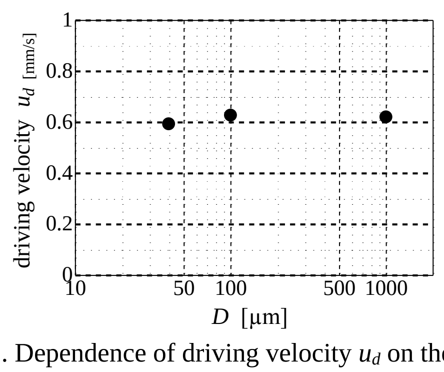

Fig. 2. Dependence of driving velocity u_d on the droplet diameter D for ΔT = 2°C.

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Laser-induced oscillatory thermocapillary convection in double-layer systems

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Thermocapillary convective instabilities in multi-layer systems have attracted great attention due to their importance in nature and industrial applications [1]. Inthepresentwork,wehavereported preliminary results of the experimental studyof the thermocapillary convection in the two-layer systems induced by local heating with the laser beam, fig. 1(a). Benzeneabsorbingthelaserirradiationand transparent silicon oil were used as the lower and top layers, respectively. Thethicknessofthe benzenelayerwasa constant (h_l =2 mm)andthe thickness of the top layer (h_t) was varied from 0.3 to 1mm. For the quantitative analysis of the thermocapillary convection, a time evaluation of a diameter of a thermocapillary response wasmeasured. The thermocapillary response is the fringe pattern formed on a screen by the laser beam reflected from the thermocapillary depression of the top layer[2],fig. 1(b).

Three modes of the thermocapillary convection depending on the thicknessratio $\varepsilon = h_t/h_l$was identified.(i) The steady state thermocapillary rupture of the top layer was observed at$\varepsilon < 0.3$. During thelaser irradiation, an increase of the diameter of thermocapillary response changes to a degeneracy of the fringe pattern, which corresponds to the reflection of the laser beam from a flat layer, fig.1(c). (ii) The steady state thermocapillary depression takes place at ε >0.35. In this case, the diameter of the response increases until reaching the constant size. (iii) Atransient mode characterized by decaying oscillations of thermocapillary response is observedatε laying in between 0.3 to 0.35,fig. 1 (c).

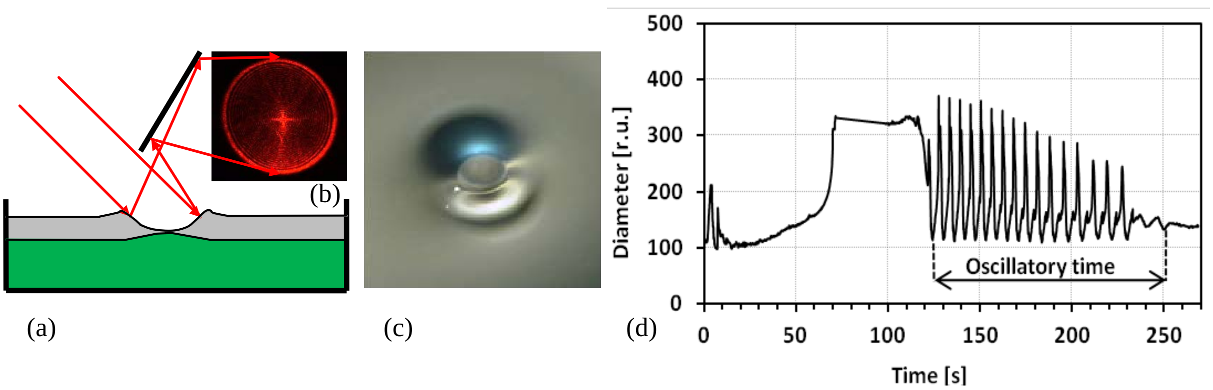

FIG. 1. (a) The thermocapillary deformation of layers. (b) The thermocapillary response. (c) An image of the rupture of the top layer. (d)Time evolution of the diameter of the thermocapillary response with the oscillations.

Theoscillatorytimeincreaseswiththeincrease of $\varepsilon$from 0.3 to 0.35 andrangingfrom 200 to400 sec. However, theperiodoftheoscillationsdecreasesfrom7 to 3 sec. Thedampingfactorwasestimatedtobe0.007.

We have surmise that the mechanism behind the oscillationsis the competition between thermocapillary and buoyancy forces, which could act in opposite directions. However, to clarify the mechanism of the oscillations more experimental and theoretical investigations to be done.

Acknowledgments: The European Space Agency Map evaporation project and the Ministry of Education and Science of the Russian Federation, no. 1019 supported the research.

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Interaction of laminar near-wake with a free surface

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I. ABSTRACT

The case of a submerged bluff-body in a free surface flow has attracted a lot of research efforts which may be categorized according to steady incident flow past a stationary or streamwise/transversely oscillating cylinder beneath a free surface ([1], [2], [3]). In the present study, Wave interactions caused by bluff-body beneath the free surface of a viscous fluid are investigated, numerically, based on a two-fluid model. Control is exerted to the fluid field by forcing the cylinder to perform rotational oscillations in the presence of an oncoming uniform flow. The method of solution is based on a finite volume discretization of the two-dimensional continuity and unsteady Navier-Stokes equations in their pressure-velocity formulation. A second-order accurate central-difference scheme is used to discretize the governing equations in space in conjunction with the first-order explicit forward Euler scheme to advance these equations in time. Well-posed boundary conditions are enforced at the inflow and outflow boundaries since they ensure correct physical development of the flow near the computational domain boundaries. The no-slip conditions are implemented on the surface of the cylinder. The free slip boundaries are assumed at the top and the bottom of the computational domain. The free surface interface is discretized with the volume-of-fluid method due to Hirt and Nichols [4]. Its advection in time is performed based on the strictly mass conserving volume-of-fluid advection method in two dimensional incompressible flows, due to Aulisa *et. al.* [5]. For the moving fluid-body interface the fractional area/volume obstacle representation method due to Hirt and Sicilian [6], and the cut cell method due to Gerrits [7] are employed.

The numerical simulations are carried out at a Reynolds number of $R = 200$ and a Froude number $Fr = 0.2$, and the cylinder submergence depth, $h = 0.75$. The flow characteristics are examined for the maximum angular cylinder displacements $15^\circ \leq \theta_m \leq 75^\circ$; and the forcing cylinder oscillation frequency-to-natural vortex shedding frequency ratio, $f/f_0 = 0.5, 1.0, 2.0, 3.0, 4.0$. The main objective of this study is to investigate the local hydrodynamics around the submerged body, especially in relation to (i) Kelvin-Helmholtz instabilities developed in the region between the free surface and the near-wake region immediately downstream of the body; (ii) the mechanism of the vorticity transfer from the free surface to the near-wake region.

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Two-layer solutal Rayleigh-Marangoni convection in the eruptive regime: a parametric study of layer heights and initial concentrations.

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Mass transfer between immiscible liquid layers potentially causes convection due to buoyancy forces (Rayleigh mechanism) and interfacial tension gradients (Marangoni mechanism). Rayleigh convection will be triggered if the potential energy is lowered, e.g. a density decreasing solute is transported against the direction of gravitational acceleration. If at the same time the solute is reducing interfacial tension and is transported out of the phase with lower diffusivity, the system is linear stable to cellular Marangoni convection but potentially produces an oscillatory flow structure, denoted as eruptions [1]. Recently, we demonstrated the mechanism underlying these patterns by three-dimensional direct numerical simulations and corresponding experiments [2]. In continuation to this work, we studied the role of layer heights and initial concentration c_0 of isopropanol on flow patterns and integral properties as the rate of mass transfer. In this talk, some of these new findings will be presented. E.g., for pure Rayleigh convection, we observed that persistent convection cells develop with a characteristic size governed by the layer height (Fig. 1 left). The additional Marangoni effect in the from of eruptions leads to a decoupling between the interfacial region and the bulk volume (Fig. 1 right). Namely, when we increased the layer height over a certain threshold, interfacial velocity and transferred solute remained relatively unaffected.

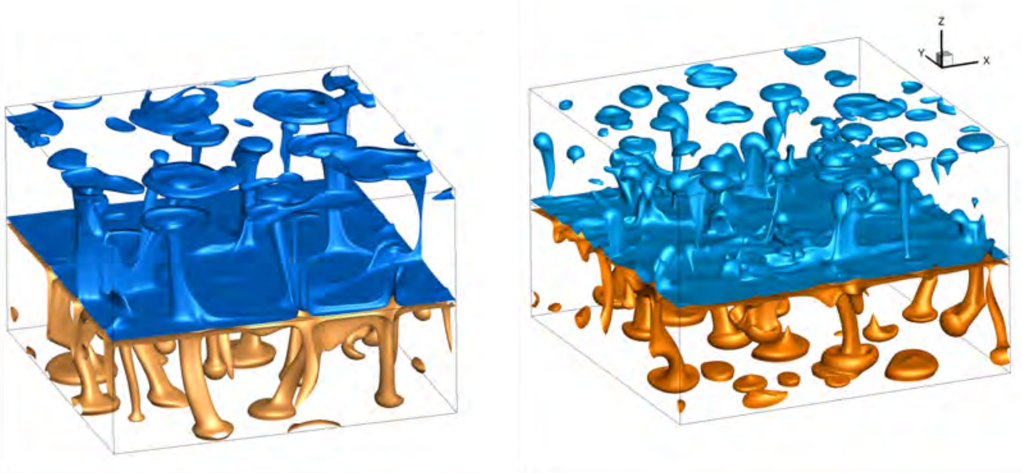

FIG. 1: Simulated isosurfaces of isopropanol concentration. Left: Simulation without the Marangoni effect, blue surface depicts $0.45c_0$ and the orange surface $0.85c_0$. Right: full simulation, blue surface depicts $0.45c_0$ and the orange surface $0.78c_0$.

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Instability of nanometric fluid films on a thermally conductive substrate

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When thin metal films are placed on substrates and exposed to laser irradiation, they melt and while in liquid state their evolution results in formation of patterns that are or relevance in many applications. In our earlier works, e.g., [1, 2], we considered evolution of these films based on the long-wave approach that ignored thermal effects. The present work focuses on the influence of Marangoni forces.

We consider thin fluid films placed on thermally conductive substrates and exposed to time-dependent spatially uniform heat source. The evolution of the films is considered within the long-wave framework in the regime such that both fluid/substrate interaction, modeled via disjoining pressure, and Marangoni forces, are relevant. The main finding, illustrated in Fig. 1, is that when self-consistent computation of the temperature field is carried out, a complex interplay of different instability mechanisms results. This includes either monotonous or oscillatory dynamics of the free surface. In particular, we find that the oscillatory behavior is absent if the film temperature is assumed to be slaved to the current value of the film thickness. The results are discussed within the context of liquid metal films, but are of relevance to dynamics of any thin film involving variable temperature of the free surface, such that the temperature and the film interface itself evolve on comparable time scales.

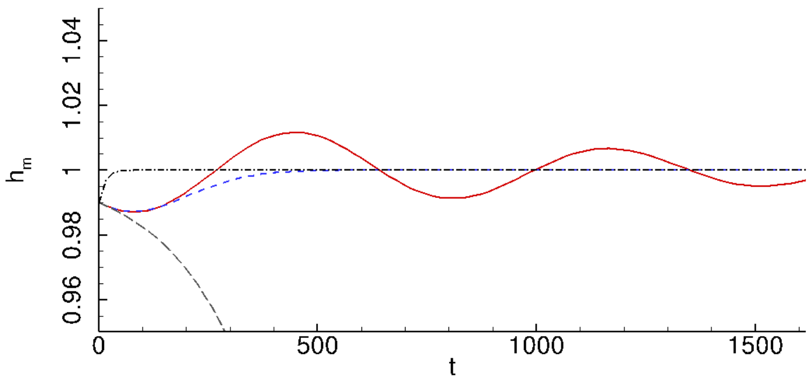

FIG. 1. The simulation consider film of uniform thickness perturbed by a perturbation of wavelength corresponding to the most unstable mode, λ_m. The computation domain size is equal to λ_m. The figure shows the film thickness, h_m, at $x_m = \lambda_m/2$ as a function of (non-dimensional) time using different approaches to compute the temperature: self consistent time-dependent temperature computation (red solid), the analytical solution assuming fixed film thickness (blue dashed), and assuming fixed value of temperature gradient (black dash dotted). The evolution computed by ignoring Marangoni effect all together is shown as well (grey long dashed).

Acknowledgements This work was partially supported by the NSF grants No. CBET-1235710 and DMS-1211713.

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Diffusion and convective instability in multicomponent gas mixtures at different pressures

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I. INTRODUCTION

Concentration gravitational convection in isothermal binary mixes is defined by the traditional mechanism of mixture displacement. Heavy gas falls, and light rises. Stabilization of convection takes place in case, when lighter mixture of gases reaches the upper position. The addition of a third component to the mixture can lead to the emergence of new effects which contradicts the traditional representations [1]. Studying the velocity of diffusive leveling of concentrations of components at different pressures in two flasks of the device connected by the vertical channel [2] the gravitational concentration convection was recorded [3].

II. EXPERIMENTS

Experiments were carried out on two flasks realizing system devices [2]. As a rule, in the upper flask was placed the binary mixture of a light and heavy component. The average on density gas was in the lower flask. Selection of concentrations of components in binary mixture in all cases achieved smaller density in the upper flask. Pressure and temperature in flasks were supported identical. The technique of carried out experiments corresponded to the traditional scheme. The composition of mixture in flasks was registered from time to time when the capillary opened. Experimental concentrations are normalized on the values, calculated at diffusion on Stephane-Maxwell's equations. Thus the received dimensionless ai parameters characterize the corresponding type of mixture displacement. Diffusion takes place, if $\alpha_i \approx 1$. Research of dependence of $\alpha_i$on pressure P showed that at a certain critical P_{cr}value the α_i parameter exceeds unit. Mechanical balance of mixture becomes unstable. There arises an abnormal concentration gravitational convection. If to investigate the convective mixture displacement at pressure considerably exceeding critical, then primary transfer of the heaviest on density component is fixed.

III. THEORY STABILITY

Emergence of convection at diffusion in mixture can be explained within the theory of stability [1]. The transition parameters defining the change of "diffusion-convection" modes are turned out from the joint solution of the equations of mechanics of the continuous medium and the equation state medium which is written down for three-component systems. Linearizing the system of equations of hydrodynamics in relation to small perturbations we will receive a uniform (homogeneous) system of the linear differential equations with independent of time coefficients, which have $exp(-i\omega t)$ solution. If among found $\omega = \omega_0 + i\omega_1$exist such for which $\omega_1 > 0$, then the state will be unstable. The borders of change of the diffusive and convective modes defined in terms of Rayleigh numbers, $R_i$shows that at some conditions the mechanical balance of mixture can be unstable, that causes convection emergence.

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Droplet Spreading and Absorption on Rough, Permeable Substrates

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Wetting of permeable substrates by liquids is an important phenomenon in many natural and industrial processes. Substrate heterogeneities may significantly alter liquid spreading and interface shapes, which in turn may alter liquid imbibition. A new lubrication-theory-based model for droplet spreading on permeable substrates that incorporates surface roughness is developed in this work [1]. The substrate is assumed to be saturated with liquid, and the contact-line region is described by including a precursor film and disjoining pressure. A novel boundary condition for liquid imbibition is applied that eliminates the need for a droplet-thickness-dependent substrate permeability that has been employed in previous models. A nonlinear evolution equation describing droplet height as a function of time and the radial coordinate is derived and then numerically solved to characterize the influence of substrate permeability and roughness on axisymmetric droplet spreading. Because it incorporates surface roughness, the new model is able to describe the contact-line pinning that has been observed in experiments but not captured by previous models.

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Dynamic Wetting Failure in Surfactant Solutions

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The influence of insoluble surfactants on dynamic wetting failure during displacement of Newtonian fluids in a rectangular channel is studied in this work [1]. A hydrodynamic model for steady Stokes flows of dilute surfactant solutions is developed and evaluated using three approaches: (i) a one-dimensional (1D) lubrication-type approach, (ii) a novel hybrid of a 1D description of the receding phase and a 2D description of the advancing phase, and (iii) an asymptotic theory of Cox [2]. Steady-state solution families in the form of macroscopic contact angles as a function of the capillary number are determined and limit points are identified. When air is the receding fluid, Marangoni stresses are found to increase the receding-phase pressure gradients near the contact line by thinning the air film without significantly changing the capillary-pressure gradients there. As a consequence, the limit points shift to lower capillary numbers and the onset of wetting failure is promoted. The model predictions are then used to interpret decades-old experimental observations concerning the influence of surfactants on air entrainment [3]. In addition to being a computationally efficient alternative for the rectangular geometries considered here, the hybrid modeling approach developed in this work could also be applied to more complicated geometries where a thin air layer is present near a contact line.

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Deformation of viscoplastic drops in non-isothermal Newtonian fluid

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The slow sedimentation of deformable viscoplastic drops with temperature-dependent yield stress in non-isothermal Newtonian fluid is simulated making use of a variation of integral equation method. The Green function for the Stokes equation is used and the non-Newtonian stress is treated as a source term. Integration over the outer unbounded domain occupied by the viscous liquid is eliminated by satisfying the boundary condition and using the integral expressions for the adjoined domains. Thus, the problem is reduced to an integral equation in a bounded domain, which is solved numerically.

The study revealed that initially spherical drop remains almost spherical, however the shape and size of unyielded zone considerably changes as the drop propagates to warmer or cooler regions. In the case of downward temperature gradient, the drop moves to the warmer regions, the yield stress decreases and the unyielded zone inside the drop shrinks. In the case of upward temperature gradient, the drop moves to the cooler regions, the yield stress increases and the unyielded zone inside the drop grows until the entire drop becomes solid and proceeds to move as a rigid body.

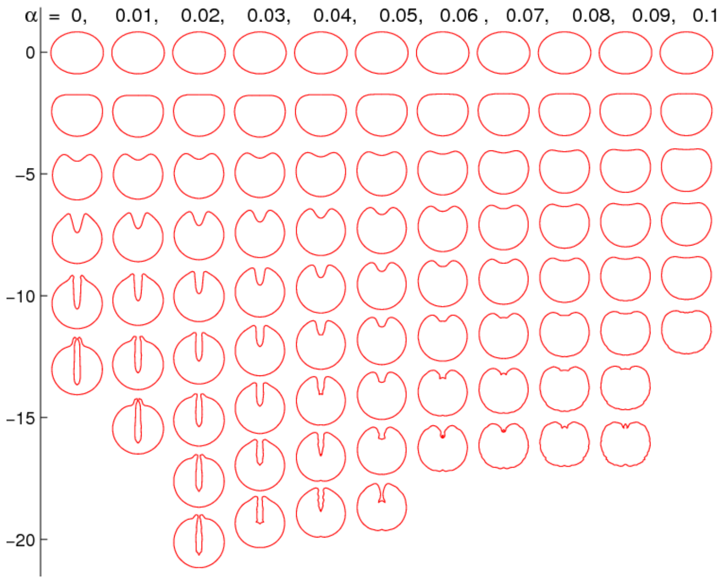

FIG. 1. Shapes of viscoplastic drop falling in an upward temperature gradient, $\tau_Y = \tau_{Y0}(1-\alpha T)$.

