IMA6 - 6th Conference of the International Marangoni Association

Interfacial Fluid Dynamics and Processes

June 18-21 2012, Haifa, Israel

Book of Abstracts

FACULTY OF MECHANICAL ENGINEERING 75

משרד המדע והטכנולוגיה
Ministry of Science & Technology
وزارة العلوم والتكنولوجيا

TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

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We appreciate Mrs. Irit Gertzwolf for her invaluable work on the numerous big and "little" issues without which the Conference would never have succeeded.

Alex Oron
On behalf of the Local Organizing Committee

The order of the abstracts included in this collection fits that of the appearance of the corresponding oral talk or poster in the Conference program.

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IMA6

6th Conference of the International Marangoni Association

Interfacial Fluid Dynamics and Processes

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Technical Program

FACULTY OF MECHANICAL ENGINEERING 75

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TEL AVIV UNIVERSITY אוניברסיטת תל-אביב

Reception and Registration Sunday 17/6 18:00-21:30

Monday 18/6 8:30-9:00 Registration and Coffee
Opening Session 9:00 -9:20 Chair: A. Oron

Session M1: Monday 18/6 9:30-10:30 Chair: R. Narayanan

9:30-9:45 R. Borcia and M. Bestehorn "Contact line dynamics, Marangoni flows and associated effects"
9:45-10:00 I. D. Borcia, R. Borcia, M. Bestehorn, C. Borcia, N. Dumitrascu "Contact lines in different geometries"
10:00-10:15 H. Riegler and S, Karpitschka "Marangoni effect from chemical gradients near contact lines"
10:15-10:30 S. Karpitschka and H. Riegler "Marangoni modified drop fusion and drop motion: thin film traveling wave description by asymptotic matching"

Session P1: Monday 18/6 10:30-11:00 Chair: A. Viviani

Short poster presentation (3 minutes each)

V.M. Starov and N. Ivanova "Surfactant-induced spreading of aqueous droplets over polymer substrates"
T. Lemee, R. Narayanan and G. Labrosse "Thermocapillarity instabilities in a free liquid film"
Y.-R. Li, L. Peng, and W.-Y. Shi "Flow pattern transition of thermocapillary convection in a differentially heated annular pool for moderate Prandtl number fluid under varying gravity level"
C. Hsueh, F. Doumenc and B. Guerrier " Evaporation of complex fluids in a Hele-Shaw cell"
L. Peng, L.-M. Zhou, Y.-R. Li and W.-Y. Shi "Global simulation of detached solidification under cusp magnetic field"
A. Ovcharova and N. Stankous "Influence of thermophysical properties of liquid on features of the rupture of film. The role of the Prandtl number
A. Lobasov, A. Minakov and V. Rudyak "Investigation of wall slipping influence on mixing efficiency and pressure drop in T-shaped microchannel at high Reynolds numbers"
V. Shevtsova, Y. Gaponenko, A. Nepomnyashchy "Oscillatory instability of thermocapilllary flow caused by gas stream along the interface"
T. Lyubimova and R. Skuridin "The influence of high-frequency vibrations on the stability of thermocapillary flow in the liquid zone"
K. Kanatani "Stability of a condensing liquid film of a binary vapor mixture"

Poster Session P1 and Coffee Break 11:00-11:45

Session M2: Monday 18/6 11:45-13:15 Chair: V. Pukhnachev

11:45-12:00 S. Semenov, V. M. Starov and R. G. Rubio "Evaporation of pinned sessile microdroplets of water: computer simulations"
12:00-12:15 F. Doumenc and B. Guerrier "Numerical simulation of an evaporative meniscus on a moving substrate"
12:15-12:30 F. Doumenc, E. Ch´enier, B. Trouette, and T. Boeck "Thermal and solutal Rayleigh-Benard- Marangoni convection induced by solvent evaporation in polymer solutions"
12:30-12:45 O. Goncharova and E. Rezanova "Mathematical modeling of the evaporating liquid films on the basis of the generalized interface conditions"
12:45-13:00 S. G. Yiantsios "Aspects of thermo-capillary and soluto-capillary instabilities in evaporating thin films"
13:00-13:15 A. Rednikov, H. Machrafi, P. C. Dauby and P. Colinet " Extremely unstable evaporative Benard-Marangoni systems: the role of transients in the gas"

Lunch 13:15-14:30

Session M3: Monday 18/6 14:30-16:00 Chair: G. P. Neitzel

14:30-14:45 A. B. Mikishev and A. A. Nepomnyashchy "Marangoni instability of a liquid layer with insoluble surfactant under heat flux modulation"
14;45-15:00 O. Haimovich and A. Oron "Nonlinear dynamics of a thin liquid film on an axially oscillating cylindrical surface subjected to double-frequency forcing"
15:00-15:15 M. Bestehorn and A. Oron "Thin film behavior under external vibrations"
15:15-15:30 I. Wertgeim, M. Kumachkov, and A. Mikishev "Parametrically excited Marangoni convection in a locally heated liquid layer"
15:30-15:45 D. Lyubimov and T. Lyubimova. "Long wave Rayleigh-Benard-Marangoni instability of a fluid layer with deformable free surface"

Poster Session P1 and Coffee Break 15:45-16:30

Session M4: Monday 18/6 16:30-17:45 Chair: M. Bestehorn

16;30-16:45 T. Pollak, C. Heining, and N. Aksel "Pattern formation and mixing in three-dimensional film flow"
16:45-17:00 D. Melnikov, D. Pushkin, and V. Shevtsova "Coherent accumulation structures formed by small inertial particles in periodic flows"
17:00-17:15 H. C. Kuhlmann, F. H. Muldoon, and R. Mukin "On the different manifestations of particle accumulation structures (PAS) in thermocapillary flows"
17:15-17:30 A. Povitsky and S. Zhao "Hybrid continuum-molecular modeling of filtration flows in the transition flow regime"
17:30-17:45 K. Schwarzenberger, K. Eckert, and H. Linde "On the transitions from cellular into wave-like patterns during the mass transfer of weakly surface-active substances in liquid-liquid systems"