Initially deformed drop is known to return to spherical shape if the interfacial tension is strong enough (the capillary number, *Ca*, is small). If *Ca* exceeds some critical value (depending on initial deformation), eventually the drop breaks up. In Smagin *et al.* [1], it was demonstrated in the case of constant yield stress, the increase of the Bingham number stabilizes the drop shape. Our present computations reveal that strong enough temperature dependence of the yield stress prevents the breakup of the drop settling in an upward temperature gradient. The terminal shape of the drop in this case is non spherical. On the other hand, a downward temperature gradient can destabilize the drop in near-critical situations. Several examples of the evolution of initially oblate drop falling in an upward temperature gradient are shown in Fig. 1. Linear dependence of the yield stress on temperature is assumed, $\tau_Y = \tau_{Y0}(1-\alpha T)$. When the drop migrates to cooler regions, the yield stress increases and inhibits deformation. When the temperature dependence is weak (α is small), the drop breaks up before the unyielded zone becomes large enough. However, if α exceeds some critical value, the drop become quasi-solid before strong deformations develop and the break up does not occur.

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Influence of rotation on thermocapillary convection in a differentially heated annular two-layer system

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I. ABSTRACT

Although thermocapillary convection in bilayer system has been investigated by numerous works, the characteristics of the oscillatory thermocapillary convection are not yet understood clearly especially when the system rotation is considered. In this work, thermocapillary convection in a differentially heated annular bilayer system consisting of 5cS silicone oil and HT-70 is investigated by a series of three-dimensional numerical simulations. Both the systems with and without rotation are considered. Results show that with the growth of Taylor number, the rotation first destabilizes the basic steady axisymmetric thermocapillary flow, and then exerts a stabilizing effect on it. The wave patterns for oscillatory flow appear in the form of hydrothermal waves. Two groups of wave with opposite azimuthal travelling direction overlap their branches and resulting in the blade-like wave patterns for non-rotation case. Once system rotation is introduced, the hydrothermal waves propagating against the surface and the interface flow develop. As the rotation rate increases, the wave number increases while the oscillatory frequency decreases. Moreover, a half-period phase difference is found between surface oscillation and interface oscillation, which is attributed to the interaction of temperature perturbation with the parabola-like temperature distribution of basic-state in the upper layer.

II. TYPICAL RESULTS

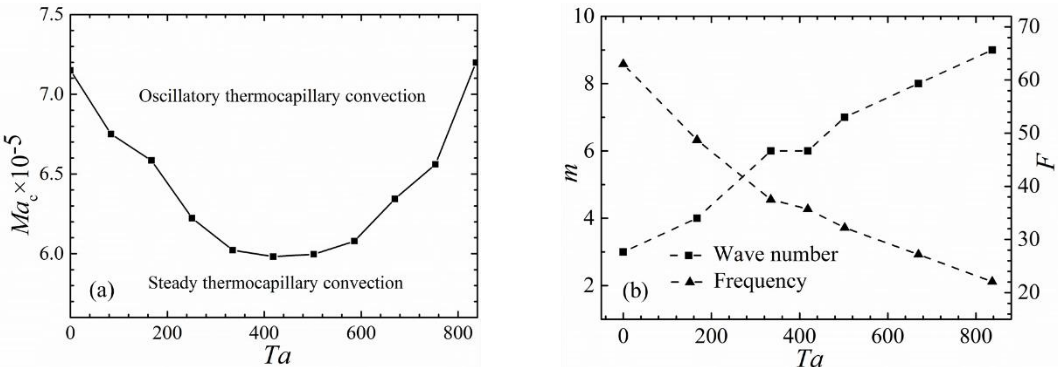

FIG. 1. Stability diagram for different values of Taylor number (a) and variation of wave number *m* (square) and oscillation frequency *F* (triangle) as a function of Taylor number when *Ma*=1.0×10^6 (b).

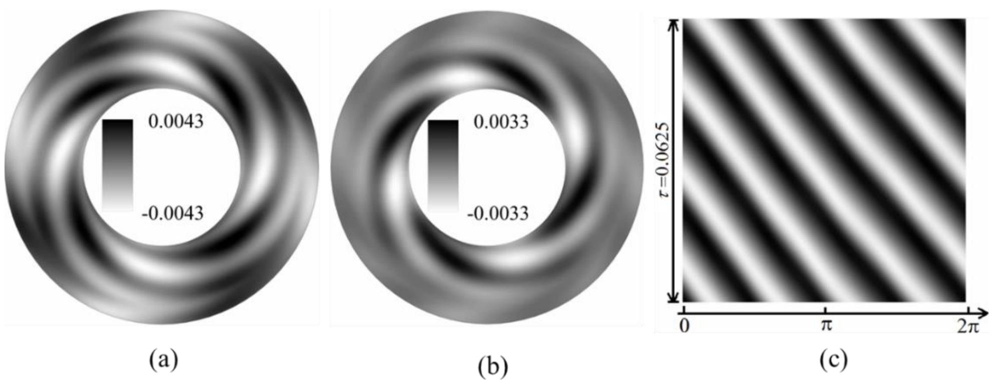

FIG. 2 Typical results of surface (a) and interface wave patterns (b) and the corresponding STD (c) on the interface when *Ma*=1.0×10^6 and *Ta*=334.8

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Instabilities of Marangoni convection in volatile liquid layer subjected to horizontal temperature gradient

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I. ABSTRACT

In order to understand the Marangoni convection instability in volatile liquid layer subjected to horizontal temperature gradient, a series of experiments are carried out in a rectangular cavity filled with 0.65 cSt silicone oil under various horizontal temperature gradients and room temperatures. Many previous works [1-3] were merely devoted to consider cellular convection instability or thermocapillary convection instability, In fact, both the cellular convection instability and thermocapillary convection instability are possible because the vertical temperature gradient induced by surface evaporation as well as the imposed horizontal temperature gradient are coupled spontaneously and they always coexist in volatile liquid layer subjected to horizontal temperature gradient. Our experimental results show that three kinds of instability modes successively occur in the liquid layer with the increase of the horizontal temperature gradient: i.e., cellular convection, cellular convection accompanied with hydrothermal waves, pure hydrothermal waves, respectively. The stability diagram for the transition of instability modes are determined and the impact of room temperature on it is considered. In addition, the influence of thermocapillary convection induced by surface evaporation on instability of convection is also discussed.

II. TYPICAL RESULTS

(a) 

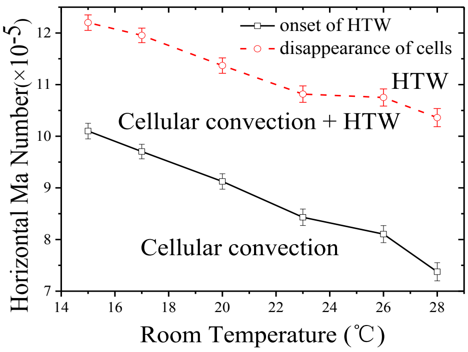
(b) 

FIG. 1. (a) The coexistence of cellular convection and hydrothermal waves with the external imposed temperature difference (ΔT=6K) in 1.2-mm-thick silicone oil liquid layer. (b) Stability diagram of different convection modes.

Acknowledgements: This work was supported by National Natural Science Foundation of China (grant No. 50976128 and No. 51176210).

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Rate-Dependent Interface Capture beyond the Coffee-Ring Effect

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The mechanism of droplet drying is a widely concerned fundamental issue since controlling the deposition morphology of droplet has significant influence on printing, biology pattern, self-assembling and other solution-based devices fabrication.[1-3]Most of traditional studies on this on this nonuniform redistribution process indicate that inner flows, including capillary flow[1] and Marangoni flow,[4] dynamics of the three-phase contact line, and particle-particle/particle-interface interaction will influence the final particle distribution. Here we reveal a striking different kinetics-controlled deposition regime beyond the ubiquitous coffee-ring effect that suspended particles tend to kinetically accumulate at the air-liquid interface and deposit uniformly. As the interface shrinkage rate exceeds the particle average diffusion rate, particles in vertical evaporation flow will be captured by the descending surface,[4] producing surface particle jam and forming viscous quasi-solid layer, which dramatically prevents the trapped particles from being transported to drop edge and results in uniform deposition. This simple, robust drying regime will provide a versatile strategy to control the droplet deposition morphology, and a novel direction of interface assembly.

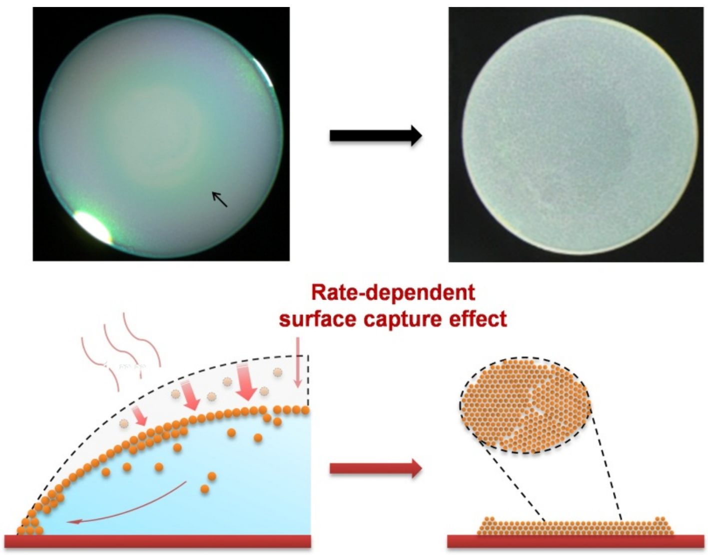

FIG. 1.Rate-Dependent Interface Capture beyond the Coffee-Ring Effect.Up: Photos of the surface aggregation and final uniform deposition; Bottom: Scheme of the rate-dependent surface capture effect caused uniform deposition

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Some Unusual Ideas on the Stability of a Pendant Drop and a Liquid Bridge

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In this talk we shall discuss the stability of two equilibrium configurations i.e., the pendant drop and the liquid bridge in common terms but with uncommon ideas. Most of the results arising in our discussion can be obtained from simple ideas in linear algebra.

The liquid in the drop is heavier than the surrounding fluid. The only scaled groups that govern the stability are the scaled volume and the Bond number. It can be shown ***without computations*** that the volume of the drop has a maximum value beyond which it must break catastrophically. However this upper bound on volume is NOT the instability limit for the drop for all Bond numbers. There exists a critical Bond number, above which the drop breaks well before the upper bound on volume can be reached. ***This first critical Bond number can be obtained without a stability analysis*** and solely from the knowing the base shape of the drop. We discuss why this occurs and what it means for the physics of the break-up.

Under the case of zero gravity, the scaled groups for bridge are scaled volumes and the ratio of bridge length to its radius. It can also be proved ***without computations*** that for a fixed length to radius, the volume of bridge has a minimum value below which it must break. Meanwhile the ratio of its length to radius exhibits a similar physical mechanism as the Bond number in pendant drops. There exists a critical ratio, above which the bridge breaks before the lower bound on volume can be obtained. ***This critical ratio can also be obtained without a stability analysis.*** This is the second part we shall discuss.

The stability of pendant drops and closed liquid bridges are also affected by the rotation about their vertical center axis. However rotation plays a very different role on the stability of a drop versus a bridge. It destabilizes the drop at small volumes and stabilizes the drop with large volumes. In bridges, it always has a destabilizing effect. We discuss why there is this difference in the last part of the talk.

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PreliminaryResults of Space Experimental Investigation of Sessile Droplet Evaporation Process onboard Chinese Satellite SJ10

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The paper will present a new project “EFILE” of the space experimental investigation of sessile droplets evaporation process onboard the Chinese Scientific Satellite SJ10 to be launched in the April of 2016. The EFILE (*E*vaporation and *F*luid *I*nterfacia*LE*ffects) experiment is one of the first fluid physical experiments to be conducted onboard SJ10 satellite. The scientific topic of the space experiments is focused on the development of the phase-change interfacial hydrodynamic theory by using microgravity environment and to obtain the novel knowledge on the coupling mechanism of evaporation and convection. During the EFILE space experiment, wewill observe the contact angle along the triple line, the curvature of the interfaces, and the convection flow in the droplet. The obtained experimental data are expected to understand the gravity effects on the heat and mass transfers of evaporation and Marangoni effects on the gas-liquid-solid contact dynamics of an evaporation dropin space environment.

The space instrument of EFILE consists mainly of central experimental module, liquid injection module, optical visualization module and electrical control module. After creating a droplet by injecting one kind of liquid (ethanol was chosen in this space experiment) on a substrate (two kind of substrates with changing wettability for ethanol were selected), the images of free evaporating process of the droplet will then be acquired from side view using a high resolution CCD camera, and geometric parameters like the liquid drop shape and its contact angle along the triple line from the side will be record, which can be calculated the evaporating rate of the droplet in space. Additionally, a heat flux-meter and some thermocouples, integrated just below the evaporation surface, will allow measuring the thermal dynamics of the droplet evaporation.

The duration of total experiments on orbit is about 25 hours in which 12 times of drop evaporations will be performed on the copper substrate and 24 times on the PTFE substrate respectively, for different heating temperature at the substrate and different injected volumes of drop. The fig. 1 shows the variations of average evaporating rate of droplet for different heating temperature and drop volumes obtained in the ground.The results of drop evaporation obtained by using the space experimentmodule in space and the preliminarycomparison of space results with the ground resultswill be given in present paper.

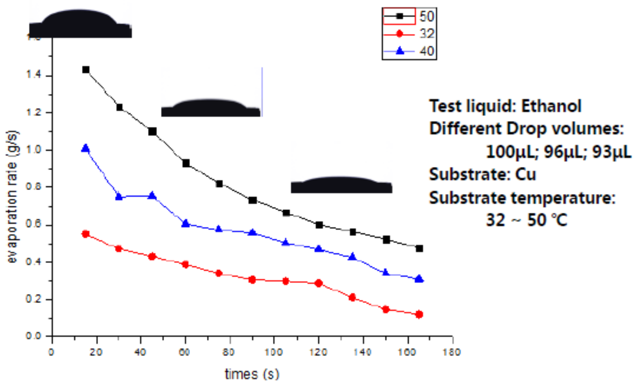

FIG. 1.Variation of average evaporating rate of droplet for different heating temperature and drop volume of caption.

Acknowledgements

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Effect of Thermocapillary on the Stability of an Exterior Coating Fibre Flow

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The dynamics of a viscous film flowing down a vertical fibre under the action of gravity and the thermocapillary is analyzed theoretically.This exterior coating flow is driven by aRayleigh-Plateau mechanism [1] modified by the presence of gravity as well as the variation of surface tensioninduced by temperature gradient along the interface. A temporal-spacial stability analysis and a nonlinear simulation areperformed to investigate the influence of the thermocapillary on the convective/absolute instability (CI/AI) and the breakup behavior of axisymmetric disturbances.The results showed that the thermocapillary play an important role in determining the CI/AI characteristics in different flow regimes.We also connected the breakup of the film with the CI/AI. It is found that the breakup behavior mainly occurs in the AI regimes.

We have tested the breakup behavior based on the numerical solution for a wide range of parameters of ***a*** and***Bo***. Infig.1, the breakup/non-breakup regime is indicated by the shaded/hollowquare in the parametric plane (***a,Bo***). The boundary between convective and absolute instability is also depicted in this figure by a solid curve to show the relation between the AI/CI and the breakup behaviors.For ***Ma***=0, as shown in fig.1(a), almost all the breakup points located in the AI regime. At very small ***Bo*** the maximum ***a*** of the AI regime nearly reaches the AI/CI bound. The maximum ***a*** of the AI regime decreases with the increase of ***Bo***.As ***Bo*** slightly exceeds the CI/AI bound, the breakup regime only exists in the regime with small ***a***. As Ma increases to 0.5 and 1, the breakup points shrink towards the small ***a*** regimes.As ***Ma*** increases to 2 (not presented here), most of the breakup points are confined in the AI regime. However, the distribution of the breakup points is irregular.

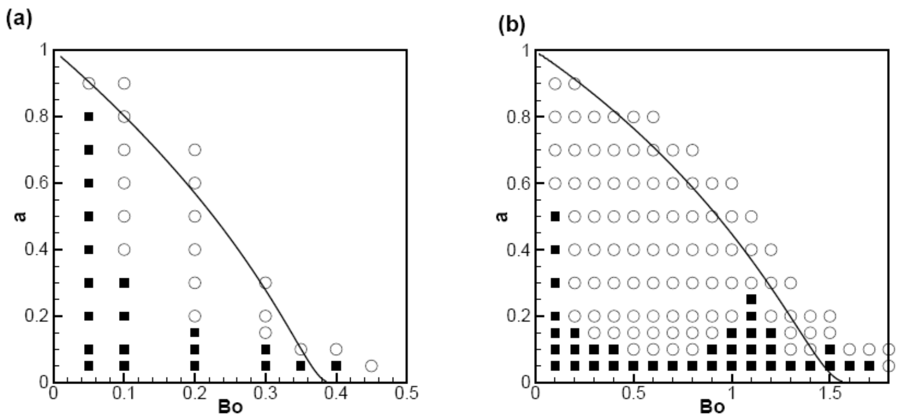

FIG. 1.Parametric space for the Bond number ***Bo*** and ***a***. Breakup and no breakup regions are marked by squares and circles. (a) Ma=0, (b) Ma=0.5.

Acknowledgements

The project have been supported by the National Nature Science Foundation of China (11532015) andthe Strategic Priority Research Program on Space Science, Chinese Academy of Sciences.

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The interaction of thermocapillary, parametric and oscillatory Kelvin-Helmholtz instabilities in a two-layer system subjected to the tangential vibrations

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The paper deals with the investigation of interaction of thermocapillary, parametric and oscillatory Kelvin-Helmholtz instability mechanisms in a two-layer system with deformable interface subjected to the tangential vibrations. The problem configuration is the following: there are two superposed horizontal layers of immiscible incompressible fluids. The layers are of equal thicknesses. The upper and lower boundaries of the two-layer system are rigid and perfectly conductive, they are maintained at constant different temperatures. The interfacial tension coefficient depends linearly on temperature. The buoyancy effect is not considered. The thermal conductivities of fluids are equal and there is no such limitation on thermal diffusivities. The layers are subjected to gravity field and horizontal sinusoidal vibrations of finite frequency. The flow closeness condition is imposed, i.e. the problem under consideration corresponds to the configuration of rectangular container with such large horizontal size that it is possible to neglect the end effects.

Two problems are considered: the influence of thermocapillary effect on the onset of parametric and oscillatory Kelvin-Helmholz instabilities and the influence of tangential vibrations on the onset of thermocapillary instability. The first problem concerns the influence of weak thermocapillary effect on a stability of fluid interface subjected to the horizontal vibrations of finite frequency and amplitude. The instability of isothermal fluid interface subjected to the tangential vibrations was studied theoretically for the first time in [1] in the framework of high-frequency small-amplitude approach. It was shown that when vibration velocity amplitude approaches a certain critical value the planar interface becomes unstable because of the development of oscillatory Kelvin-Helmholz instability and quasi-stationary wave pattern arises. The case of isothermal fluids subjected to the tangential vibrations of finite frequency and amplitude was studied for the first time in [2] neglecting the viscosity and in [3] taking into account the viscous effects. It was shown that in this case additionally to the oscillatory Kelvin-Helmholz instability there is parametric instability related to the capillary-gravitational waves. We study the influence of weak thermocapillary effect on these instabilities assuming that the viscosities of both fluids are low such that the Stokes boundary layer thicknesses are small in comparison with the fluid layer thicknesses. The multiple scale method and formal expansions are implemented to obtain the analytical solution.

The second problem concerns the effect of weak vibrations on the Marangoni instability in a two-layer system with deformable interface subjected to vertical temperature gradient. For the case when vibrations are absent, the onset of thermocapillary convection in a two-layer system with deformable interface subjected to the vertical temperature gradient and gravity was studied neglecting buoyancy effect in [4]. We analyze the impact of weak vibrations considering the case of low-viscous fluids. The formal expansions with respect to small parameter associated with the vibration amplitude and viscosities coupled with the multiple scale method are used to take into account the boundary-layer effects. The analytical expressions describing the impact of vibrations are obtained.

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Vertical vibration effect on the Rayleigh-Benard-Marangoni instability in a two-layer system of fluids with deformable interface

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In [1] the onset of thermal buoyancy convection in a two-layer system of immiscible fluids of close densities was investigated for the case of constant vertical heat flux at the external rigid boundaries. The problem was studied taking into account the interface deformations, in the framework of generalized Boussinesq approximation suggested by D. Lyubimov in [2]. It was shown that there are two branches of monotonic longwave instability. Between them there is an oscillatory longwave instability boundary in the form of straight line. Stability boundaries to the perturbations with finite wave numbers are obtained numerically.

Investigation of the contribution of thermocapillary effect performed in [3] has shown that in the case of heating from below the perturbations with finite wave numbers are most dangerous at any values of the parameters and in the case of heating from above, for any values of the Marangoni number, at the Rayleigh numbers small in modulus, the monotonic long-wave perturbations are most dangerous and at the Rayleigh numbers large in modulus, the monotonic perturbations with finite wave numbers.

Investigation of the effect of vertical high frequency vibrations on the onset of convection in this system in the absence of thermocapillary effect performed in [4] has shown that the vibrations increase the instability threshold to the oscillatory perturbations with finite wave numbers (Fig 1, left).

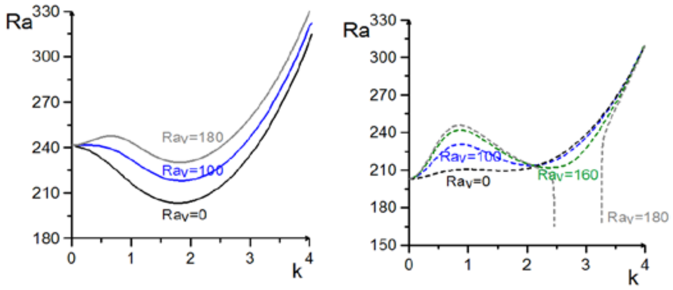

FIG. 1. Neutral curves for $Ga = -250, Ma = 0$ (left) and $Ga = -250, Ma = 100$ (right); the instability domains are located above the curves.

In the present work the influence of vertical high frequency vibrations on linear stability of the conductive state of the two-layer system with deformable interface is studied taking into account the thermocapillary effect. It is found that with the increase of the vibration intensity new finite-wavelength instability mode appears and with further growth of the vibration intensity this mode leads to a complete loss of stability (Fig 1, right). For the two-layer system formic acid - trasformer oil, in the case of normal thermocapillary effect, the vibrations decrease the stability of the conductive state to mononomic finite-wavelength perturbations and increase the stability to the oscillatory finite-wavelength perturbations.

The work was supported by Russian Science Foundation (grant 14-21-00090).

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Vibration effect on thermo- and solutocapillary flows in crystal growth by floating zone method

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The paper deals with the numerical investigation of axial vibration effect on the convective flows in crystal growth by floating zone method in zero gravity conditions. The surface tension is considered as dependent of both temperature and solute concentration. Vibration period is assumed to be small in comparison with all hydrodynamical time scales (viscous, thermal and diffusion) and their amplitude – small in comparison with the liquid bridge radius and height. These assumptions allow to neglect the dissipative and non-linear terms in the description of fast processes and to obtain the close system of equations and boundary conditions for average and pulsational components [1]. The study is performed taking into account pulsational deformations of free surface and neglecting average free surface deformations and curvature of melting and crystallization fronts.

The first part of the paper concerns axisymmetric steady flows. The calculations [2] have shown that the evolution of convective flow with the variation of thermal Marangoni number at fixed value of solutal Marangoni number is accompanied by the hysteresis phenomenon, which is related to the existence of two stable steady regimes in certain parameter range. One of these regimes is thermocapillary dominated, it corresponds to the two-vortex flow, and the other is solutocapillary dominated, it corresponds to the single-vortex flow. The coexistence of two stable axisymmetric stationary flow regimes in the FZ crystal growth with surface tension depending both on temperature and concentration was also observed in the calculations and experiments on the FZ crystal growth under gravity field and strong magnetic field in [3,4].

In the FZ configuration, vibrations of one of rigid rods induce pulsational surface waves propagating from oscillating rod. These waves result in generation of strong time-average flow with the direction along the free surface from the oscillating rod. As the result of interaction of this vibration-induced flow with the thermocapillary and solutocapillary flows, the range of thermal Marangoni number values where the hysteresis takes place becomes narrower. It is shifted to the area of larger thermal Marangoni numbers at positive values of the solutal Marangoni number and to the area of smaller thermal Marangoni numbers at negative values of the solutal Marangoni number.

The second part of the paper concerns stability of axisymmetric thermo- and solutocapillary flows and transition to three-dimensional regimes. Dependences of critical value of thermal Marangoni number on the dimensionless vibration amplitude are obtained for different fixed values of the solutal Marangoni number and different instability modes. Stability maps in the parameter plane thermal Marangoni number - solutal Marangoni number are obtained for different values of vibration parameters. It is found, that the character of the vibration effect on axisymmetric flow stability is different for different instability modes and different vibration amplitude ranges. Thus, the vibrations can modify the scenario of the transition to three-dimensional flow regimes.

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Marangoni influence on the melting dynamics of Phase Change Materials

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The large latent heat involved in the solid/liquid phase change allows Phase Change Materials (PCM) to store or release a large amount of energy during melting or solidification. The phase change takes place barely changing the temperature. This stability with respect to temperature changes and thermal storage capacity is key in many industrial applications of these materials such as electronic cooling, air conditioning in buildings, waste heat recovery or to compensate the time offset between energy production and consumption in solar power plants [1].

In addition to ground applications, the usual cycles of operation of devices on-board spacecrafts suits well with the the heat storage and discharge phases of PCMs. Thus thermal control using PCMs in microgravity has been widely used in space systems for low and high temperature applications to avoid temperature peaks from electronic devices, electrical power components, control battery temperature in lunar and Mars rovers, or even to refrigerate food and biological waste samples in manned spacecrafts [2]. However, a mayor issue in thermal regulation with these materials is their low conductivity. This leads to very long times during the heat storage and discharge phases, reducing their usability and performance on heat control.

On ground applications the main choice to reduce the problem of low conductivity is to promote convective motions within the liquid phase of the PCM. Convective motions driven by gradients of density induced by differences of temperature enhance the heat transfer rate about an order of magnitude. However, this approach is not applicable in microgravity. Other approach to accelerate the heat transfer is to place a large area of PCM in contact with high conductivity materials, like metallic fins or foams [3]. Whereas this solution is also applicable under microgravity conditions, it increases the mass and size of the devices, and the absence of convective driving is not compensated.

Prompted from the above considerations a mechanism to enhance the heat transfer on PCMs in microgravity, without increasing the mass and volume, is to maximize the Marangoni flow induced by thermal gradients of surface tension. This requires selecting a PCM with a phase change temperature complying with design limits, high latent heat and best possible thermal conductivity in liquid and solid phases.

We carry out simulations of Navier-Stokes equations modified with a Darcy porous term and coupled with an energy equation including a source of latent heat. We present an extensive comparison of the melting process for i) conductive transport, ii) Marangoni convection, iii) Rayleigh-Bénard convection and iv) combined Marangoni and Rayleigh-Bénard convection. In addition, we show the effect of the geometry on the melting dynamics in presence of thermocapillary effects [4].

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Pattern deposition off an evaporating solution under the influence of a MHz surface acoustic wave (SAW)

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We excite an evaporating solution on an ultrasonic actuator, supporting a propagating MHz vibration in the substrate in the form of a Rayleigh surface acoustic wave (SAW). Transfer of momentum from the MHz SAW in the solid to the neighboring liquid translates to a convective stress within the liquid and on its free surface. Thisinvokes various flow mechanisms that are generally known as acoustic streaming. In particular we investigate an acoustic streaming mechanism, associated with the Schlichting boundary layer flow, that governs the dynamics of sub-micrometer to micrometer thick films of liquid and may support dynamic wetting or dewetting.

We use theory and the experimental procedure in figure 1 to study the interference of the SAW with the natural self-organization mechanism of the deposited solute particles, following the dewetting of the evaporating solution. The interplay between the flow field within the evaporating solution and the dewetting dynamics governs the pattern deposition of the solute particles on the solid substrate. We show the SAW alters the state of pattern deposition. The SAW imposes a drift of liquid mass that alters the local geometry of the meniscus of the solution and the transport of the solute particles within the meniscus. Using the SAW we actively alter the dynamic state of the deposition, changing the qualitative geometry of the deposited patterns from dots to stripes and from stripes to solid films. We give an examplein figure 2.

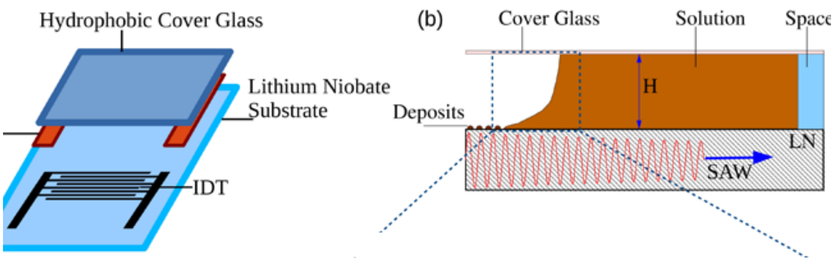

Figure 1: On the left we show a chamber, containing an evaporating solution, weattach to a SAW device, comprising an interdigitated transducer (IDT)atop a lithium niobate (LN) substrate. On the right we illustrate the evaporating meniscus of the solutionthat de-wets the solid while depositing the solute, where the drift velocity in the meniscus V_{SAW}, invoked by theSAW, opposes the natural velocity field, V_{Evap}, generated by evaporation.

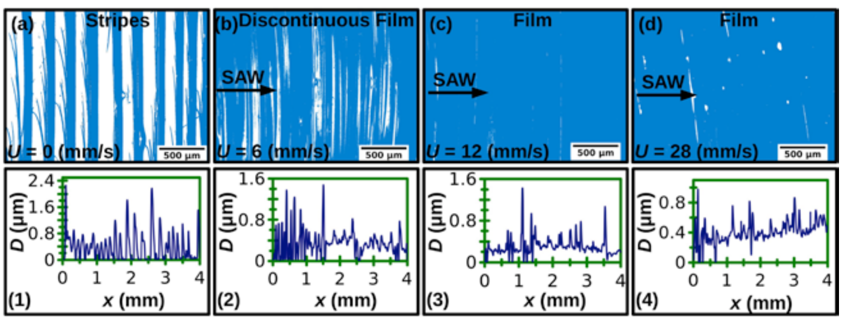

Figure 2: (a-d) Variations in the patterns of the deposits (colored blue for distinction)at different SAW intensities (*U*), obtained by evaporating a solution of 1 mg/ml bromcresol purple in water at 90^{O}C, and (1-4) their respective topographies, given as the local thickness of the deposit*D*along the spatial coordinate *x*, where the deposited mass approaches the topography of a solid film when increasing *U*.

Axisymmetric Buoyant–Thermocapillary Convection in Sessile Droplets

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The combined buoyant–thermocapillary flow in sessile droplets is investigated numerically. The droplet sits on a flat plate whose temperature is kept constant. The flow is driven by buoyancy and thermocapillary forces which arise due to a linear variation normal to the wall of the ambient temperature. Assuming Newton's law for the heat transfer along the liquid-gas interface, the inhomogeneous temperature distribution along the free surface of the droplet results in thermocapillary stresses driving an axisymmetric fluid flow. Therefore, the fluid motion can be assumed to be axisymmetric. Neglecting evaporation we assume a steady flow which is justified for sufficiently weak driving forces. In the limit of large mean surface tension the liquid–gas interface is spherical [1] which allows to formulate the problem in body-fitted orthogonal toroidal coordinates such that the interface is a coordinate line. The flow is governed by the non-dimensional Navier–Stokes, continuity, and energy equations in the Boussinesq approximation as in [2]. Steady-state axisymmetric solutions to the incompressible Navier–Stokes equations are obtained using a vorticity-stream function formulation discretized by a second-order central finite differences on a non-uniform grid. The resulting nonlinear difference equations are solved iteratively employing a Newton–Raphson method.

A parametric study is carried out by varying the contact angle as well as the Reynolds, Prandtl, Grashof, and Biot numbers. Furthermore, the balance between the buoyant and thermocapillary forces are studied thoroughly for a wide range of key parameters (an example is given in fig. 1). Results in terms of isotherms, streamlines, and velocity vectors are discussed.

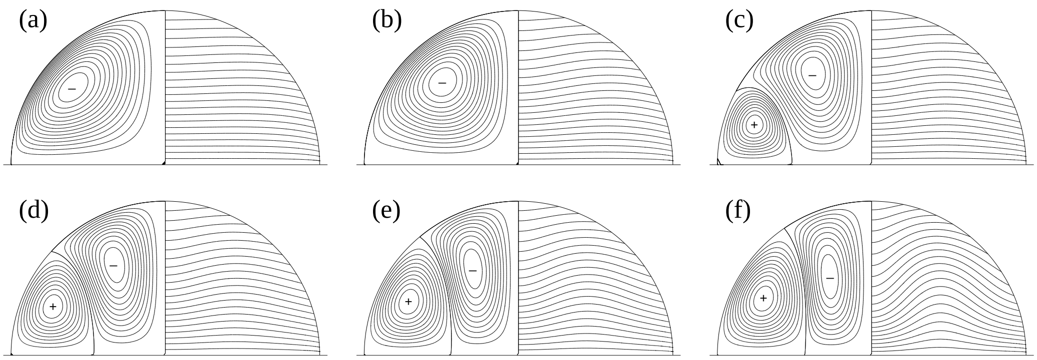

FIG. 1: Streamlines and isotherms for mixed buoyant–thermocapillary flow. The minus/plus sign ($\mp$) indicate the direction of rotation (clockwise/counterclockwise). The parameters are $\mathrm{Re} = 1$, $\mathrm{Pr} = 4$, $\alpha = \pi/2$, $\mathrm{Bi} = 0.5$, and $\mathrm{Gr} = 100$ (a), 1000 (b), 2000 (c), 2500 (d), 3000 (e), 4000 (f).

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Flow pattern dependance on aspect ratio for double free-surface film subjected to thermo-capillary force

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Abstract

Recent experiments in double free-surface film subjected to thermo-capillary force clearly revealed two radically different base flows when changing the film thickness: a sheet-like pattern appears for the thicker film while a cellular-like pattern arises for the thinner one [1]. These experiments were conducted with a 6 cst Silicone oil making up a rectangular double free-surface film in air submitted to a horizontal thermal difference. Two film thicknesses were considered in this study ($d_1 = 0.2$ and $d_2 = 0.6$ mm), leading to aspect ratios in the thermal gradient direction of $\Gamma^i_{xz} = L_x/d_i = 10,\ 10/3$ and in the spanwise direction of $\Gamma^i_{yz} = L_y/d_i = 20,\ 20/3$, respectively.

Puzzled by the above experimental results we have conducted a parametric study aimed at finding out the critical aspect ratio where the transition between the two base flow patterns occurs for $d_1 \leq d \leq d_2$. In a first attempt, it is assumed that the free surfaces remain perfectly flat, i.e., are not deformed by the fluid flow. For each considered aspect ratios, steady-state solutions are computed up to the first steady-state bifurcation with our continuation algorithm based on the Asymptotic Numerical Method [2–4]. Under this restrictive "not-deforming-interface" assumption it turns out that the sheet-like pattern is the base flow for all the considered film depths ($d_1 \leq d \leq d_2$). However, the first steady state bifurcation switches from the sheelt-like pattern to the cellular-like one and the thinner the film, the lower is the critical thermal gradient at which this first steady-state bifurcation occurs. So, it first appears that three length scales are relevant to define the critical Marangoni number for this problem: (i) the film thickness; ii) the longitudinal aspect ratio Γ_{xz}; ii) the spanwise-to-longitudinal aspect ratio $\Gamma_{yx} = L_y/L_x$. The former length scale controls viscous stresses in the sheet-like pattern whereas the two latter enter into the game in the cellular-like pattern and the pattern transition switches to the less dissipative fluid flow.

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Variety of particle accumulation structures in thermocapillary flows

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I. ABSTRACT

Dynamic coherent structures formed by inertial particles (dubbed as PAS) in three-dimensional incompressible oscillatory flows [1] are a topic of interest in the present study. We performed experiments on the transport by advection of small solid particles in thermocapillary oscillatory flows. The flow of interest is a superposition of a single vortex ring flow and of counter-rotating vortices revolving in the angular direction with a constant speed. Particles of various size and density are found to form PAS revolving with the speed of the vortices. Such attracting structures are a mere illusion of a solid rotating body whose apparent existence is the outcome of presence of many non-interactive particles moving in a synchronous manner with each other (an effect similar to the stadium wave): the structure-forming objects are correlated in space and time and follow alike trajectories.

With the aim of the developed ad hoc image processing technique, based on calculation of the global contrast of recorded images, similar to that in [1], we computed time it takes for a structure to emerge. It is found to depend upon the particles' inertia. Furthermore, while experimenting with very large particles, in addition to a conventional symmetric PAS (fig. 1(a)), we observed two new types of stable coherent structures: (1) non-symmetrical (fig. 1(b)); and (2) ones with almost periodic stability, whose existence is interrupted by timespans during which the particles are dispersed over the bulk (see fig. 2 demonstrating an almost periodically stable PAS).

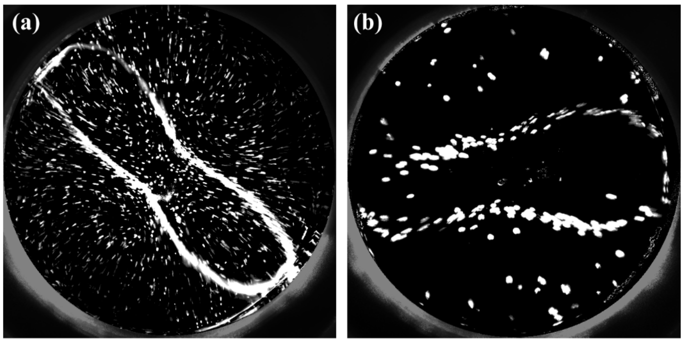

FIG. 1. Particle accumulation structures. Left: A conventional PAS; Right: A stable non-symmetric PAS.

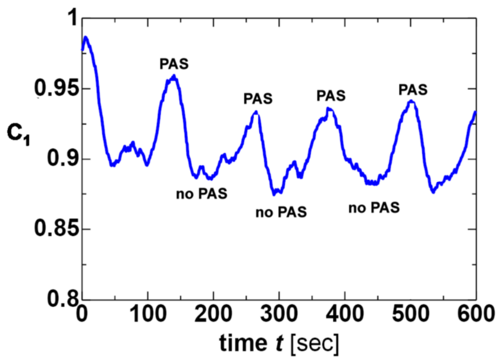

FIG. 2. Contrast of images calculated for an intermittently stable PAS showing its almost periodic stability.

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Oscillatory Marangoni instability and capillary-gravity waves in a heated liquid layer covered by insoluble surfactant

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We consider a liquid layer covered by an insoluble surfactant and subjected to a transverse temperature gradient (heating from below or from above). Two types of wavy motions can be observed, namely, transverse (capillary-gravity) waves and longitudinal Marangoni waves caused by the dependence of the surface tension on the surfactant concentration and temperature. In the absence of heating, both kinds of waves decay due to viscosity of the liquid, but they can appear spontaneously when heating is applied. We investigate, analytically and numerically, the generation of waves due to an instability of the quiescent state. When the frequencies of two oscillatory modes approach each other, we observe a mixing (shown in Figure 1) or reconnection between them.