Session T1: <u>Tuesday 19/6</u> 9:00-10:45 Chair: A. Nepomnyashchy

9:00-9:15 **W. Batson, F. Zoueshtiagh and R. Narayanan "Faraday wave dynamics of immiscible systems in finite cells"**

9:15-9:30 **O. Gottlieb, G. Habib, Z. Aginsky, and L. Ioffe "Model-based estimation of nonlinear dissipation mechanisms in free and modulated surface flows"**

9:30-9:45 **S. Duruk and A. Oron "Nonlinear dynamics of a liquid film on an axially oscillating cylindrical surface in the high-frequency limit"**

9:45-10:00 **A. Alexeev, W. Mao and A. Oron "Thermocapillary pumping by periodical heating"**

10:00-10:15 **Q.-S. Liu and Z, Ding "Oscillatory instability of thermocapillary convection in a bilayer liquid system"**

10:15-10:30 **A. A. Alabuzhev and M. Khenner "Large parametric instability of a Marangoni convection in a thin film"**

10:30-10:45 **A. Ye. Samoilova and N. I. Lobov "The buoyancy effect on oscillatory Marangoni instability in liquid layer"**

Session P2: <u>Tuesday 19/6</u> 10:45-11:15 Chair: Q.-S. Liu

Short poster presentation (3 minutes each)

D. Laroze, J. Martinez-Mardones, H. Pleiner "Benard-Marangoni instability in a viscoelastic magnetic fluid"

S. Vasin, A. Filippov and E. Sherysheva "Movement of composite microcapsules in a viscous liquid"

N. J. Alvarez and K. Uguz "Thermocapillary instability of three immiscible phases flowing through a channel"

N. J. Alvarez, C. Jeppesen, K. Yvind, N. A. Mortensen, I. Teraoka and O. Hassager "The continuous separation of molecules on the basis of their polarizability using optical electric fields"

K. E. Uguz and R. Narayanan "Instability in the presence of evaporation for binary liquids

K. Eckert and K. Schwarzenberger "On the interaction between Marangoni cells and double diffusive fingers in a reactive liquid-liquid system"

W. Batson, F. Zoueshtiagh and R. Narayanan "Faraday wave dynamics of immiscible systems in finite cells"

A. Nurocak and A. K. Uguz "Effect of the direction of the electric field on the interfacial instability between a Newtonian fluid and a viscoelastic polymer"

M. Sellier "Droplet actuation induced by coalescence: experiments and modeling"

T. Lyubimova and M. Alabuzheva "The influence of thermocapillary effect on the stability of fluid interface subjected to the horizontal vibrations"

Z. Ding, R. Liu and Q.S. Liu "Stability of an evaporating falling film"

Poster Session P2 and Coffee Break 11:15-12:00

Session T2: <u>Tuesday 19/6</u> 12:00-13:00 Chair: H. C. Kuhlmann

12:00-12:15 **M. Muraoka, T. Kamiyama, T. Wada, I. Ueno and H. Mizoguchi "Creeping motion and coalescence of droplets in a tube flow"**

12:15-12:30 **G. P. Neitzel and J. Black "Thermocapillary levitation of nanoliter-volume single- and compound-phase droplets"**

12:30-12:45 **M. Sellier "Droplet actuation induced by coalescence: experiments and modeling"**

12:45-13:00 **Y. Holenberg, U. Shavit, O. Lavrenteva and A. Nir "Translation of droplets in viscoplastic fluids"**

Lunch 13:00-14:15

Session T3: <u>Tuesday 19/6</u> 14:15-15:45 Chair: A. Nir

14:15-14:30 **A. Nurocak and A. K. Uguz "Effect of the direction of the electric field on the interfacial instability between a Newtonian fluid and a viscoelastic polymer"**

14:30-14:45 **W. Rohlfs, G. F. Dietze, H. D. Haustein and R. Kneer "Experimental investigation of 3-dimensional wavy liquid films under the coupled influence of thermo-capillary and electrostatic forces"**

14:45-15:00 **N. J. Alvarez, C. Jeppesen, K. Yvind, N. A. Mortensen, I. Teraoka and O. Hassager "The continuous separation of molecules on the basis of their polarizability using optical electric fields"**

15:00-15:15 **K. Shvarts, J. Shvarts and N. Knutova "Effect of the influence of slow rotation to stability of thermocapillary incompressible liquid flow in infinite layer in microgravity situation"**

15:15-15:30 **W.-Y. Shi, J. Li, M. K. Ermakov and Y.-R. Li "Effect of system rotation on thermocapillary convection and stability of silicon melt in differential heated annular pools"**

15:30-15:45 **K. E. Davis, Y. Huang and B. C. Houchens "Investigation of instabilities in a thermocapillary-driven, low Prandtl number liquid bridge with magnetic stabilization using three-dimensional simulations and linear stability theory"**

Poster Session P2 and Coffee Break 15:45-16:30

Session T4: <u>Tuesday 19/6</u> 16:30-18:00 Chair: L. Pismen

16:30-16:45 **R. Liu, Q.-S. Liu and O. Kabov "Effect of interfacial shear on the longwave Marangoni instability in a locally heated falling film"**

16:45-17:00 **P. H. Gaskell, D Slade, S Veremieiev and Y.-C. Lee "Thin film flow: rivulet formation, evolution and merger"**

17:00-17:15 **H. Haustein, G. Tebrugge, W. Rohlfs, and R. Kneer "Preliminary results of the influence of thermo-capillary forces on two-dimensional wavy falling films of water"**

17:15-17:30 **S. Shklyaev, A. A. Nepomnyashchy and A. Oron "Modulation instability for a longwave oscillatory Marangoni convection"**