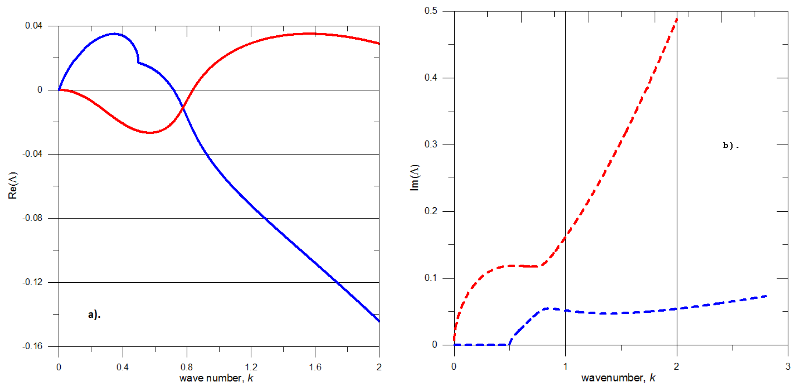

FIG. 1: Dependence of the complex growth rate on the wavenumber k. Left (a): The instability growth rate $Re(\Lambda)(k)$ and Right (b): the frequency $Im(\Lambda)(k)$. The blue color lines correspond to Marangoni instability, red color lines correspond to capillary-gravity waves.Parameters: the Marangoni number $M = 10$, the Galileo number $G = 5$, the Prandtl number $P = 0.01$, the elasticity number $N = 0.1$, and the Lewis number $L = 0.01$.

Both kinds of waves can be generated also by vibration [1] or temporal modulation of the temperature gradient [2]. The parametric modulation creates subharmonic and harmonic "tongue-like" instability regions. We perform analytical and numerical analysis using the Floquet method. The influence of the coupling between two types of waves on their parametric excitation is studied.

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Diffusion of a surfactant from the drop of “constant” density

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Traditionally, the terrestrial modeling of hydrodynamic phenomenon in microgravity is accomplished via a reduction of vertical dimension of the liquid layer or increase of liquid viscosity. Such an approach essentially lowers the intensity of gravitational convection but leaves open the possibility of its development. Furthermore, in the case of three-dimensional flow pattern a decrease of vertical dimensions hinders visualization and analysis of the flows and concentration fields and the growth of viscosity involves changes of all physical-chemical parameters of the liquid.

In the problems of substance diffusion through the interface there is one more approach, which is based on a reduction of the local density variation, which allows minimization of the gravitational effect. The use of this technique suggests the equality of densities of all system liquids – the base liquids generating the interface and diffusing liquids. Unfortunately, this approach is unfeasible for systems composed of three pure liquids. In the case of using mixtures or solution as the base liquids of the system, the situation changes essentially.

Our report presents the results of studying the solutal convection in similar systems composed of chlorobenzene- benzene (base liquid I), aqueous solution of sodium chloride (base liquid II) and acetic acid (diffusing surfactant). The examine system of liquids fills a narrow horizontal channel with transparent side walls, which allowed us to visualize the flows and concentration fields of the acid. A drop of the chlorobenzene-benzene mixture partitions the channel interior forming a vertical interface, through which the acid diffuses from the drop into the surrounding solution. A change in the density of the drop mixture is caused by contraction and an order or two orders of magnitude lower than in the case of diffusion of the acid from its mixture with chlorobenzene or benzene. Because of the initial equality of the acid and solution densities the intensity of the gravitational convection in the surrounding liquid medium weakens. In such conditions the effect of the Marangoni convection increases drastically.

A similar situation is investigated numerically. It has been shown that the structure and intensity of convection essentially depends on the Marangoni number and the ratio of adsorption to desorption coefficients.

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The effect of insoluble surfactant on thermocapillary flow in Hele-Shaw cell

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It is well known that presence of an adsorbed surfactant can exert a profound influence on interfacial flows. This influence is due to the dependence of surface tension on a surface concentration of a surfactant. Redistribution of a surfactant by a flow with non-zero divergence results in appearance of tangential stress directed opposite to an interfacial flow. The resulting flow is the result of the balance of both the applied, e.g. thermal, and compositional tangential stresses. Different theoretical studies in this case predict development of both monotonic [1] and oscillatory [2] instability. Direct experimental investigations of this situation are absent in the literature.

In the paper we present the results of experimental study of development and structure of thermocapillary flow on the water surface comprising an insoluble surfactant. The experiments were carried out in a Hele-Shaw cell that allows us both to simplify experimental methods and to compare obtained results with theoretical studies. Oleic acid was used as a surfactant. Constant temperature gradient along the surface was created with radiation formed by the light source and the lens system. The IR camera was used for temperature profile measurements on the water surface. A small amount of preliminary cleaned tracer particles was added to water for flow visualization purpose. To avoid the meniscus effects we make the interface flat by pouring the water to a level of the upper edges of the cell walls.

Experiments show that the flow structure strongly depend on the Elasticity number $E = \gamma_\Gamma \Gamma / \gamma_T \ \Delta T$ (here γ_Γ and γ_T are the compositional and thermal coefficients of surface tension, Γ is the surface concentration of the surfactant, ΔT is the temperature difference along the surface) which defines the relation of surface tension variations due to compositional and temperature dependencies.

In the case when $E > 1$ the flow on the surface is very slow. The surface velocity strongly depends on the surface concentration varying in order from $10^{-1}\, cm/s$ for gaseous phase to $10^{-3}\, cm/s$ for beginning part of the liquid-extended phase. Because the surface motion is due to surface diffusion of the surfactant molecules the measurement of the surface velocity allow us to measure the surface diffusion coefficient. Our measurements show that this parameter is of the order of $10^{-3}\, cm^2/s$ for gaseous phase decreasing to $10^{-4}\, cm^2/s$ for beginning part of the liquid-extended phase. It should be noted that the obtained values is much higher of those used usually in theoretical studies.

In the case when $E < 1$ two different parts of the surface are observed. The first one which is closer to the hotter end is free of surfactant and is characterized by intensive thermocapillary flow. The second one is occupied with surfactant and almost stagnant. These mixed boundary conditions of stagnant and mobile surface are obtained in the whole region of E between 0 and 1. The position of the stagnant point depends on the value of Elasticity number. The flow is stationary at any Elasticity number values.

Possible mechanisms of the observed phenomenon and comparison with theoretical studies are discussed.

The work was supported by the RFBR project 16-01-00662.

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Modified Landau-Levich model for dragging thin liquid films by means of MHz surface acoustic waves (SAW)

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Recent experimental observations revealed complex dynamical behavior of thin liquid films spreading over substrates excited with MHz acoustic waves [1]. However, theoretical modeling of these experiments is cumbersome due to the presence of the three-phase contact line. In this work we propose a novel experimental setup allowing for investigation of thin liquid films in the absence of three-phase contact line and develop a corresponding theoretical model. In the future we expect to employ this setup to measure interfacial properties of liquids.

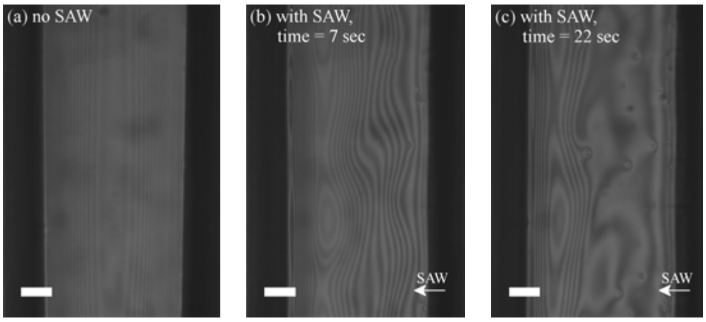

FIG. 1: Top view of a thin film of silicone oil sandwiched between an air bubble and a piezoelectric substrate. The density of the interference fringes is proportional to the gradient of the film thickness. All three panels correspond to the same experiment: a freshly deposited film in the absence of SAW is shown in the panel (a); snapshots in the panels (b) and (c) were taken 7 sec and 22 sec after the forcing with SAW was initiated, respectively. On panels (b) and (c) acoustic waves propagate from right to left. Scale bar $= 50\,\mu$m.

We study a micron-thick liquid film sandwiched between an air bubble and a piezoelectric substrate as shown in Fig. 1. In particular, we excite the substrate with a surface acoustic wave (SAW) and assess ensuing deformations of the film by detecting the displacement of light fringes of equal chromatic order (FECO). Using this technique we observe that the excitation of the thin film results in the net transport of liquid in the direction of the propagating SAW. A flat plateau is formed upstream, whereas the bulk of the liquid is pushed downstream.

Our theoretical model is based on the assumption that the cross section of the bubble, confined in the microchannel, is composed of static menisci in the corners of the channel and a thin liquid film connecting the menisci [2]. By means of lubrication approximation we derive an evolution equation governing the dynamics of the film in the region where the static meniscus connects with the flat plateau downstream. We show that in the steady state the evolution equation reduces to the modified Landau-Levich equation. The latter has two branches of steady states meeting at a saddle-node bifurcation point. We also show that in the absence of stable steady states the thin film decays and eventually ruptures.

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Effect of Reynolds number on coalescence of droplets with particle in creeping flow through a tube

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The coalescence of droplets in creeping flow through a tube is potentially useful for different purposes including the handling of fluids, control of chemical reaction, and in drug delivery systems. The phenomenon is also the basis for analyzing the flow of multiphase fluids through porous media such as in enhanced oil recovery and the breaking of emulsions in porous coalescers.

With regard to examples of studies on the creeping motion of droplets in a flow through a tube, Hetsroni G. et al.[1] theoretically examined the motion of a spherical droplet or bubule with small d/D, where d is the undeformed diameter of the droplet or bubble, and D is the tube diameter. Higdon J.J.L. and Muldowney G.P.[2] numerically obtained the resistance functions for a spherical particle, droplet, and bubble. Olbricht, W.L. and Kung D.M.[3] and Aul R.W. and Olbricht, W.L.[4] mainly investigated the coalescence time of droplets. Aul R.W. and Olbricht W.L. proposed a semi-theoretical formula of the coalescence time. Based on the formula by them, Muraoka, M. et al. [5] proposed other semi-theoretical formulas of the coalescence time in terms of the resistance experienced by the liquid droplet in creeping flow through a tube. The latter formulas take the eccentricity of the following droplets into consideration.

In the present study, a glass tube of inner diameter 2.0mm, outer diameter 7.0mm, and length 1500 mm was used as the test tube. Silicon oil with a kinematic viscosity of 3000cSt was employed as the test fluid of the droplet. A mixture of glycerol and pure water was used as the surrounding fluid of the creeping flow through a tube. A large volumetric syringe pump was used to maintain steady flow through the tube at a designated average velocity. The test tube was immersed in temperature-controlled water contained in a tank to maintain constant temperature of the system. The droplets were injected into the test tube. The behaviors of the droplets were monitored by a digital video camera and two high-speed cameras place on a sliding stage. The motion of the stage on which the cameras were mounted was electrically controlled to follow the movement of the droplets through the test tube. The coalescence time of two droplets in creeping flow through a tube was experimentally measured and compared with the predictions of semi-theoretical formulas[5] . In addition, the effect of the Reynolds number of the tube creeping flow on the coalescence of the droplets with particle was investigated. This work was supported by JSPS KAKENHI Grant Number 15K05809.

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Photochemical migration of liquid column in a glass tube

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I. MIGRATION PHYSICS OF AZTMA SOLUTION

In our study, we report about migration of a liquid column in a glass tube by photochemical isomerization. This activation is implemented by using photoresponsive surfactant solution modified with azobenzene called as AZTMA [1] with concentration of several mM. As shown in FIG.1, because AZTMA has photochromism it undergoes reversible *cis-trans* isomerization by light irradiation with different wavelength and then its interfacial tension also changes. We observed behavior of the liquid column of AZTMA solution in a glass tube with a diameter of 0.5 mm when light with effective wavelength is illuminated. In our experiments, the AZTMA solution isomerized by the wavelength combination of 350 nm and 439 nm was selected. Therefore, the corresponding UV and visible lights were irradiated. As for migration physics, when UV or visible light is illuminated into one side of the liquid column, the difference of interfacial tension at each side occurs due to the isomerization of AZTMA. Then, the nonuniform interfacial tension generates the dirrefence of the pressure which would be the driving force for the migration of the column along the tube. This migration is reversible because of the nature of isomerization. The liquid column migrates closer to the irradiation spot of UV light, and it migrates away from the irradiation spot when visible light is illuminated.

II. OBSERVATION OF WAVELENGTH-DEPENDENT ACTIVATION

FIG.2 shows behavior when 2 ml of liquid column in the state of *cis* was irradiated with the visible light. We can observe that decreasing contact angle makes curvature of the meniscus increase resulting in migration of the column. Moreover, internal flow of the column was visualized by the use of 4.5 μm fluorescent particles.

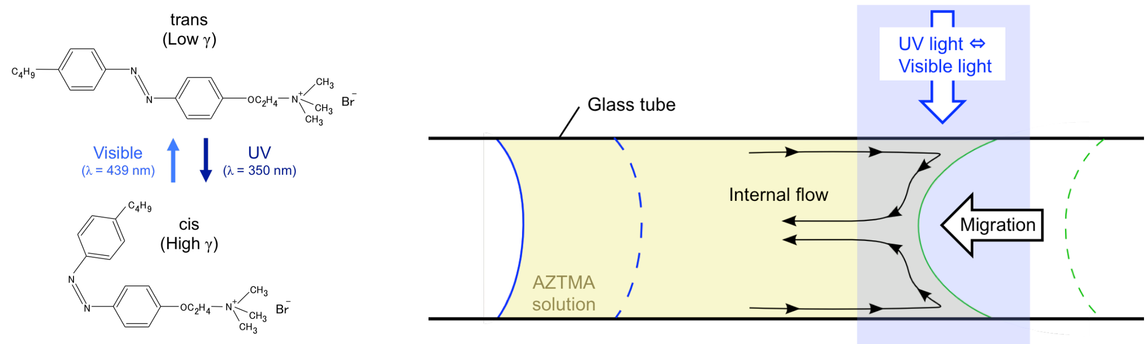

FIG. 1. Photochemical migration of a liquid column by *cis-trans* isomerization.
Left: Molecular structure of AZTMA; Right: Schematic of migration physics by light irradiation.

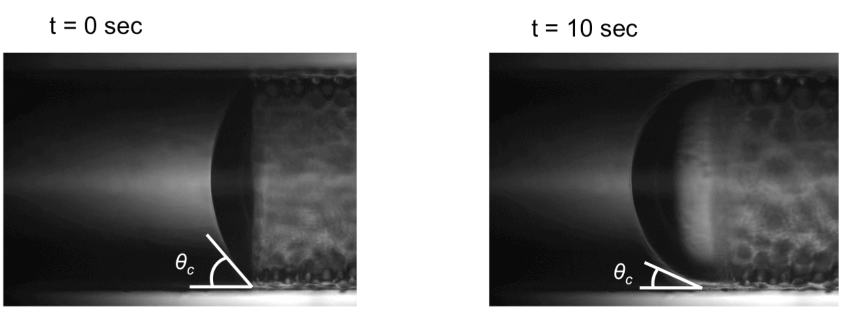

FIG. 2. Pictures of activated interface. Left: Initial state; Right: 10 s later from the visible light irradiation.

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Evaporation of aqueous solutions of salts on the horizontal heating surface

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Knowledge of the laws of aqueous salt solutions evaporation is important for the design of absorption heat pumps and chilling machines. In the present work, the evaporation rate of droplets and films of aqueous solutions of NaCl, $CaCl_2$, LiCl, and LiBr, as well as a mixture of LiCl and $LiNO_3$, was studied on a horizontal titanium heating surface within the temperature range t_W = 80÷600°C. Installation diagram of the experimental setup is presented in Fig.1. In the experiments we measured current values of the solution mass and the heating surface temperature. Besides, a film camera and a thermal imager were employed for process visualization.

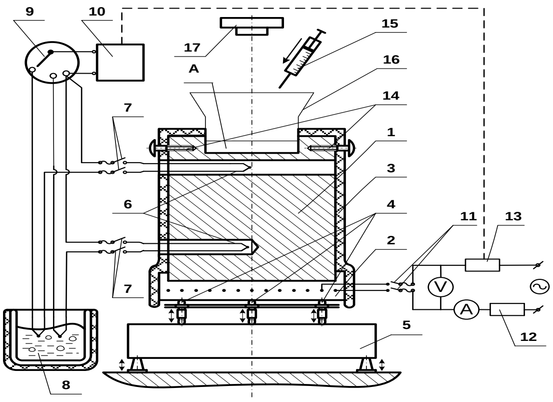

Fig. 1. Schematic diagram of the experimental setup: A – heating surface; 1 – titanium cylinder; 2 – electric heater; 3 – multi-layer screen thermal insulation; 4 – adjustable supports; 5 – chemical balance; 6 – thermocouples;
7 – flexible dismountable thermocouple unit; 8 – Dewar vessel with ice; 9 – thermocouple switch; 10 – millivoltmeter; 11 - flexible detachable wiring unit; 12 – laboratory transformer; 13 – temperature controller; 14 – lifter; 15 – dosing device; 16 –protective screen; 17 –filming and video-recording means.

The experimental data was obtained for various unsteady evaporation regimes: at the full and periodic contact of solutions with the heating surface, as well as at the developed film boiling. A new physical phenomenon was revealed, namely the bulk boiling up of LiBr water solution with the availability of a thin continuous vapor film between the heating surface and the solution (Fig. 2). The nature of this phenomenon is due to the diffusion processes in solution, high solubility of LiBr in water and thermodynamic instability of the solution.

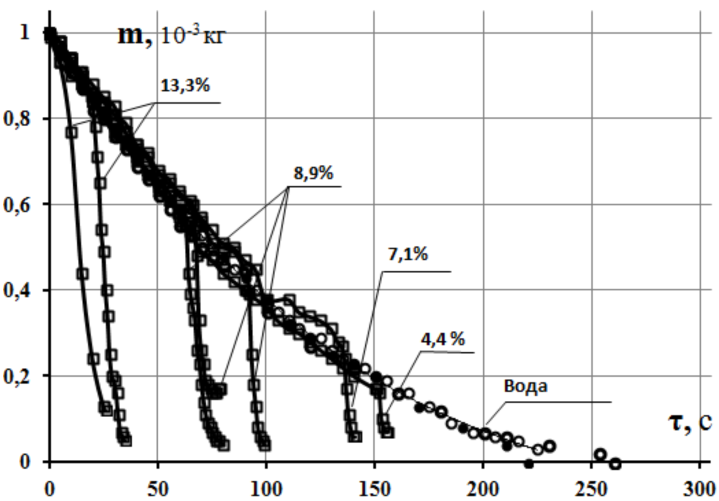

Fig.2. The evaporation rate of aqueous LiBr solutions depending on the initial concentration of salt at t_W = 400°C

Parametric excitation of the axisymmetric flow down a vertical cylinder

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The waviness of the interface of the liquid film falling down on a vertical plane was shown to be able to be suppressed by its tangential excitation in the framework of linear stability analysis[1]. Oron et. al[2] derived a set of nonlinear partial differential equations of the evolution type that govern the spatiotemporal dynamics of a liquid film falling on an in-plane oscillating planar substrate. Stability of the flat time-periodic base flow was also investigated using Floquet theory.

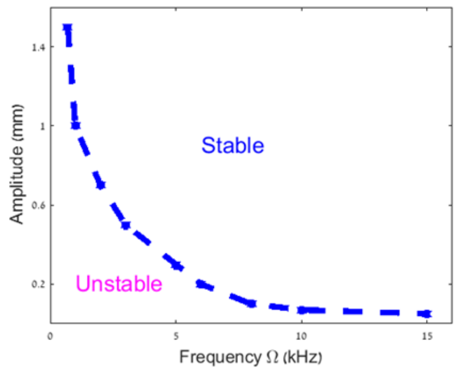
We now extend the theory to the case of an axisymmetric falling film on the outer surface of a vertical, harmonically oscillating cylinder. We investigate the nonlinear dynamics of such liquid film in the framework of a set of two coupled partial differential nonlinear evolution equations in terms of the local instantaneous film thickness and volumetric flow rate derived using the Galerkin method.

The Floquet stability analysis is carried out to investigate stability of the time-periodic thickness-uniform base state of the set of evolution equations derived here. We also perform numerical investigation of the flows emerging in the system in the framework of these equations. Figure 1 (left) presents the stability diagram in the plane spanned by the amplitude and frequency of forcing.

The film evolution in the system investigated here, as described by the set of evolution equations derived here, yields quasiperiodic tori and several kinds of strange attractors ranging from coherent (Fig.1, right) to fully irregular. It is shown that periodic parametric excitation affects the spatial topological structure of the interfacial waves and may modify its type from depression wave (γ_1) to elevation wave (γ_2).

Time-periodic excitation of films falling on a vertical cylinder is found to lead in general to a significant decrease of the wave amplitude in various parameter domains.

The research was partially supported by the Germany-Israel Foundation (GIF) via Grant no. 1228-405.10.



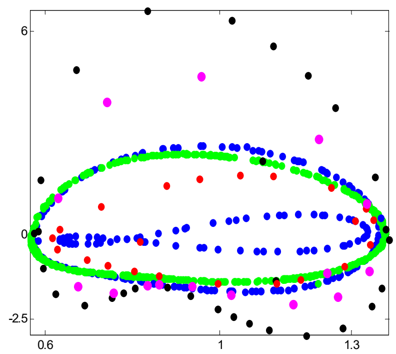


FIG.1. Evolution of a castor oil film (Kapitza number 0.45) on a harmonically oscillating vertical cylinder (cylinder radius 0.19mm). **Left:** Stability diagram in the plane of forcing parameters. The thickness-uniform base state for the average film thickness 1.23mm of the unforced system is unstable. **Right:** Poincaré map for the temporal evolution of the dimensionless film thickness (the average film thickness is 0.47mm): coherent strange attractor with the total infinite number of points for the forcing frequency 20Hz and amplitude 1mm. The evolution consists of several closed orbits containing a finite number of points (total 868 points in this figure) that are depicted by different colors, e.g., the first green orbit contains 150 points.

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Nonlinear Dynamics of Thin Liquid Films on a Corrugated Substrate Subjected to High-Frequency Forcing

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In this work, we have studied the effect of high-frequency horizontal harmonic vibration on the dynamics of a thin liquid film covering a wavy periodic substrate. Based on the long-wave approximation combined with an introduction of two time scales (slow and fast) and decomposition of the velocity and pressure fields as well as the interface location into their averaged (with respect to fast time) and pulsating components, the full set of hydrodynamic equations together with the boundary conditions is reduced to a single nonlinear partial differential equation which includes the effects of gravity, capillarity along with those of vibration and topology of the substrate. This evolution equation has been investigated analytically and numerically for various parameter sets and periodic substrate configurations.

First, the flat averaged in fast time interface does not represent an equilibrium of the system for any parameter set for a forced system, so when vibration acts on a corrugated wall, deformation of the film interface is unavoidable. Based on the results of our numerical investigation, we conclude that the evolution of the averaged film interface results in either film rupture or the emergence of a continuous steady state whose configuration depends not only on the forcing parameters but also on the substrate shape. One of the possible steady state configurations taking place for a certain domain of vibration frequencies is that of a droplet emerging in the wall depression. The emergence of a drop within the wall depression is associated with reflection of the liquid from the substrate walls that confine the depression and the resulting uplift of the average film interface. The droplet profile may assume various configurations inherited from the substrate topography, such as a regular drop or a flat-top shape on a symmetric cavity or a tilted-top droplet for an asymmetric saw-tooth profile. We note that replicated steady states may be prone to instability in replicated domains but the instability evolves very slowly, so they are metastable but may be considered as *effectively* stable. An alternative effect of vibration takes place in another domain of vibration frequencies where uniformization of the film occurs for relatively small wall amplitudes resulting in the emergence of the average film interface with the shape following that of the underlying substrate with an approximately uniform thickness.

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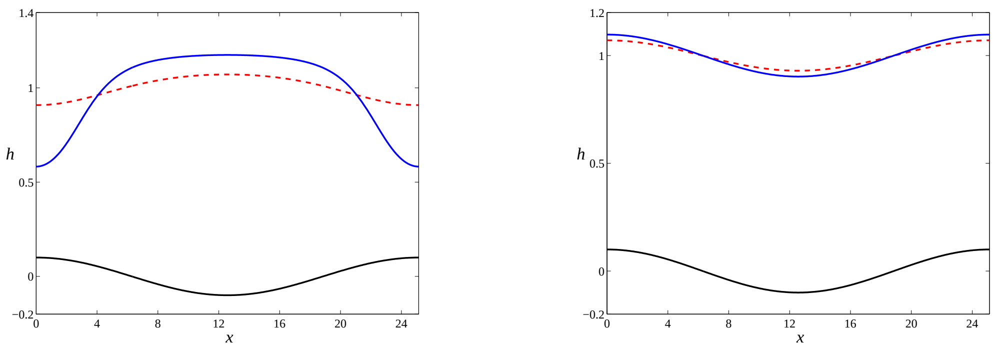

FIG. 1: Typical steady configurations in terms of the averaged film interface, each for two different forcing amplitudes. On the left: drop-like states; on the right: uniformization states of the film.

A simple 1D Shear-thinning Model: A Challenge for Reliability of Numerical Solution or Fake Instabilities

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A 1D shear-thinning model is considered as a first approximation of the synovial-fluid flow which occurs in an infinitely long channel bounded by moving solid boundaries. The viscosity is assumed to obey a power law expression, namely Modified Cross Model. The concentration of the hyaluronic acid influences the shear-thinning behavior. Consequently, the viscosity depends on both the concentration and the shear rate. Parameters of the viscosity model are found by fitting experimental data from the literature. The resulting 1D nonlinear differential equation is solved using a Chebyshev spectral collocation method. An important conclusion drawn from the results is that a reliable numerical solution can only be obtained if the solver has a full control of the machine accuracy via a parameterization of the zero-machine level. Otherwise the solver provides a non-physical numerical solution and a lack of accuracy can lead, in particular, to fake instabilities.

Instability and Breakup of Interacting Fluid Interfaces

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The principle that the dominant length scale of a patterned state is determined by the disturbance with the fastest growing linear growth rate (peak of the dispersion curve) was first propounded by Rayleigh in his seminal analysis of the breakup of liquid jets [1]. Since then it has been widely applied and has become one of the central paradigms in pattern formation research [2, 3]. However, this principle of wavelength selection runs into trouble when applied to flows with multiple unstable fluid interfaces. Such flows can exhibit dispersion curves with multiple peaks! It is not clear how the modes corresponding to these peaks will interact to decide the final pattern. In a quest for understanding, we study carefully selected model problems containing multiple unstable interfaces. An example of such a problem is a vertical arrangement of three fluid layers in a Hele-Shaw cell, bounded by walls at the top and bottom. A dispersion curve for this flow, exhibiting two distinct peaks, is presented in Fig. 1(a).

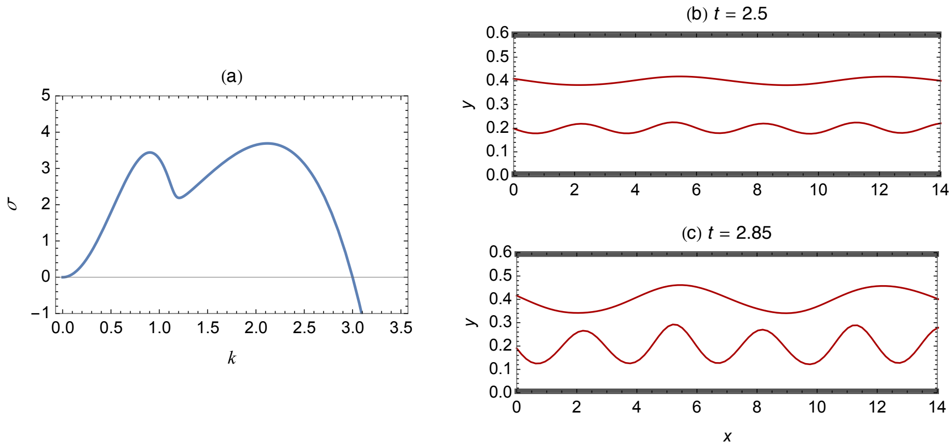

FIG. 1: Dispersion curve (a) and numerical simulations (b) for the three-layer Rayleigh-Taylor instability. The heaviest fluid is on top and the lightest fluid is at the bottom, rendering both interfaces unstable. Spatial coordinates are scaled with the capillary length of the bottom fluid

To track the nonlinear evolution of the interfaces, we derive a low-dimensional model for thin fluid layers by exploiting the long wave nature of the instability [4]. The evolution of a small initial perturbation, composed of an equal superposition of the two peak modes, is depicted in Figs. 1(b) and 1(c). In this simulation, both peak modes have grown simultaneously and each has dominated the evolution of a different interface. Further calculations show that the final pattern is sensitively dependent on the relative growth rates of the peaks, the initial perturbation and the time to breakup. Unlike single interface problems, the emergent pattern is not simply related to the fastest growing linear mode.

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Stability of three-layered core-annular flow

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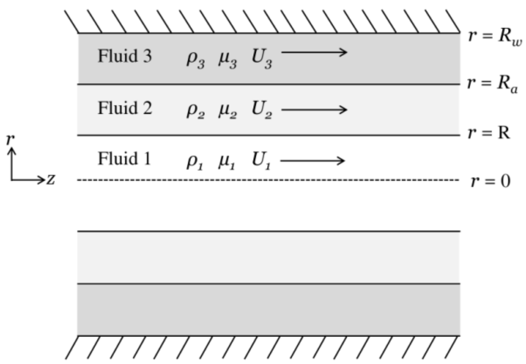
Three-layered co-axial flow of immiscible fluids in a confined channel are commonly employed in inkjet printing, synthesis of hollow metal spheres, encapsulated drops, double emulsions among others[1].In this work, we investigate the linear stability of three laminar fluids flowing coaxially in a confined circular channel. We retain the viscous effects in each fluid phase, neglect the effects of gravity and restrict ourselves to axisymmetric disturbances since they are expected to be the most unstable. A Chebyshev spectral collocation method with boundary-bordering technique is used to solve the generalized eigenvalue problem [2].

A temporal stability analysis shows that the flow exhibits atleast 5 different modes of instability as shown in Fig 1. The observed modes of instability aresubjected to energy budget analysis to determine their dominant cause of origin. This reveals that the flow can exhibit two capillary modes (C_1 and C_2) associated with the capillary forces at each fluid-fluid interface as well as three Reynolds stress modes (R_1, R_2 and R_3) associated with the base velocity gradient within in the bulk of each fluidas possible causes of instability.It is shown that the degree of confinement can stabilize two Reynolds stress modes. When there is no confinement of the outer annulus only the two capillary modes can become unstable. For intermediate confinements, instabilities can arise from the two capillary and three Reynolds stress modes

Further, a spatio-temporal stability analysis is carried out to predict the convective-absolute transition of this flow system. Encapsulated drops are possible to obtain only when the system shows convective instability. Thus, convective-absolute transition of instability helps in predicting the parameter space associated with encapsulation.



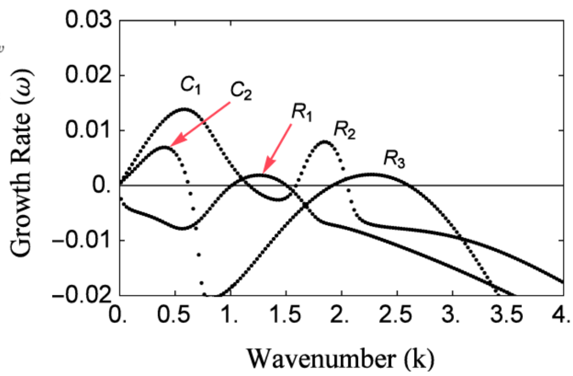


FIG. 1.Three-layered core annular flow.**Left**: Schematic; **Right**: Temporal modes of instability (Two capillary and three Reynolds stress modes)[We_1=200, ρ_{21}=0.3, ρ_{31}=0.3, μ_{21}=0.8, μ_{31}=0.6, α=1.5, H=2.75, σ=1].

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Thermocapillary instability of a liquid layer on interior surface of a rotating cylinder

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Stability problem of a liquid partially filling a cylinder, which rotates with constant angular velocity ω, is considered. Isothermal problem was studied in [1–5]; see also references to [4, 5]. In this paper, the flow is assumed to be non-isothermal. Radial heat flux is provided by the temperature difference between solid and free boundaries of a liquid layer. Besides, we suppose that gravity force is absent. The basic solution to the Navier-Stokes and heat conduction equations in cylindrical coordinates has the form $\overrightarrow{V} = (0, \omega r, 0)$, $p = \rho\omega^2 r^2/2 + p_0$, $T = T_1 \log(r/r_2) + T_0$, where p_0, T_1, T_0 are constants. Surface $r = r_2$ is free one. It is known that region of stability with respect to plane disturbances exists [5]. It turned out that axisymmetric disturbances of basic flow are capable to destabilize it. Neutral disturbances are considered in analogy with [6], where Marangoni number was taken as the spectral number. The temperature at the free boundary satisfies the condition of the third kind with a given Biot number. Independent dimensionless parameters of the problem are $a = r_1/r_2$ (aspect ratio), $\mathrm{Ma} = \kappa\delta T r_2/\rho\nu^2$ (Marangoni number), $\mathrm{We} = \rho\omega^2 {r_2}^3/\sigma_0$ (Weber number), $\mathrm{Bi} = \beta r_2$ (Biot number), $\mathrm{Cr} = \kappa\delta T/\sigma_0$ (crispation number), $\mathrm{Pr} = \nu/\chi$ (Prandtl number). Critical values of parameter Ma are obtained for various wave numbers, when other parameters are fixed. Besides of Pearson-type instability, there exists long-wave capillary instability, which also takes place for isothermal flow. As for instability due to buoyancy force, it can arise for very large Prandtl numbers only.

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Surface instabilities in vibrating thin fluid films

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We study the formation of vibration-induced surface instabilities on a thin, toroidal fluid layer (periodic boundary conditions) located on a horizontal, planar substrate. The spatiotemporal evolution of the liquid is simulated numerically, whereby the underlying model is obtained from the incompressible Navier-Stokes equations considering the limit of a thin fluid geometry and using the lubrication approximation. The investigated system is subjected to various saw-tooth, harmonic and superposition of two harmonic excitations, respectively, which can be descripted either as vibrations of the substrate or as time-periodic external force field. The model takes into account inertia and viscous friction. For excitation amplitudes above a certain threshold, the free surface of the fluid forms three-dimensional, time-dependent waves (Faraday instabilities). A Floquet analysis is used to determine the stability of the linearized system which takes the form of a damped Mathieu equation. After a certain amount of time, the system converges to a time-periodic final sequence of states, depending on the initial conditions, fluid properties and form of the external forces. Harmonic excitations in normal direction generate the experimentally already known hexagonal patterns for low frequency ranges, oscillating with the driver's frequency (ω), and subharmonically ($\omega/2$) oscillating square structures at higher frequencies [1]. In case of superpositions of two harmonic vertical forces, due to wave vector interactions we find more complex squarelike and quasiperiodic patterns for appropriate initial conditions (see fig. 1). Additional lateral excitations act as disturbance and, in case of a saw-tooth oscillation, we can generate a horizontal controllable movement of the patterns.

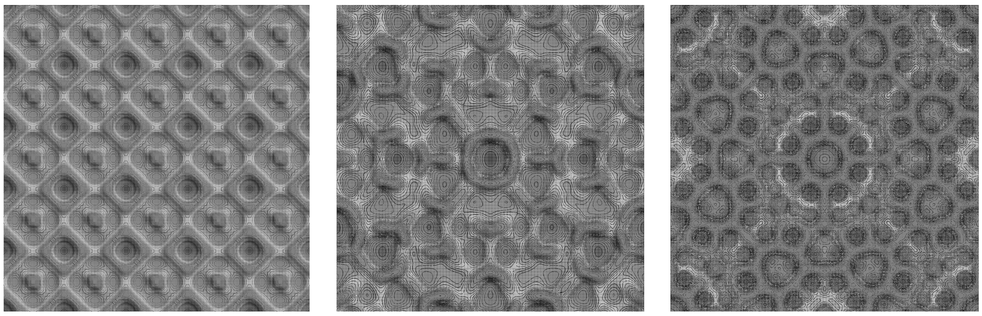

FIG. 1: Faraday instabilities for various excitations with two different harmonic oscillations. Square structures (left) usually received for random initial conditions and quasiperiodic patterns (middle) resulting from point-symmetric initial conditions (small disturbance in the middle of the layer).

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Universal Power Law Behavior for the Marangoni Contraction of Evaporating Sessile Droplets of Binary Mixtures

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Experimental results on theMarangoni contraction of evaporating sessile drops of binary solvent mixtures are presented, analyzed and compared to simulation results.

The evaporation rate of sessile drops is locally non-uniform. It increases towards the periphery (thecause ofthe coffee ring effect). With mixtures of a nonvolatile component (carbon diols) of a lower surface tension and a volatile component (water) of a higher surface tension this evaporation behavior causes a surface tension gradient and thus an inward Marangoni flow[1]. This flow can lead to an apparent contact angle $\Theta > 0$ ("Marangonicontraction"), even if both liquid components individually wet the substratecompletely. The contraction is quasi-stationary for a rather long time (compared to typical spreading processes) with a quasi-constant,apparent contact angle. We presenta new, universal power law relation between the apparent quasi-constant contact angle and the solvent properties (volatility), the solvent mass fractions, and the vapor environment (evaporation rate). The experimental findings are in quantitative agreement with numerical simulations.

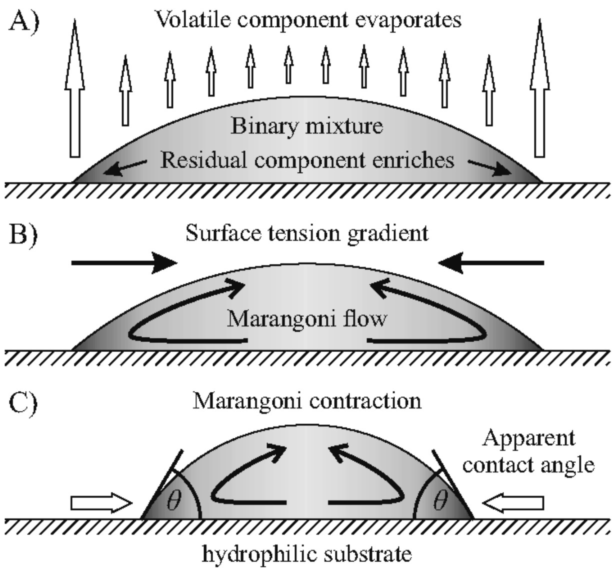

FIG. 1.Drop of binary solvent mixture of a volatile and a non-volatile component. If the nonvolatile component has a lower surface tension, upon locally non-uniform evaporation (as it is characteristic for sessile drops), a Marangoni flow is directed towards the center of the drop. This leads to an increase of the contact angle ("Marangoni contraction").