17:30-17:45 **T. Lemee, R. Narayanan and G. Labrosse "Thermocapillarity instabilities in a free liquid film"**

17:45-18:00 **Y. Gaponenko, T. Matsunaga and V. Shevtsova "Dynamic interface deformation under the actions of Marangoni convection and coaxial gas stream"**

<u>Wednesday 20/6</u> Day trip to and banquet in Jerusalem

Session Th1: <u>Thursday 21/6</u> 9:15-10:00 Chair: H. Riegler

9:15-9:30 S. Matsumoto, S. Yoda, A. Komiya, M. Kawaji and N. Imaishi "Onset of oscillatory thermocapillary convection in liquid bridge with various Pr numbers"
9:30-9:45 T. Yano, K. Nishino, H. Kawamura, I. Ueno and S.Matsumoto "Flow and temperature field associated with hydrothermal wave of Marangoni convection in liquid bridge under microgravity"
9:45-10:00 I. Ueno, F. Sato, H. Kawamura, K. Nishino, S. Matsumoto, M. Ohnishi and M. Sakurai, "Hydrothermal wave instability in $\Gamma \geq 2.0$ liquid bridge of high Prandtl number fluid"

Poster Session P3 and Coffee Break 10:00-11:00

Session Th2: <u>Thursday 21/6</u> 11:00-12:00 Chair: K. Nishino

11:00-11:15 I. Frankel and R. Shabtay "The internal fluid motion within highly viscous adherent droplets"
11:15-11:30 J. J. Feng "Moving contact lines: diffuse-interface model and applications"
11:30-11:45 M. Zabarankin, I. Smagin, O. Lavrenteva and A. Nir "Deformation of a viscous drop in compressional Stokes flow"
11:45-12:00 E. Katz, A. M. Leshansky, M. Haj, and A. Nepomnyashchy "Thermocapillary motion of a slender viscous droplet in a channel"

Presentation for IMA7 12:00-12:15

Lunch 12:15-14:00

Session Th3: <u>Thursday 21/6</u> 14:00-15:30 Chair: V. Shevtsova

14:00-14:15 O. A. Frolovskaya and A. A. Nepomnyashchy "Influence of density stratification on stability of a two-layer binary-fluid system with a diffuse interface"
14:15-14:30 S. Madruga, F. Bribesh and U. Thiele "Decomposition and interface evolution in films of binary mixtures"
14:30-14:45 K. Kanatani "Stability of a condensing liquid film of a binary vapor mixture"
14:45-15:00 M. Morozov, A. Oron and A. Nepomnyashchy "Marangoni convection in binary fluids with soluble surfactant"
15:00-15:15 O. V. Admaev, V. V. Pukhnachev and O. A. Frolovskaya "Cahn-Hilliard equation and anomalous Marangoni effect"
15:15-15:30 M. H. Kopf, S. V. Gurevich, and R. Friedrich "Micro- and nanoscale pattern formation in Langmuir-Blodgett transfer: Control mechanisms and bifurcation analysis"

Coffee Break 15:30-16:00

Session Th4: <u>Thursday 21/6</u> 16:00-16:45 Chair: V. Starov

16:00-16:15 A. Mizev, A. Trofimenko and A. Viviani "Instability of Marangoni flow in the presence of insoluble surfactant. Experiment"
16:15-16:30 K. G. Kostarev, M. O. Denisova, A.V. Shmyrov and A. Viviani "Surfactant transfer enhancement between the drop connected to the reservoir and the surrounding fluid due to Marangoni convection"
16:30-16:45 T. Horn, T. Gambaryan-Roisman and P. Stephan "Marangoni convection in liquid films on heated structured walls at normal and reduced gravity"

IMA6 Closing 16:45 Chair: A. Oron

Contact line dynamics, Marangoni flows and associated effects

Rodica Borcia and Michael Bestehorn[1]

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Brandenburgische Technische Universität Cottbus,
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Wetting liquid films occur everywhere, even in the driest deserts, and play a major role in a wide range of applications. Some examples are: nano- and micro-fluidics, print technology, fuel supply in a spaceship under microgravity, control of nucleation, and lubrication to reduce wear and friction.

In our contribution is studied the behavior of two thin liquid layers with a body of different materials, connected through an ultrathin bridging film. In this aim we use a systematic expansion of the basic hydrodynamic equations of a binary mixture with deformable surface in the sense of long-wave approximation. All variables are expanded with respect to the small geometry parameter $\delta = d/\ell$, where d represents the mean depth of the film, and ℓ is the typical lateral length scale. Two coupled conservative equations are obtained in the lowest non-trivial order of δ that govern a mixture of two miscible liquids [1]. One equation describes the location of the free surface and the second one the dynamics of the vertically averaged concentration field. Substrate properties are included by incorporating different forms of disjoining pressures, characterizing different liquid-solid interaction forces.

We investigate numerically in two and three dimensions the mixing dynamics along the ultrathin bridging film, coalescence and spreading phenomena. The results are compared with recent experiments and phase field simulations on coalescence of droplets with different miscible liquids [2, 3].

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[1] Bestehorn, M., Borcia, I. D., *Phys. Fluids*, **22**, 104102, 2010.
[2] Borcia, R., Menzel, S., Bestehorn, M., Karpitschka, S. and Riegler, H., *Eur. Phys. J. E*, **34**, 24, 2011.
[3] Borcia, R., Bestehorn, M., *Eur. Phys. J. E*, **34**, 81, 2011.