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On the role of the heat transfer in modelling axisymmetric particle accumulation in thermocapillary liquid bridges

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The trajectories of finite-size particles in the axisymetric flow in a thermocapillary liquid bridge are investigated numerically. Due to the driving of the flow by thermocapillary shear stresses the streamlines are very dense in proximity of the free-surface. This implies a significant percentage of particles initially randomly distributed in the fluid domain to be advected very close to the free-surface within a given time. Hence, the interaction of particles with the free surface is a frequent event and plays an important role in determining the particles' trajectories and, thus, particle accumulation structures (PAS).

Owing to these characteristics of the thermocapillary flow a dedicated model for the particle–free-surface interaction (PSI) is required if particle trajectories are to be calculated accurately by a numerical method based on the one-way-coupling approximation. A basic PSI model has been introduced by [1]. In their ad-hoc approximation the centroid of a spherical particle is prevented to approach the free surface closer than its radius. Recently, this basic PSI model has been corrected by taking into account the lubrication film between the particle and the free-surface [2]. A comparison with experiments on particle accumulation structures (PAS) in a quasi-axisymmetric liquid bridge shows a significant improvement: taking into account the lubrication gap between the particle and the liquid–gas interface both the radius of the particle depletion zone and the minimum distance of the particle from the free surface are predicted much more accurately [4].

In the present study we investigate the influence of the heat transfer between the liquid bridge and the ambient atmosphere on the axisymmetric flow and thus on the particle's trajectory and turn-over time. To that end the heat transfer is modelled by Newton's law assuming a constant ambient temperature. Two-dimensional PAS is determined numerically using the Maxey–Riley equation supplemented by the PSI model of [2]. The result obtained are compared with experiments using 2 cSt silicone oil [3, 4].

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Chemically-driven convection around autocatalytic fronts in parabolic flights

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When traveling in horizontal solution layers, autocatalytic chemical fronts can induce both buoyancy-driven and Marangoni-driven convective flows arising from concentration and thermal gradients across the front (see Fig. 1 left)). This chemically-induced convection can, in turn, deform and accelerate the propagation of the front. On earth, both types of flow can act in solution layers open to the air [1,4] while only buoyancy effects operate in covered liquid layers [5]. Here, we analyze the respective effect of density and surface tension induced convective motions by studying the propagation of autocatalytic fronts in both covered and uncovered liquid layers during parabolic flight experiments. In such a situation, the gravity field is modulated periodically and we observe that the propagation velocity of the front and its deformation are increased during hyper-gravity phases and reduced in the microgravity phase (see Fig. 1 right). We numerically integrate a model coupling the incompressible Navier-Stokes equations for the flow field to reaction-diffusion-convection equations describing the evolution of the concentration of the autocatalytic product. A comparison between the experimental and numerical results allows for a better understanding of the propagation dynamics of the front in a modulated gravity field [6].

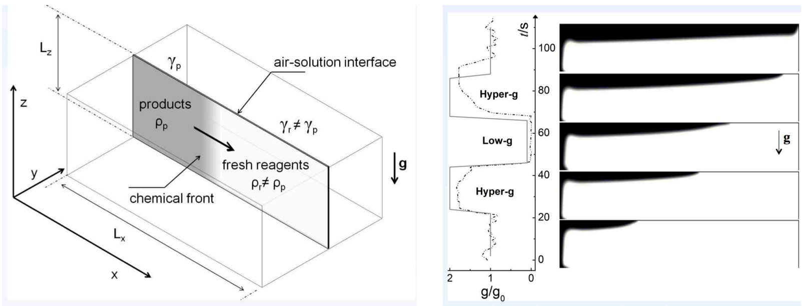

FIG. 1: (left) Sketch of the set-up. (right) Numerical results: Concentration of the autocatalytic species at $t = 22$ s, 44 s, 66 s, 88 s and 110 s (from bottom to top), during a single parabola in an uncovered reactor. The dynamics is driven by both Marangoni and buoyancy flows, with a slowing down of the buoyancy effect in the low-g phase.

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The Marangoni effect on small-amplitude surface capillary waves in viscous fluids

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Viscous capillary waves in freely oscillatory systems admit non-linear transient behaviours typically elusive to normal mode analysis [1], where the approximation of the solution as the least-damped mode is unsatisfying. Prosperetti [2] recast the equations of motion for viscous fluids as an integral-differential initial value problem (IVP) for the wave amplitude which yields the small-time transient behaviour whilst being equivalent to the normal mode approach in regions where the waves are damped out.

We investigate the behaviour of the viscous capillary waves with the Marangoni effect due to the presence of a surfactant solution in concentration below the critical micelle concentration (CMC) by deriving a more general form of the IVP, which is solved analytically in the case of a diffusion-controlled surfactant. Comparisons are made with the Marangoni-free result for a range of viscosities in different damping regimes for various values of the Schmidt number $\mathrm{Sc} = \nu/D$, where ν is kinematic viscosity, D is surfactant diffusivity, and wavelength λ.

In thin films such as that of a soap bubble, the soluto-Marangoni effect, in addition to contributing to the overall damping mechanism in the Levich sense [3], is also crucial to its stability. And the determination of critical wavelength λ_c at which surface waves become damped could help shed light on the understanding of the onset of the rupture process. Above the CMC limit (while surfactants still remaining dilute), we explore the destructive effect of the evolving micellar structures [4] on capillary wave stability.

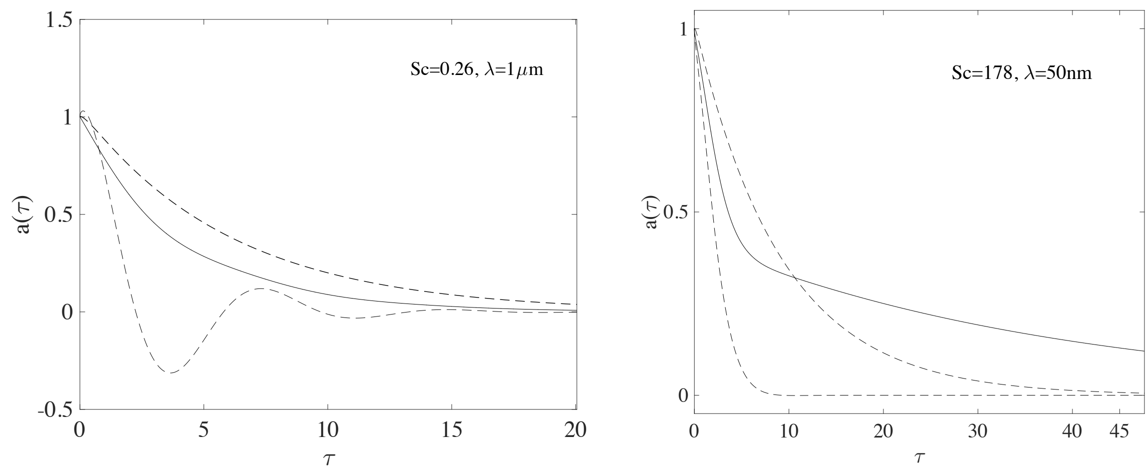

FIG. 1: (dashed) Marangoni-free analytical solutions for wavelengths (left) $1\mu\mathrm{m}$ and (right) $50\mathrm{nm}$ with viscosities $\mu = \mu_0$ (bottom dashed) and $\mu = 4\mu_0$ (top dashed) where μ_0 correspond to the viscosity of water at room temperature. (Solid) Analytical solution with Marangoni effect using (left) $\mathrm{Sc} = 0.26$, $\mu = \mu_0$ and (right) $\mathrm{Sc} = 178$, $\mu = \mu_0$

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Instability of thermocapillary-buoyancy convection in weakly evaporating liquid.

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The variation in temperature of a liquid-gas interface results in the formation of surface tension gradients which induce tangential stresses, known as Marangoni stresses. The thermocapillary flow associated with Marangoni stresses may lead to instabilities for the first time experimentally observed by Schwabe [1]. The stability of the thermocapillary flow has been studied extensively in the geometry of a thin liquid layer and in a cylindrical liquid bridge. Lately, the effect of ambient gas on the stability of aflow inside a liquid bridge has become an object of investigation. The results of a numerical study on instability caused by a gas stream along the interface of an axisymmetric liquid bridge [2] have shown that the cooling of the interface may cause Pearson-like type of instability prior to the appearance of typical hydrothermal waves. This study is connected to the microgravity experiment JEREMI (Japanese European Research Experiment on Marangoni Instabilities) where the use of a forced coaxial gas stream is proposed to control the hydrothermal instabilities in liquid bridges.

We present an experimental study on flow stability in a liquid bridge whose interface is surrounded by gas with well-controlled temperature. The experiments are conducted in ground laboratories where the stationary flow appears at arbitrary tiny values of imposed ΔT due to thermocapillary stresses and evolves under the action of both Marangoni and buoyancy forces. We have observed that the appearance of oscillatory flows depends on the temperature of the surrounding gas as well as the mean temperature of the liquid. The experimental observations are supported by two-phase non-linear numerical simulations.

The working liquid (n-decane) is weakly evaporating and the chamber with gas around the liquid bridge is large, thus, vapour diffusion is not the rate-limiting mechanism for evaporation. The evaporation is faster if the liquid on the interface is warmer. Our set-up provides the possibility to change the mean temperature of the liquid and, consequently, the temperature of the interface. The role of evaporation in the stability of a thermo-capillary flow is quite complex: on the one hand, it stabilizes the flow by removing heat from the interface; on the other hand, it destabilizes it by inducing higher thermal gradients along the interface. Our experiments have shown that the increase of the mean temperature destabilizes the flow. Figure 1 shows the evolution of the frequency of temperature oscillations with the increase of ΔT at different mean temperatures. The strongly non-linear behavior of the frequency with ΔT provides a hint that different regimes of instability may occur.

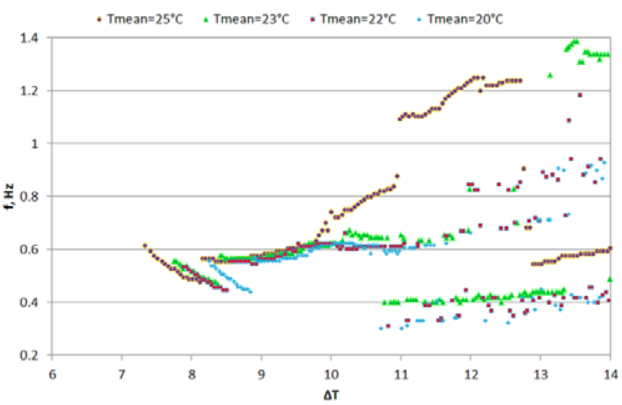

Fig. 1.Evolution of frequency with ΔT in a liquid bridge of constant volume when the mean temperatures are: T_{mean}=20°C (blue rhombi), 22°C (magenta squares), 23°C (green triangles) and 25°C (brown circles).

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Marangoni Convection Instability in a Sessile Droplet on Heated Substrate

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I. ABSTRACT

In order to investigate the Marangoni convection instability caused by surface tension gradient in a sessile droplet on heated substrate, a series of three-dimensional numerical simulations are carried out in a wide range of Marangoni number from 0 to 9935.8. A low volatile fluid of 1cSt silicone oil is adopted and thus the mass loss and deformation of the droplet due to evaporation are neglected. In contrast to the previous works[1-2], we consider that both Bénard-Marangoni instability and thermocapillary convection instability are possible because the tangential temperature gradient as well as the normal temperature gradient are coupled spontaneously and they always coexist in sessile droplet due to its curved surface. Thus, the Marangoni convection instability in a sessile droplet will be more complex than that in the flat liquid layer and need to be further studied. The simulation results show that four kinds of convection modes occur in sequence in the droplet with the increase of the Marangoni number: i.e. steady thermocapillary convection, oscillatory thermocapillary convection, steady Bénard-Marangoni convection and irregular oscillatory Bénard-Marangoni convection, respectively. The characteristics of each kind of convection mode have been described and the critical Marangoni numbers for the incipience of the unstable modes are determined. One of the most interesting phenomenon is that the shape of the Bénard-Marangoni cell in the sessile droplet is not hexagonal but circular except for the linked boundary, which is different from that of the classical Bénard-Marangoni cell in flat liquid layer.

II. TYPICAL RESULTS

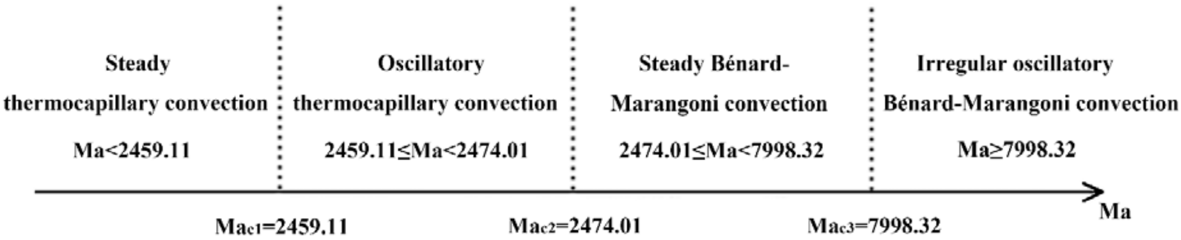

FIG. 1. Four kinds of convection modes within the *Ma* between 0 and 9935.8. Here the Marangoni number is defined by the temperature difference between the substrate and ambient.

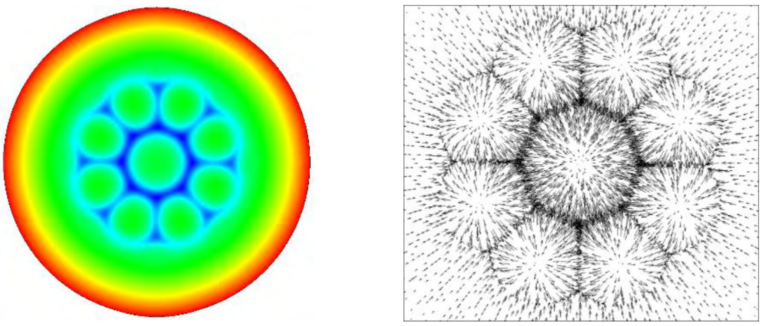

FIG. 2. Temperature distribution and velocity field on the droplet surface when the *Ma*=4471.11. Left: temperature distribution; Right: velocity field at the center of free surface.

Acknowledgements: This work was supported by National Natural Science Foundation of China (grant No. 50976128 and No. 51176210).

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CFD Simulation of Colloid Evaporation in Confined Convective Coating

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Convective assembly coating based on the evaporation of a colloidal suspension including nanoparticles has been extensively investigated as a novel fabrication method for micro- and nano-structures in the last decade, as reviewed by Wang and Zhou [1]. The convective assembly has been further improved employing a confined geometry, such as between two parallel plates, for rapid and well-controlled fabrication of micro film structures. However, a general predictive model for the confined convective coating has not yet been developed due to the complexity of the evaporating interface phenomena coupled to the heat and mass transfer in the liquid-gas phases and the particle deposition near the liquid-gas-solid contact line.

The present numerical approach is based on a sharp-interface level-set (LS) method for liquid film evaporation and particle distribution in dip coating developed in our previous work [2] and extended for the confined convective coating. The liquid-gas interface is tracked by the LS function ϕ, which is defined as a signed distance from the interface. The conservation equations of mass, momentum, energy and vapor mass fraction for the liquid-gas region are solved employing a calculation procedure for the coupled interface conditions for the temperature, vapor fraction, particle concentration and evaporative mass flux. The particle distribution in an evaporating colloidal suspension is also determined from the conservation equation of particle concentration Y_p and the boundary conditions for contact angle (θ_w) and particle deposition at the solid surface *(y=0)*, which are expressed as

$$\frac{\partial Y_p}{\partial t} + \mathbf{u}_l \cdot \nabla Y_p = \nabla \cdot \hat{D}_l \nabla Y_p \quad \text{if } \phi > 0; \qquad (u - U) \cdot \mathbf{n} Y_p = \hat{D}_l \nabla Y_p \quad \text{if } \phi = 0 .$$

$$u = u_w, \quad v = 0, \quad T = T_w, \quad \frac{\partial \phi}{\partial y} = -\cos\theta_w, \quad \hat{D}_p \frac{\partial Y_p}{\partial y} = k_d Y_p \quad \text{at } y = 0 .$$

CFD simulation is performed for the evaporation of a colloidal suspension between a lower moving plate and an upper stationary plate. The results are plotted in Fig. 1. The computation demonstrates liquid circulation due to plate movement, vapor expansion caused by non-uniform evaporation and particle accumulation near the contact line. The LS method is proved to be applicable to investigation of the effect of plate velocity on the particle deposition pattern in the confined convective coating.

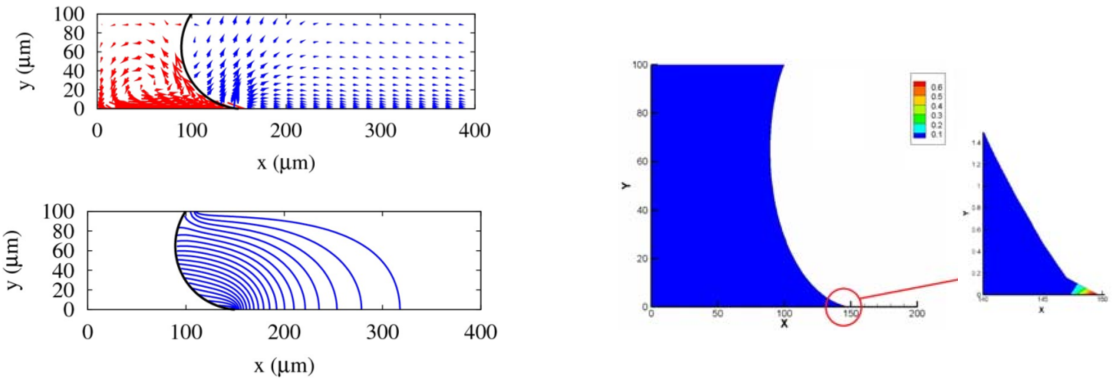

FIG. 1. Colloid evaporation in convective coating: velocity, vapor fraction and particle concentration fields.

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Printable Electronics and Photonics Based on Nanoparticles

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Nanoparticles have aroused great attentions due to their board applications. The research and development of pigment nano-particles has greatly improved the performance of printing products. With deep studying the mechanism of droplet spread and drying, which refer complex interfacial fluid dynamics/processes andsurface chemistry control, we havedesignedmonodispersed nanoparticles with core-shell structure and developed severalsimple methods for preparing large-area polymer photonic crystals (PCs),[1]such as ink-jet printing and spray coating.[2]The as-prepared colloidal PCs possess high mechanical strength, controllable wettability and tunable stopbands. The extended applications of colloidal PCs are demonstrated in high density information storage, ultra-sensitive detectingand high-efficient catalysis.[3]

Based on preparation of nano-composite transfer materials and modification of surface structure and property of plate, we have developed a green platemaking process for printing, which avoids discharge of chemical pollutant during traditional platemaking processes.[4] The development of metal nanoparticle inks is expected to achieve a green revolution in printed circuit board industry, i.e. metal nano-particles could be applied as ink to print conductive circuit directly,[5] which simplifies the complicated preparation process of traditional photolithography method, and significantly prevents discharge of chemical pollutant. Over all, nanoparticles have shown promising prospects in industry, and will lead the printing industry into a new age of greenization and digitalization.[6]

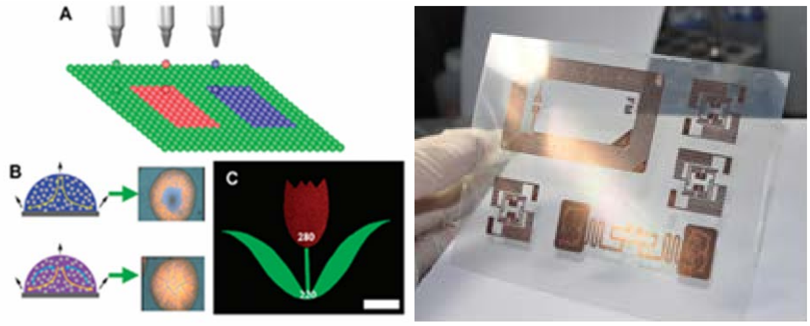

FIG. 1. Left: a photonic crystal pattern prepared by inkjet printing polymer nanoparticles; Right: printed flexible circuits on paper based on Ag nanoparticles.