Contact lines in different geometries

Ion Dan Borcia[1,2] Rodica Borcia[1,2], Michael Bestehorn[1], Catalin Borcia[3], Nicoleta Dumitrascu[3]
[1] *Lehrstuhl Statistische Physik/Nichtlineare Dynamik, Brandenburgische Technische Universität Cottbus, Germany*
[2] *Lehrstuhl für Aerodynamik und Strmungslehre, Brandenburgische Technische Universität Cottbus, Germany*
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borciai@tu-cottbus.de

Static and dynamic contact angle measuremets for liquid lying on plane surfaces and wires are important for describing the adhesion properties of the surfaces. For example, these measurements can give information about the modifications induced to the surface characteristics of polymers, in film or fiber forms, after a dielectric barrier discharge treatment at atmospheric pressure. Giving the sensitivity of these quantities to small variations of the measured contact angles, the interest is to establish reliable and simple methods which would improve the accuracy of the measurements. The phase field method is a good tool for investigating fluid systems when complicated interfaces are present. For the point of view of numerical implementation a great advantage of the method is to avoid complicated boundary conditions when the interfaces are allowed to deform. In order to describe the interfaces, gradient terms of the phase field are included in the free energy functional. A study of static and dynamic contact angles is possible by including the solid-liquid interactions into the boundary conditions on the solid substrate. Due to the fact that the phase field model works with diffuse interfaces, determination of the position of the contact lines is not obvious. Some solutions for this problem and preliminary results will be presented.

Marangoni Modified Drop Fusion and Drop Motion: Thin Film Traveling Wave Description Closed by Asymptotic Matching

Stefan Karpitschka[1] and Hans Riegler[1]

[1]Max-Planck-Institut fuer Kolloid- und Grenzflaechenforschung, D-14476 Potsdam, Germany

Sessile droplets on solid surfaces will fuse due to capillary forces arising from minimizing the liquid-gas interfacial energy. The droplet fusion can be delayed if the droplets consist of different (but still completely miscible) liquids. Quite unexpected, even after initial contact at the three phase line, the main droplet bodies remain separated. The droplets are connected only through a neck via a thin liquid film and move together over the substrate surface [1]. This "non-coalescing" state can last up to minutes. Its origin are the different surface energies of the liquids: The difference induces a Marangoni flow between the droplets which keeps them separate [2].

Based on new experiments, we present – for the first time – an analytical treatment in the framework of a thin film description. The key ingredient is a balance of advective and diffusive transport mechanisms in the vicinity of the neck, which induces a Marangoni flow. By piece-wise asymptotic matching of meso- and microscopic solutions we determine the global free surface topology and the capillary number from first principles [3]. We find traveling wave solutions in (semi-)quantitative agreement with the experimental observations. The findings are generally relevant for (shallow, steady-state) free surface flows that involve (are caused by) surface tension gradients (e.g. due to local compositional variations).

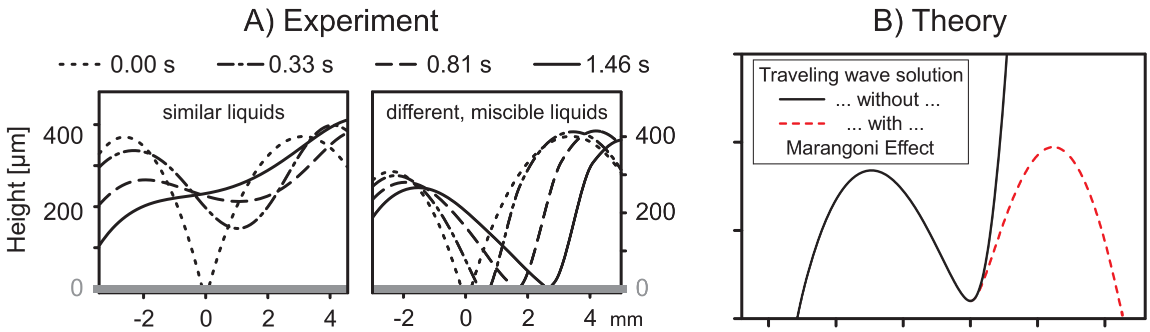

FIG. 1: A) Experimental center-to-center profiles of droplets with instantaneous (left) and delayed (right) coalescence. B) Traveling wave solutions to a thin film equation: classical, semi-infinite solution without surface tension gradient vs. localized (i.e., two droplets) solution with local surface tension gradient (dashed).

[1] Riegler, H. and Lazar, P., *Langmuir* **2008**, *24*, 6395.
[2] Karpitschka, S. and Riegler, H., *Langmuir*, **2010**, *26*, 11823.
[3] Karpitschka, S. and Riegler, H., *Manuscript in preparation*

Marangoni Effect from Chemical Gradients near Contact Lines

Stefan Karpitschka[1] and Hans Riegler[1]
[1]*Max-Planck-Institut fuer Kolloid- und Grenzflaechenforschung, D-14476 Potsdam, Germany*

In recent publications we have shown experimentally how the fusion of sessile droplets of completely miscible but different liquids can be delayed compared to the rapid fusion that is expected due to capillary forces arising from minimizing the liquid-gas interfacial energy [1, 2]. Meanwhile the delayed coalescence of contacting sessile droplets has been successfully explained theoretically in the framework of a thin film description [3].

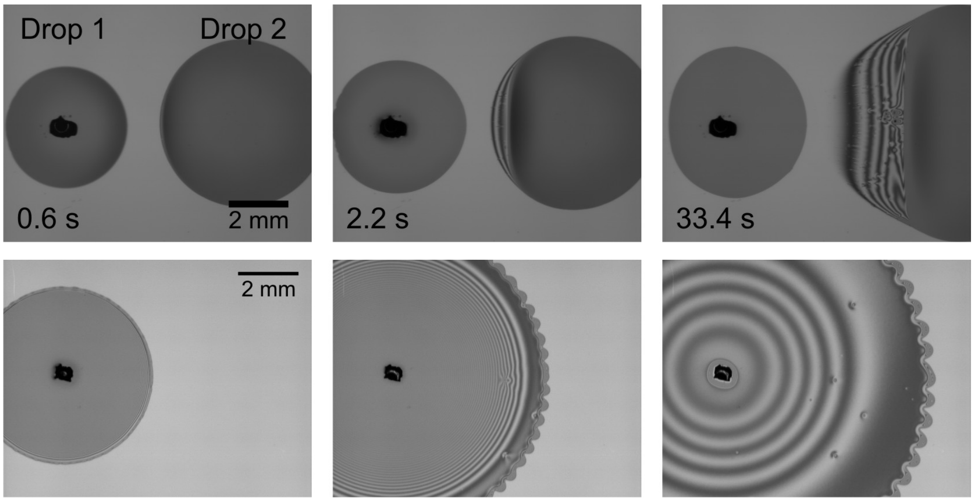

FIG. 1: **Top:** Interaction of left drop (volatile liquid, lower surface tension) with right drop (non-volatile liquid, higher surface tension). **Bottom:** Single droplet of a mixture of C9 and C16 alkanes spreading.

Motivated by the studies with non-volatile liquids we present new experimental data with volatile liquids on (I) the interaction between sessile droplets that are *not contacting* each other at the three phase contact line and on (II) the contact line behavior of a *single* sessile drop of (binary) mixtures whose composition varies spatio-temporally due to the selective evaporation/condensation of (one of) its components. In case (I) we observe a "remote" interaction (repulsion/shape distortion) between distant drops caused by liquid exchange through the vapor phase: The vapor adsorption leads to chemical gradients respectively surface tension gradients because of locally varying diffusive/advective properties (e.g. subphase depth, volume). In case (II) the spatio-temporal composition can reverse the contact line movement from spreading to receding or even cause contact line instabilities ("tears of wine without gravity").

[1] Riegler, H. and Lazar, P., *Langmuir* **2008**, *24*, 6395.
[2] Karpitschka, S. and Riegler, H., *Langmuir*, **2010**, *26*, 11823.
[3] Karpitschka, S. and Riegler, H., *Manuscript in preparation*

Flow pattern transition of thermocapillary convection in a differentially heated annular pool for moderate Prandtl number fluid under varying gravity level

You-Rong Li, Lan Peng, and Wan-Yuan Shi

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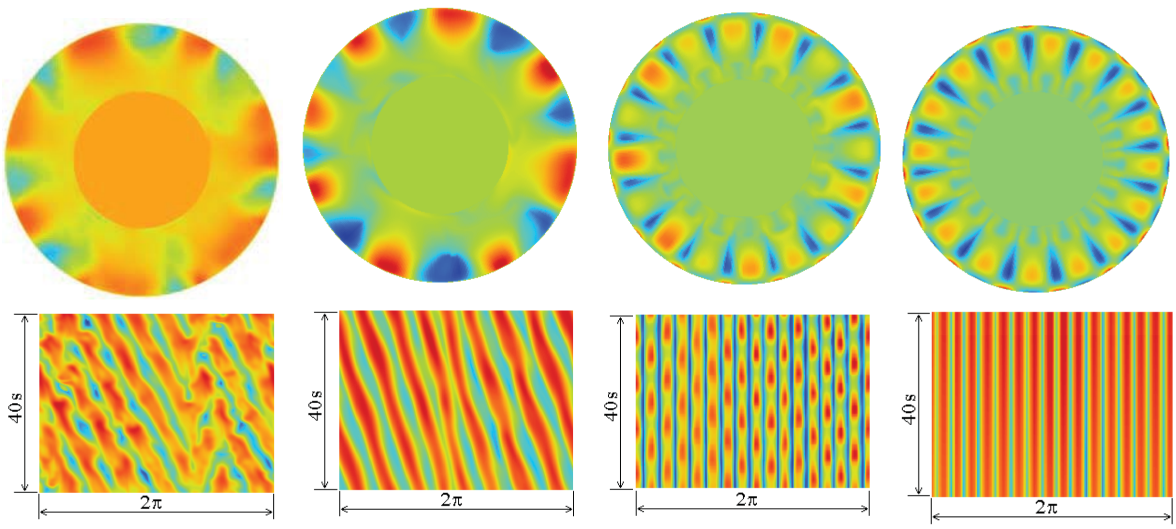
The dynamic behavior of flow driven by a horizontal temperature gradient in fluid layer with a free upper surface has attracted the attention of the researchers for many years. It is well-known that thermocapillary convection penetrates fully into the fluid layer under microgravity whereas it is a separated surface tension driven convection roll at the free surface under normal gravity. And it is also found that gravity significantly stabilizes thermocapillary convection [1-3]. In order to understand the flow pattern transition process under varying gravity level, we conducted a series of unsteady three-dimensional numerical simulations of thermocapillary convection of 0.65cSt silicone oil (Prandtl number Pr=6.7) in an annular pool with the depth d=6mm heated from the outer cylinder (radius r_o=40mm) and cooled at the inner cylinder (r_i=20mm) with an adiabatic solid bottom and adiabatic free surface. Gravity level varies from 0 to 5g_0 (g_0=9.80665m/s^2). The simulation results show that the three-dimensional oscillatory thermocapillary convection appeared at microgravity when the radial temperature difference exceeds the critical value. If the gravity level is increased to 0.1g_0, the flow pattern transits extended roll cells traveling in the azimuthal direction. If the gravity level is increased to 0.5g_0, the stable three-dimensional flow happened. Further, when $g \geq 3.0g_0$, the thermocapillary convection transits the steady axially symmetric flow.



(a) $g=0.02g_0$ (b) $g=0.1g_0$ (c) $g=0.3g_0$ (d) $g=1.0g_0$

Fig. 1 Flow pattern transition process at ΔT=10K. Upper plot: snapshots of surface temperature fluctuation; Down plot: space-time diagram of surface temperature distribution at a given radius

[1] Benz, S., and Schwabe D., *Experiments in Fluids*, **31**, pp.409-416, 2001.
[2] Schwabe D., *J. Crystal Growth*, **237-239**, pp. 1849-1853, 2002.
[3] Peng L., Li, Y. R., Shi, W. Y., and Imaishi N., *Int. J. Heat Mass Transfer*, **50**, pp. 872-880, 2007.