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Free Drainage of non-Newtonian Foams

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Foams are multiphase colloidal systems, which are formed by trapping a gas in a continuous phase (a liquid or a solid).A flow of liquid in between the gas bubbles through Plateau borders, nodes and films in foam driven by capillarity and/or gravity is referred to as drainage.The drainage equations in the case of Newtonian liquids have been solved numerically and/or analytically in different prototype situations including free,forced, and pulsed drainage. A recently proposed type of these situations is foam drainage placed on a porous substrate [1, 2] where foam is in contact with a porous substrate and the presence of unsaturated pores inside the porous layer results in an imbibition of liquid from foam into the unsaturated pores.

Foams are conventionally stabilised by surfactants; however, polymers (polyelectrolytes) grow in popularity during the last decade as alternative stabilising additives to foaming solutions.In our previous Study [3,4] the influence of rheology of commercially available polymers AculynTM22 (A22) and AculynTM33 (A33) on foam drainage was investigated experimentally and the results of the properties modification (polymer type, concentration, mixtures, salt and iso-propanol addition) of A22 and A33 polymeric solutions were presented. Here a theory of foam drainage is presented for the non-Newtonian polymeric solutions in the case of free drainage and its results are compared with experimental data.

The deduced dimensionless equations are solved using finite element method with appropriate boundary conditions. The numerical simulations show that the decrease in the foam height and liquid content is very fast in the very beginning of the drainage; however, it reaches a steady state at long times (Fig. 1). Under the assumption of rigid surface of the Plateau border, the predicted values of the time evolution of the foam height and liquid content are in good agreement with the measured experimental data for lowly viscous polymeric solutions. However, in the case of highly viscous solutions an interfacial mobility at the surface of the Plateau border has to be taken into account.

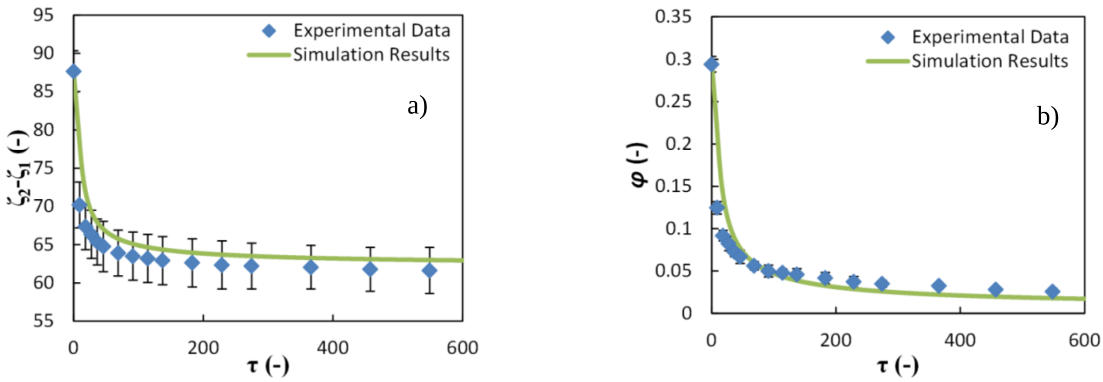

FIG. 1.Comparison of the predicted and experimental time evolution of a) the height of the foam, ζ2-ζ1, and b) the average liquid volume fraction along the foam height, φ, for A33_1.0% solution

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Influence of Marangoni-driven flows on A + B → C reaction-diffusion fronts

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When the two reactants of an A + B → C reaction are brought into contact, a reaction front is formed and the spatially localized zone where the reaction occurs evolves in time due to the interdiffusion of A and B. The properties of such fronts are well studied in reaction-diffusion systems where no flow can affect the dynamics [1, 2]. Here we consider horizontal aqueous solutions where the three species A, B, and C can affect the surface tension of the solution, thereby driving Marangoni flows (see Fig. 1). The resulting dynamics is studied by numerically integrating the incompressible Navier-Stokes equations coupled to reaction-diffusion-convection equations for the three chemical species. We show that the front propagation cannot be predicted anymore on the sole basis of the reaction-diffusion properties as was still possible in the presence of buoyancy-driven flows around such fronts [3]. We relate this observation to the structure of the Marangoni-driven flow. Based on an analytical description, we propose a classification of the convective effects on A + B → C reaction-diffusion fronts as a function of the different Marangoni numbers quantifying the effect of each species on the surface tension (see Fig. 2).

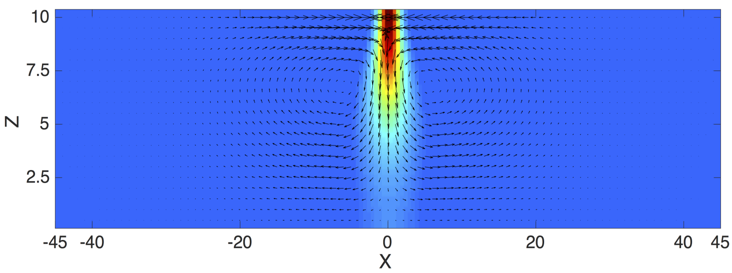

FIG. 1: Focus on the convection rolls centered on the reaction front shown at $t = 30$. The fluid velocity field is superimposed on a 2D plot of the production rate which ranges between its maximum value (reaction front), ab_{max} shown in red, and its minimum value, $ab_{min} = 0$, shown in blue. The $z-$direction has been magnified to see the details of the velocity field. The velocity vectors are here tripled compared to their effective length. The results are shown for $M_a = M_b = 40$, $M_c = 30$ and $ab_{max} = 0.050$, where $M_{a,b,c}$ are the Marangoni numbers of each species A, B, C.

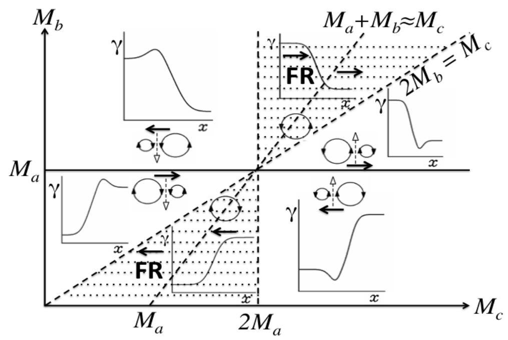

FIG. 2: Classification of the different observed dynamics in the (M_b, M_c) parameter plane at fixed M_a. Typical surface tension profiles as well as a sketch of the observed vortex dynamics are illustrated within the corresponding regions. The dark filled arrow indicates the initial direction of propagation of the front. For $M_c < M_a + M_b$ in the shaded regions, we surprisingly observe the possibility of a front reversal (FR), i.e. the front changes its direction in the course of time.

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Wetting properties of cosmetic polymeric solutions on hair tresses

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Hair care products are expected to wet hair well, even when the hair is hydrophobic (undamaged or covered with greasy deposits). Thus wetting properties of various cosmetic formulations on hair are very important, as they influence consumer satisfaction with the product. Wettability of a single hair fibre is an important characteristic; however, it may not be representative of a hair array on head, as it does not take into account complex packing of multiple hair strands. Also, wetting behaviour of polymer solutions on hair is less studied than the properties of surfactants. The objective of the present work is to investigate wetting of hair tresses with the solutions of two polyacrylate polymers broadly used in cosmetic products.
Rheology and wetting properties of the neutralized Aculyn22™ (A22) and Aculyn33™ (A33) polymer solutions on dry hair tresses are studied. Spreading kinetics of the solution droplets is analysed, including penetration, spreading and evaporation, as well as the influence of several additives common in cosmetic formulations [1].

The solutions of both polymers spread on hair tresses. However, they show markedly different behavior presented in Fig. 1.

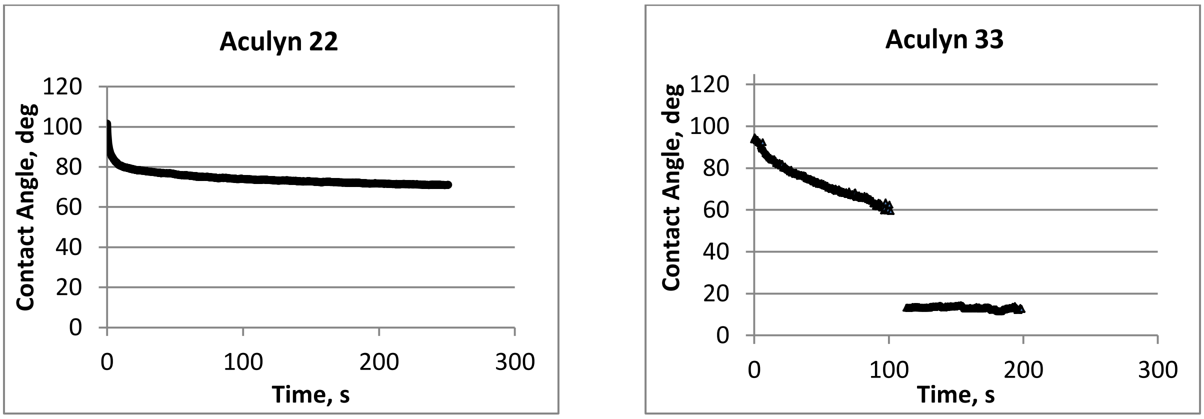

Figure 1. Contact angle of Aculyn 22 and Aculyn 33 solutions on a hair tress.

For the A22 solutions, the droplet remains on the surface of the hair for almost half an hour, and only slow (if any) imbibition is observed. For the A33 solutions, the complete penetration/imbibition happens fast, after the contact angle reaches a critical value (around 60°). This can be attributed to the so−called Cassie−Wenzel wetting transition, when the liquid starts to penetrate inside the hair array. The conditions for this transition are more favourable for the A33 solutions in comparison to the A22.

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Effect of Electric Field on Three-Layer Thermocapillary Instability

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Three-layer thermocapillary instability is well-known. In this paper, the liquids are allowed to have different physical properties and share deformable interfaces. They are assumed to flow in a channel due to an externally applied pressure gradient. The liquids are assumed to be leaky-dielectric and the applied electric field is normal to the flat interfaces between the liquids. The system is very rich in dimensionless numbers. The linear stability of the system is studied to delineate the interaction between the thermal and the electrical Marangoni numbers. The results would further our mixing abilities in microdroplets flowing in a microchannel. It is known that in the absence of an electric field, the effect of the deflecting interface and base Poiseuille flow on the critical Marangoni number are not negligible. These effects are now studied under the effect of an electric field. It is hypothesized that their effects might be magnified or diminished depending on the electrical parameters, i.e., electrical conductivity and permittivity ratios of the liquids.

Thin Film and Kinetic Monte Carlo Modeling of Rayleigh-Plateau Instabilities of Liquid Ridges

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We study the Rayleigh-Plateau instability of ridges formed by molecules on chemically pre-patterned substrates by means of microscopic Kinetic Monte Carlo (KMC) simulations and a mesoscopic thin film continuum model. A good qualitative agreement of the transversal instability observed in the continuum model with the dynamics observed in KMC simulations is seen on time- and length scales which are large compared to the scales of thermodynamic fluctuations. For both models, we consider a ridge on a single pre-pattern stripe and two weakly interacting ridges on neighbouring pre-pattern stripes.

For the continuum model, the eigenmodes and growth rates of the transversal instability are obtained by means of the numerical solution of a corresponding eigenvalue problem. The dependence of the dispersion relation on system parameters is investigated by employing numerical continuation techniques. The results obtained for the thin film model are compared to direct numerical simulations of the KMC model through appropriate ensemble averages.

Furthermore, we discuss the possibilities of mapping the KMC model quantitatively to a model of the same gradient dynamics structure as the thin film equation through a mean field approach and the subsequent extraction of an effective interface potential.

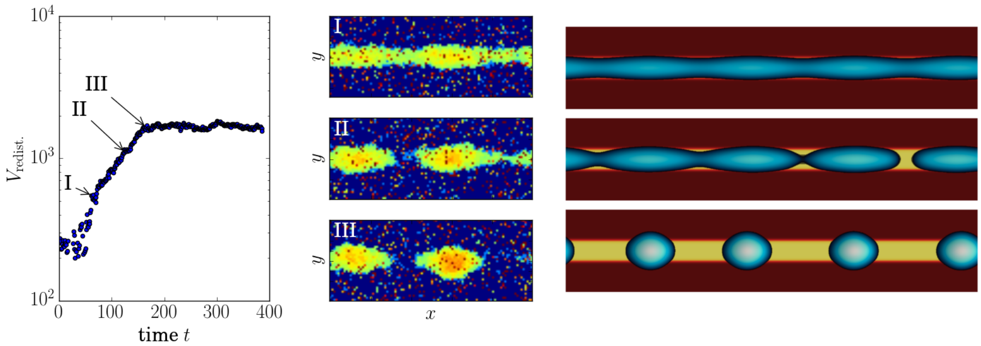

FIG. 1: Direct numerical simulations of transversal instabilities on pre-patterned substrates. Left and center: Results of a KMC simulation, namely, the evolution of the transversally redistributed volume for the dominant wavelength and three corresponding snap-shots; Right: Numerical simulation of the thin film equation with chemical pre-pattern.

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CFD by TchebyFlow : from 19th Century to 21st Century

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CFD as it is known today was first introduced on 1944 at Los Alamos. Since then it has been widely used in many different fields of research and industrial applications. Many different families of methods can be designed for solving CFD problems. One of these families (Spectral methods) comes directly from the Theory of Approximation which dates back from 19th Century. TchebyFlow utilizes this mathematical framework with the current computation power. This allows us to produce the numerical solutions for today's and tomorrow's problems, with efficiency and with a controlled and unlimited level of accuracy. Our developments currently make it possible to solve diffusion and flow problems for academic research and industrial applications. Many applications can be treated, such as direct turbulence simulation, or also, for example, diffusion and flow in non-orthogonal geometries, for multiphase configurations.

From laser-induced self-organized structures to wettability and controlled liquid pattern formation

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Wettability properties of large areas covered with laser-induced self-organized structures (LIPSS, ripples) generated upon femtosecond multipulse ablation (100 fs @ 800 nm) on stainless steel surfaces were investigated in this work.

Dependent on the applied irradiation dose, characterized by laser fluence and scanning speed, surface morphologies with different spatial characters have been observed at the irradiated area, from uniform high-periodic linear structures with lateral periods about of 500 nm to complex arrays of patterned cones with a feature size up to 3.5 µm. Contact angle (CA) measurements on the laser treated samples reveal an abrupt change of wettability from hydrophilic (CA slightly above 20°) to high-hydrophobic (CA about 120°) in dependence on the laser induced surface morphologies.

Drops and thin liquid layers on such patterned surfaces have been already theoretically investigated by using appropriate boundary conditions in the frame of a phase field formalism [1, 2].

Phase field models are continuum thermodynamic approaches, successful in many instances with complex structures or complicated boundary conditions. With the help of a supplementary variable (phase field), all system parameters are expressed as functions varying continuously from one medium to another with a rapid but smooth variation across interfaces. For a liquid-vapor system the most natural phase field is the fluid density ρ (fluid density ρ=1 characterizes the liquid bulk and ρ=0 the vapor). The two-phase problem is treated like an entire and the interface conditions are substituted by some extra terms in the Navier-Stokes equation. The theoretical description is based on the Navier-Stokes equation and the continuity equation. The contact angle is controlled through the density at the solid boundary ρ_S, a free parameter varying between 0 and 1, achieving thus static contact angles between 0° and 180° [3].

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Theoretical and experimental study of Faraday instability in electrostatically forced systems

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To date, extensive theoretical and experimental research on mechanically forced Faraday instability has been conducted. However, Faraday instability resulting from electrostatic forcing remains a largely unexplored area of research. In this work, we first present a theoretical model for the prediction of Faraday instability thresholds in electrostatically forced bi-fluid systems derived via linear stability analysis. The approach is modeled after that of Kumar and Tuckerman [1], with additional terms added to account for the nature of the electrostatic forcing. The fluids are considered to be viscous, leaky dielectrics and are forced by an oscillatory voltage drop imposed over a constant voltage drop across the fluids. The instability arises as a result of an imposed oscillatory electric field generated by the voltage drop, which provides both body and surface forces on the system. Stress-free conditions are used for the sidewalls, with hope that this boundary condition can be successfully approximated with appropriate fluid choices similar to those used by Batson et al. [2].

Next, we present experimental data obtained using the electrostatic levitator at the Japan Aerospace Exploration Agency (JAXA) in Tsukuba, Japan. These experiments have successfully generated Faraday instability in liquid-air electrostatically oscillated systems. The design and methodology for the experiments are discussed, in addition to experimentally mapped stability curves. High-speed videos of captured modes are also shown and compared to theoretically predicted eigenfunctions. The experiments presented utilize cylindrical geometries constrained radially by insulating sidewalls and axially by externally controlled electrodes. Distinct physics obtained by eliminating the constant voltage drop are also discussed. The subharmonic responses indicative of Faraday instability are observed experimentally, and only supercritical bifurcations have been observed to date. To conclude, distinctions and commonalities between mechanical and electrostatically forced Faraday instability are highlighted.

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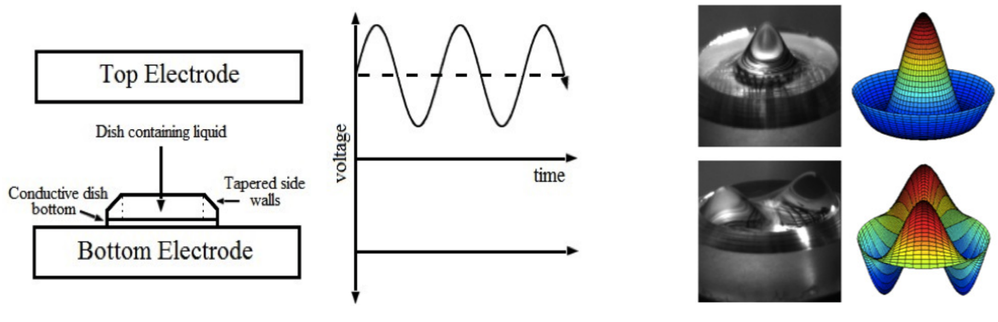

FIG. 1: Left: Schematic of JAXA electrostatic levitator apparatus and applied voltages; Right: Experimentally observed electrostatically excited Faraday modes. The graphical representations on the right show the theoretical predictions for the mode shapes.

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Enhancement of contact line mobility by infrared laser illumination

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The shape of a droplet moving over a solid substrate is determined by the mobility of its contact line [1]. Above a critical speed, the droplet will disintegrate and leave behind residual liquid.