Evaporation of complex fluids in a Hele-Shaw cell

Ching Hsueh,[1] Frédéric Doumenc,[2] and Béatrice Guerrier[3]

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We study self-assembly of drying complex fluids (colloidal suspensions or polymer solutions) induced by solvent evaporation in a meniscus. A Hele-Shaw cell made of two paralleled glass plates separated by 1mm spacers is vertically immersed into a reservoir which contains the colloidal suspension or polymer solution. Due to the 1mm-thin gap, there is a spontaneous capillary rise. The setup principle is then similar to classical dip-coating. Indeed, in dip-coating the substrate is withdrawn from a reservoir which contains coating materials, while in our set up the substrate is motionless and the solution is pumped out from the reservoir. The flow rate of the pumping system controls the contact line velocity V. The set-up is put inside a chamber of volume 50.4L, where temperature and humidity are regulated by a PID system. A fan blows an air flow to the meniscus through a vertical channel set above the two plates. Deposit morphology is studied as a function of the process parameters (substrate velocity and evaporation rate) and the solution properties (polymer solution or colloidal suspension, initial concentration, viscosity).

A model has been developed to describe the flow induced in the bulk by solvent evaporation at the free surface. Concentration and velocity fields are obtained by solving the Navier-Stokes equations and Fick law. At the upper boundary (meniscus) a known but non uniform evaporation flux is imposed. The description of the tip of the meniscus is achieved by introducing an a priori cut-off where boundary conditions result from a small scale description using lubrication approximation. An iterative procedure is used to define these boundary conditions. The concentration and velocity fields are analyzed as a function of the process parameters. Deposit thicknesses are compared to experimental results.

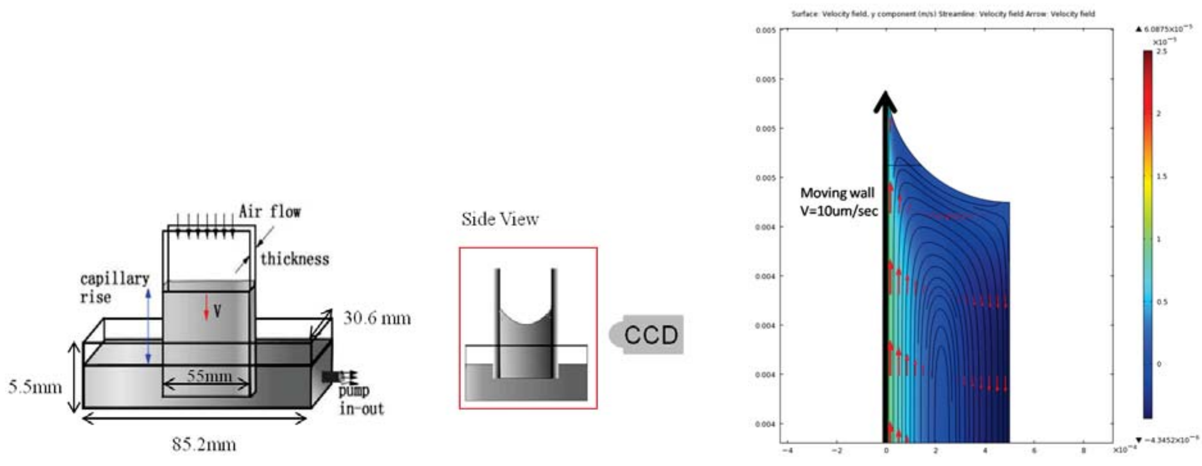

FIG. 1: Left: experimental set-up - Right: Simulation results: Flow field for a polymer solution drying on a moving substrate.

Global Simulation of Marangoni Convection in Detached Solidification under Cusp Magnetic Field

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The traditional methods about crystal growth from melt are the Bridgman method and the Czochralski method. The detached solidification technique combines superiorities of the both methods, so grows better quality crystals. Some microgravity experiments exhibited the detached solidification processes[1]. However, the physical and chemical properties of the crystal can be affected by the flow which exists in the melt. The usage of magnetic field is known to be an efficient way to control the flow of electrically conductive fluid and therefore affect the heat and mass transfer in the melt.

CdZnTe is a very important semiconductor material. Until now, most of the researches focused on the experiments, and it is indispensable for the theory work of the detached solidification process for CdZnTe especially applying the global simulation under cusp magnetic field. A set of global analyses for heat and momentum transfers of Marangoni convection in crucible was carried out using the finite-element method. The rules by changing the main affecting factors on CdZnTe crystal growth such as crucible radius, gravity level, temperature gradient and magnetic field strength were researched. Figure 1 shows distributions of the stream function at the different gravity levels at B_o=1.0T. Figure 2 shows distributions of the velocity on the upper surface at the different magnetic field strength. The melt Marangoni convection is suppressed by applying a cusp magnetic field. It sets stage for the preparation of high quality and bulk mass crystals of CdZnTe on the ground condition.

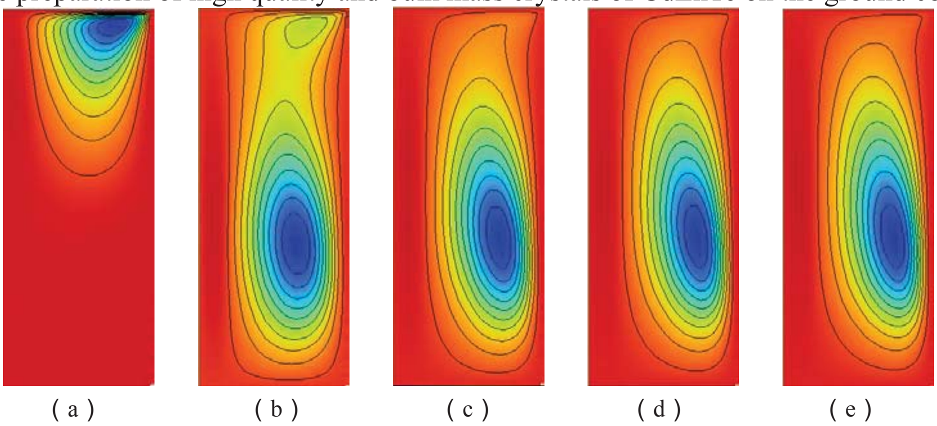

Fig. 1 Distributions of the stream function at the different gravity levels at B_o=1.0T.
(a) G=0, ψ_{max}=0.400×10^{-7} m^3/s. (b) G=0.1g, ψ_{max}=0.723×10^{-7}m^3/s. (c) G=0.5g, ψ_{max}=1.51×10^{-7} m^3/s. (d) G=0.8g, ψ_{max}=1.78×10^{-7} m^3/s. (e) G=g, ψ_{max}=1.91×10^{-7} m^3/s.

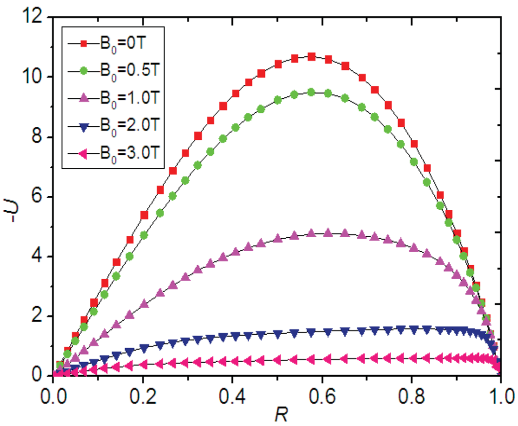

Fig. 2 Distributions of the velocity on the upper surface at the different magnetic field strength.

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Influence of thermophysical properties of liquid on features of the rupture of film. The role of the Prandtl number.

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We investigate the influence the Prandtl number on the character of the film rupture under the action of thermal load. A weightless thin film is hanging between two flat rigid walls. The film has length L and thickness $2h_0$. At initial moment of time the film is in the rest. The thermal load acts onto the free surface of the film. In this case the film can change its form and have discontinuity. To investigate this process, the two-dimensional mathematical model based on the Navier-Stokes equations was applied. The thermal load is modeled by prescribed temperature on the free surface in the form:
(1) $\theta(x,t) = \theta^*$, if $L/2 - mh_0 \le x \le L/2 + mh_0$ At the rest of the film surface $\theta(x,t) = 0$.
(2) $\theta(x,t) = \theta^*$, if $L/2 - mh_0 \le x \le L/2 + mh_0$ At the rest of the film surface $\partial\theta / \partial n = 0$.
Here, h_0 is the half of film thickness, m is a positive number which determines a width of thermal ray acting on the free surface of the film. To reveal the character of the film rupture we performed the computational investigations using parameters $Re = 1$; $Ca = 0.025$; $Mn = 30$; $Pr = 0.1 \div 10$. The ratio of film length to its half thickness $L/h_0 = 90$, $m=3$. Because the problem is symmetrical, we consider the half of domain only.
The investigations have shown: if the temperature on the film free surface is prescribed by type (1), i.e. it is predetermined at any time moment, then the lifetime, the character of the film rupture and the location of the free surface are not depend on the Prandtl number. At the same time, the isotherms have essential distinctions for different Prandtl numbers.

If the temperature on the free surface is prescribed by type (2), Prandtl number plays a vital part. How it is shown in [1], the film rupture happens with the generation of the drop for such type of thermal load. Figure 1 presents the results of calculations for case, when the temperature is determined in small domain $d=6h_0$ on film free surface only. At the rest of the film surface we could find it in the process of solution of the problem. If the thermal load is intense enough ($\theta^* = 0.75$), the film rupture occurs quickly and generated drops have insignificant distinctions for both Prandtl numbers. However, the more fast warming-up of the film no leads to the more quick rupture of the film. Opposite, the lifetime of the film $t^*(Pr = 0.1)$ is 1.5 time more than $t^*(Pr = 10)$.
The smaller the thermal load, the smaller the difference between the lifetimes of the film for both Prandtl numbers. At that, the location of free surface and form of drops have sharp distinction.

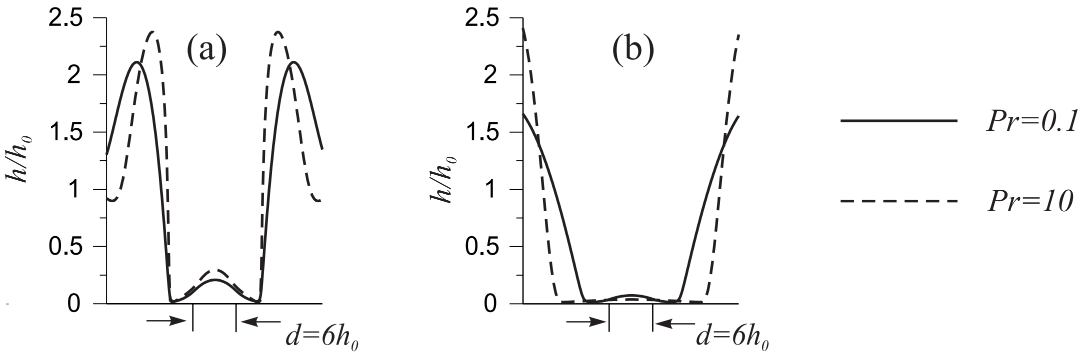

Fig.1. The location of the film free surface for the thermal load of different intensive: (a): $\theta^*=0.75$; (b): $\theta^*=0.25$;

[1] A.S. Ovcharova Droplet Formation in the Rupture of a Liquid Film under Action of a Thermal Load, *Fluid Dynamics*, 46, pp. 108-114 , 2011