We have experimentally studied how infrared laser illumination can be used to control the shape of the droplet and to increase the critical speed [2]. Fig. 1 shows the experimental setup. A droplet (ethylene glycol) is attached to a concentric needle. A polycarbonate substrate is rotated underneath the needle with speed U_{sub}. An infrared (IR) laser beam with an elliptical intensity profile is located close to the receding contact line of the droplet. By means of two CCD cameras, we obtain bottom-view and side-view images of the droplet.

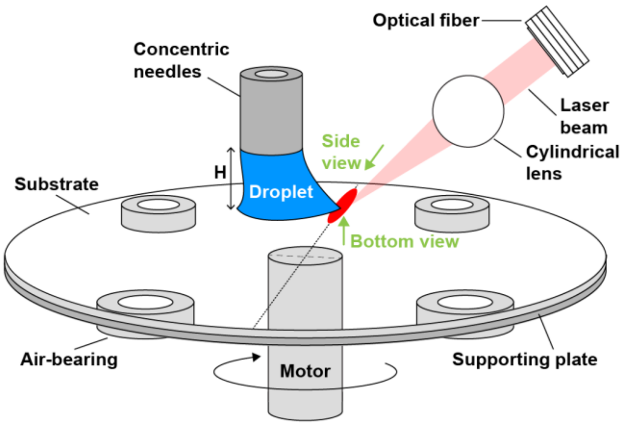

FIG.1. Schematic experimental setup.

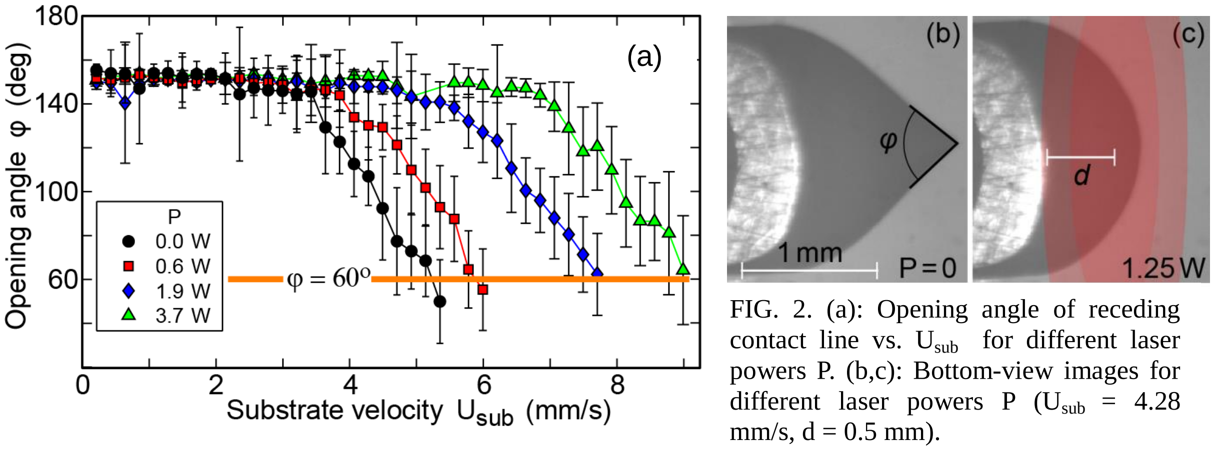

FIG. 2. (a): Opening angle of receding contact line vs. U_{sub} for different laser powers P. (b,c): Bottom-view images for different laser powers P (U_{sub} = 4.28 mm/s, d = 0.5 mm).

Fig. 2(b,c) show two typical bottom-view images. The red ellipse in Fig. 2(c) schematically indicates the IR intensity distribution, where *d* is the distance between the outer edge of the needle and the position of maximum intensity. From the bottom-view images, we obtain the opening angle φ of the receding contact line (indicated in Fig. 2(b)). A higher laser power results in a more rounded contact line. Fig. 2(a) shows the opening angle φ vs. U_{sub} for different laser powers. For larger values of U_{sub} the droplet obtains a more pointed shape. When φ reaches approximately 60°, the droplet will leave behind residual liquid. The speed at this point is the critical speed. Fig. 2(a) shows that the critical speed significantly increases with increasing laser power. We also studied the effect of the distance *d*.

The non-uniform temperature distribution influences the receding contact line by thermocapillary Marangoni stresses and by a reduction of the liquid's viscosity. We developed a 2D numerical model that couples the fluid flow and heat transfer near the receding contact line with the dynamics of the contact line [3]. Although the experiments are intrinsically 3D in nature, the 2D model reproduces the experimental data for the critical speed reasonably well.

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Infrared laser induced thermocapillary deformation and destabilization of thin liquid films

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A thin liquid film on a partially wetting substrate can be destabilized by means of an air-jet [1]. The film will typically rupture at multiple points leading to residual droplets on the substrate. In this study, we deform and rupture thin liquid films by means of infrared (IR) illumination [2,3].

Fig. 1 shows a schematic image of the experimental setup. We deposit a thin liquid film of a non-volatile liquid on a wetting or partially wetting substrate by spin-coating. During the experiment, an IR laser beam heats up the substrate and liquid film while the substrate is rotating. This will induce a non-uniform temperature distribution that drives the thermocapillary flow of the liquid. We measure the deformation of the thin film using dual-wavelength interference microscopy.

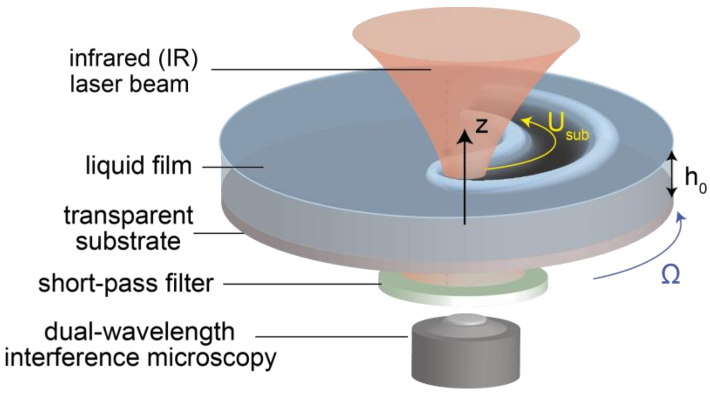

FIG.1. Schematic experimental setup (not to scale).

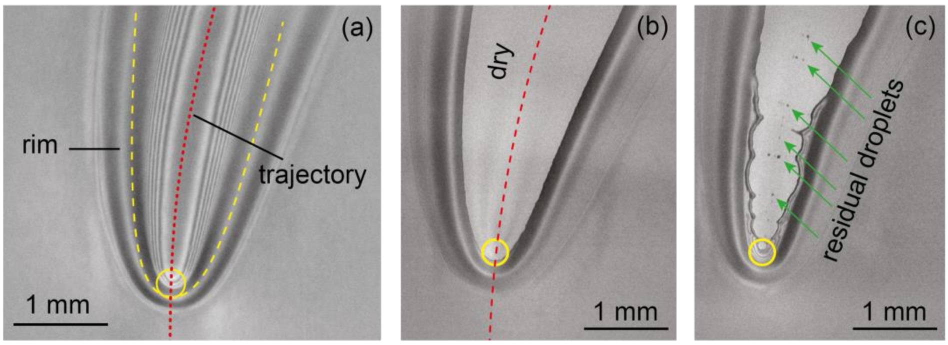

FIG. 2. Interference micrographs of (a) the deformation on a wetting substrate and (b,c) the deformation and rupture on a partially wetting substrate for different substrate speeds.

Fig. 2(a) shows the deformation of the thin film on a wetting substrate. The substrate speed U_{sub} was 5 mm/s, the laser power P = 8 W. The yellow circle indicates the size and position of the laser beam. The red line indicates the trajectory of the laser beam. We studied the effect of P and U_{sub}.

Fig. 2(b,c) shows the deformation and break-up of the thin film on a partially wetting substrate. In both cases P = 8 W whereas U_{sub} was 5.3 mm/s for (b) and 8.2 mm/s for (c). Fig. 2(b) shows that a completely dry track is formed along the laser trajectory. The first dry-spot rapidly dewets the substrate, up to the rim of the deformation. This prevents the formation of other dry-spots. However, when we increase the substrate speed (Fig. 2(c)) we see that residual droplets are deposited on the substrate. We measured the critical substrate speed at the transition from the 'dry'-regime to the 'residual droplets'-regime for different laser powers.

We developed a numerical model that combines heat transfer with thin liquid film dynamics, based on the lubrication approximation and a phenomenological expression for the disjoining pressure. Our simulations reproduce the experimental data for the critical speeds well.

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Solutions of Different Symmetry and their Parametrization for Long-Wave Model of Marangoni Convection from Localized Heat Inhomogeneity

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The problem of Marangoni convection caused by heat source localized in the horizontal plane in a thin horizontal layer of viscous incompressible fluid with a free surface and the rigid thermally insulated bottom is considered in the long-wave approximation [1]. Amplitude equations contain temperature, deformation of the surface and vorticity. Simplifying the full problem, the sequence of the more simple equations are derived, starting from linear Schrodinger equation with localized potential determined by the form of the heat source inhomogeneity, and including non-linear equations assuming undeformable free surface and those with account of surface deformation. The equations are investigated numerically. Stationary and non-stationary solutions of nonlinear amplitude equations are obtained by pseudospectral method.

Properties of solutions being common to the whole sequence of approximation are identified. Dependence of parameters of the linearized system solutions is characterized by the presence of break points of the second kind with unlimited growth or decay of a solution. Characteristic feature of nonlinear problems is the existence of multiple solutions at fixed parameters, differing by number of local extrema. It is shown that under some form of thermal inhomogeneity self-similar solutions of nonlinear equations are possible. This allow to transform the evolution equations in partial derivatives to the ordinary differential equations.

Solutions of different symmetry could be realized depending on parameters and initial state, like in the case of homogeneously heated layer [2,3]. For local heating case they include localized solutions of axial and dipolar symmetry and more complex structures, including spiral waves, and global steady and nonsteady structures. Co-existence of patterns of different types of symmetry, including rotational, quasycristal and self-similarity can occur at some parameter ranges. In particular, global structures could be considered as composition of some patterns of rotational symmetry in the region around the local heating and global patterns of translational symmetry outside it, similar to those at homogeneous heating, namely formed by hexagons, squares and quasicrystal structures.

Based on the analysis of steady solutions [1] their evolution in time at change of parameters of system is studied numerically. Starting from state close to one of steady solutions, the change of contributions of structures of different symmetry and different scales is determined at different time instants and values of parameters, using wavelet based methods [4]. This parametrization allows to determine boundaries of stability domains of steady states and to evaluate important properties of symmetry and self-similarity of developing nonlinear patterns.

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Sliding Drops - Dynamics of Large Ensembles

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We analyze the dynamics of a thin liquid film on a substrate using the thin film equation for partially wetting liquids. When including a lateral driving force due to, e.g., an inclined substrate and gravity, structures described by the equation, like drops and ridges, begin to move. In addition, also stability properties of the structures can change. In particular, large drops may undergo a pearling instability, where they emit small satellite droplets until their volume is small enough to be stable [1].

We conduct direct numerical simulations on a large spatial domain in order to examine the interaction of many sliding drops. As the sliding velocity of the drops depends on their volume, larger drops overtake smaller drops and merge with them, possibly leading to an overall volume which is large enough for the pearling instability to occur. Studying a large ensemble, we find that this merging and pearling behavior can lead to a stationary distribution of drop sizes, whose shape depends on the inclination angle of the substrate and the overall volume of liquid in the system.

We explain the long-term evolution of the drop size distribution using stability properties of single drops obtained when studying families of droplet solutions with continuation techniques.

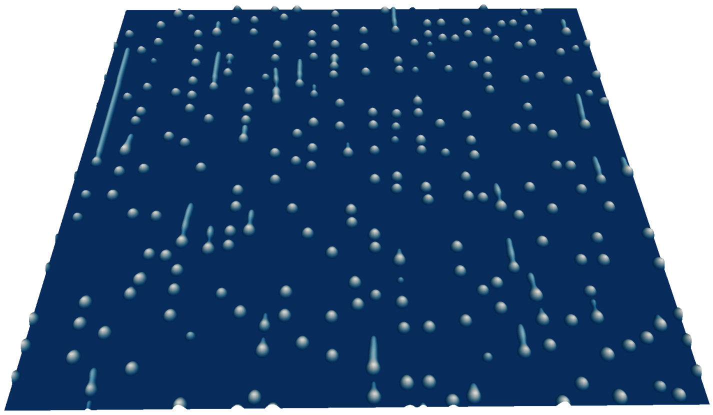

FIG. 1: Snapshot of a simulation of the thin film equation for an inclined substrate. While sliding downwards, the drops interact with each other, merge and split up, leading to an intricate dynamics of the drop size distribution.

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Effect of Interfacial Heating/Cooling on the Hydrothermal Wave of Thermocapillary Liquid Bridges of High Prandtl Number Fluids

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A series of microgravity (μg) experiments of thermocapillary convection in liquid bridge (LB) have been conducted to clear its instability mechanism since the utilization of the Japanese Experiment Module "Kibo" of the International Space Station (ISS) started in 2008, . LBs of high Prandtl number (*Pr*) silicone oil are suspended in the gap between the heated and cooled disks and their temperature difference (ΔT) is the driving force of thermocapillary convection. As reported by Nishino et al. [1], onset conditions of oscillatory flow were measured for a wide range of *AR* (i.e., *AR*=0.1-2.0) and *Pr* (i.e., *Pr*=67-207) on the ISS, where *AR* is the ratio of the LB height to the disk diameter. The stable high *AR* LB can only be realized under μg environments; therefore, to understand the instability of thermocapillary convection of high *AR* LB is the main target of the present μg experiments.

It is well known that traveling hydrothermal waves (HTW) appear when the ΔT exceeds a certain critical value but their characteristics for high *AR* condition are not clearly understood yet. The present study reports the effect of heat transfer at the liquid-gas interface on the HTW instability. Some previous studies [2] reported a striking impact of the interfacial heat transfer on the onset condition of oscillatory flow and we found that the interfacial heat transfer significantly affects the characteristics of HTWs. Figure 1 shows the surface temperature fluctuation measured with an IR camera at slightly super critical condition for *Pr*=112 and *AR*=1.50, where cooled disk temperature (T_C) for fig. 1(a) is 15°C and that for fig. 1(b) is 20°C. Note that axial position (*z*) is normalized by LB height (*H*) and time (*t*) is normalized by oscillation period (τ). It is recognized from fig. 1,the traveling direction of HTW is from the cooled disk side (z/H=0) toward the heated disk side (z/H=1) for T_C=15°C, while that for T_C=20°C is opposite. According to the numerical computation, the LB surface is heated by the ambient gas for T_C=15°C while cooled for T_C=20°C and it follows from these results that the traveling direction of HTW depends on the direction of interfacial heat transfer.

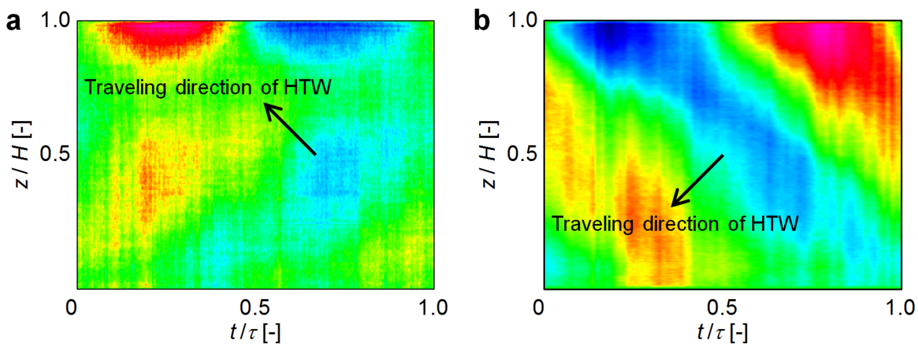

FIG. 1: Temperature fluctuation of liquid bridge surface for *Pr*=112 and *AR*=1.50; the cooled disk temperature is (a) T_C=15°C and (b) T_C=20°C.

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Numerical Study on Heat/Mass Transfer from a Neutrally Buoyant Sphere in Simple Shear Flow with Natural Convection due to Centrifugal Force

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Many multiphase transport, separation and reaction equipments with shear flow are being used for large scale chemical production. To understand the mass/heat transfer mechanisms, researchers investigate the mass/heat transfer from a neutrally buoyant particle in simple shear flow. The present study is focused on the effect of the natural convection due to the centrifugal motion of the surrounding medium, and the mass/heat transfer from the neutrally buoyant sphere immersed in a simple shear flow is investigated by using the body force term with the centrifugal force in Navier-Stokes to change the natural convection. Based on the previous study[1], the finite difference method with the control volume formulation and the Boussinesq approximation are applied to solve the time-dependent Navier-Stokes, continuity and mass/heat equations in the spherical coordinate system. Simulations of mass/heat transfer at zero Reynolds number and finite Grashof numbers agree with Geoola's prediction[2]. Through the changes of streamlines and the contours of the solute concentration, a deeper understanding of the effect of natural convection is achieved. The combined convection can be divided into three cases: the natural convection dominated process, the hybrid transfer process, and the forced convection dominated process. The simulated results of the natural convection dominated and forced convection dominated processes are consistent with the theory of the pure natural convection and pure forced convection cases. In the case of hybrid transfer process, the natural convection is weakened by shear flow which can take away the solute and diminish the density difference. In terms of the numerical results obtained in this work, the correlations are derived to predict *Nu* at *Pr*=constant for variable *Gr* and *Re*.

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Instability of a Liquid Ring in Binormal Direction

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Liquid ring is a sort of stream of matter widely encountered in nature, technology and basic science. For example, a toroidal drop or bubble could be gained by constant extruding liquid from a precise controlled injecting needle into a rotating base of some other immiscible liquid [1]. Once formed, the ring evolves and transforms by breaking up into small spherical droplets. This could be understood as a result of Rayleigh-Plateau instability.

Distortion of centerline during the evolution is another important but less comprehended phenomenon [2]. Once we create a model of liquid ring with a curvilinear coordinate system adhering to centerline, the distortion mainly in the binormal direction $\mathbf{b}$. In order to understand the mechanism, instability analysis is carried out by introducing perturbations a', B' and V'_τ, which represent the disturbance of cross section radius, centerline and mass transfer velocity, respectively. In addition, a quasi-steady-state hypothesis is claimed by assuming a sufficiently rapid development of perturbations.

The dispersion relation denotes the most unstable mode exist only when the ring is expanding [3]. At the same time, the ambient fluid, which is actually static, equivalently flows towards the ring center. If a binormal distortion $B' > 0$ ($B' < 0$) is imposed on, there will be a rotation $\Omega_\tau < 0$ ($\Omega_\tau > 0$) of the ring segment owing to the finite curvature effect. A velocity circulation is hereby created, together with a lift force brought by the ambient fluid which amplifies the perturbation. As consequence, the binormal distortion of centerline is strengthened. Of course, if the ring is shrinking, the force from ambience will become a restoring one which smooths the perturbation.

The analysis to weakly nonlinear stage could further explain the feature which a' and B' couple. The binormal translation effect, denoted by $\overline{V}_{a,b}$, should be considered. During an upward translation, which is equivalent to a downward blow of ambient fluid ($\overline{V}_{a,b} < 0$), the most unstable mode of instability belongs to the case where swell sections are raised upmost. In another word, an expanding ring always tends to destabilize with a' and B' synchronous in phase. Referring to the linear theory [3], this confirmation could be ascertained only after nonlinearity is taken into account.

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