Investigation of wall slipping influence on mixing efficiency and pressure drop in T-shaped microchannel at high Reynolds numbers

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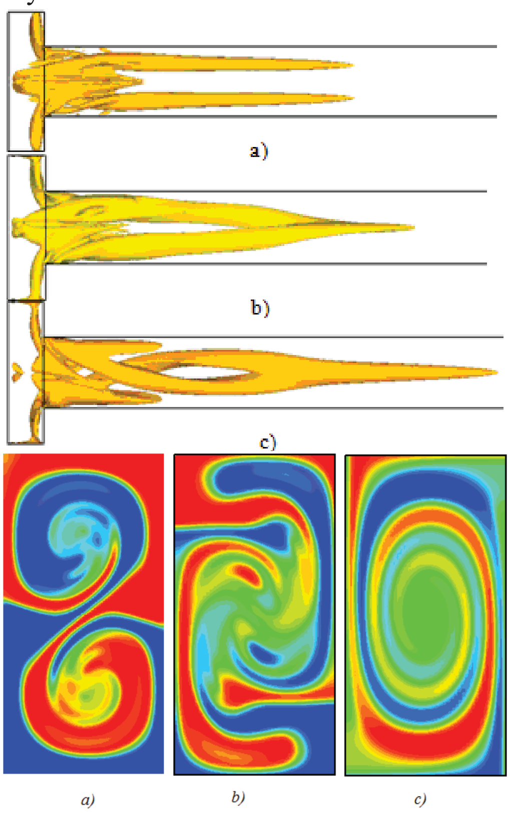
Fluid mixing in microchannels is an extremely important problem in various applications of microflows. In macroscopic flows, mixing usually occurs in a turbulent flow regime. Microflows, however, are usually laminar, and corresponding Reynolds numbers are not so large. The mixing at low Reynold numbers has been studied well [1]. However, in fairly large microchannels, the Reynolds number can be a few hundreds. These flows have many interesting features. The purpose of this work was to study the flow regimes and mixing efficiency in a T-type micromixer at high Reynolds numbers. The Reynolds numbers were varied from one to one thousand. The cross section of the mixing channel was 100 μm×200 μm, and its length was 1400 μm. The transverse inlet channels were symmetric to the mixing channel, and their cross-section was 100 μm×100 μm, and the total length was 800 μm.

The simulation results lead to the following main conclusions. At Reynolds numbers Re < 5, stationary vortex-free flow occurs in the mixer. At Reynolds numbers 5 < Re < 150, stationary symmetric vortex flow occurs in the mixer. In this flow regime, two symmetric horseshoe vortices form at the end of the mixer, which propagate into the mixing channel. At Reynolds numbers 150 < Re < 240, stationary asymmetric vortex flow occurs in the mixer. The horseshoe vortices formed at the entrance lose symmetry and rotate by 45 degrees to the central longitudinal plane of the mixer (see Fig. 1a). Because of this, two equally swirling vortices form in the mixer. The flow nevertheless remains stationary. The presence of vortices in the mixer dramatically increases the mixing efficiency. At Reynolds numbers 240 < Re < 400, nonstationary periodic flow occurs in the mixer. The pulsation frequency of the velocity (and other characteristics) agrees with experimental data with an accuracy of 1–2%. At Reynolds numbers 400 < Re < 1000, the flow in the mixer becomes stochastic. The S-shaped vortex structure observed at lower Reynolds numbers is destroyed. The destruction of the coherent structure leads to a sharp decrease in the mixing efficiency. Nevertheless, at such Reynolds numbers, one still cannot argue that a turbulent flow regime occurs.



Flow vortex structure and contours of mass fraction of dye in the outlet of microchannel at various value of the slip length b. Re = 186. a) b = 0; b) b = 10 μm; c) b = 30 μm.

Also in this work we studied the effect of the slip boundary conditions on the flow structure. Applying the hydrophobic coatings in microchannels we can significantly decrease the pressure drop. The main conclusion here is the following. The flow structure is not practically changes at small and moderately slip lengths (up to 5 μm). However, the flow structure is considerably changed at large slip lengths (see Fig.1b-c). As we mentioned above the two-vortices structure is formed in the mixer flow field at zero slip length (see Fig. 1a). But this structure is transformed to a single whole vortex at large slip length (see Fig. 1b and 1c). Naturally the mixing efficiency grows also when the slip length increases. This growth is about 30 % for this mixer. pressure drop at the same time decreased by 20% . Thus, controlling the structure of the flow through the slip length, can increase of the mixing efficiency and reduce the pressure loss.

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The influence of high-frequency vibrations on the stability of thermo-capillary flow in the liquid zone

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The Floating Zone is a promising method of growing of high-quality semiconductor monocrystals, which allows avoid the unbeneficial contact between the melt and crucible walls. However, even when the process is carried out in the microgravity conditions, the thermocapillary convection may be important. At high values of Marangoni number it becomes oscillatory and leads to the deterioration of the crystal quality. So, the problem of determination of optimal conditions of carrying out the technological process and to control the convection in the liquid zone arises.

For this purpose a model configuration of so-called half-zone is used frequently. It is a capillary bridge, located in-between two rigid discs of equal diameter, maintained at different temperatures. To control the convective flow during the crystal growth process a number of methods was suggested, such as rotation of supporting discs or application of magnetic fields of different configuration. Another relatively new method is the use of vibration.

This paper deals with the numerical study of influence of vibrations of one of the supporting rods on the stability of stationary axe-symmetrical thermo-capillary flow in the half-zone in the microgravity conditions. A high-frequency, low-amplitude axial vibrations are considered. This assumption allows to decompose hydrodynamic fields into pulsating and mean components and to obtain governing equations and boundary conditions for this components (see [1]). The study was carried out accounting for pulsating deformations of the free surface. Mean deformations of the free surface were neglected.

The linear stability of stationary solution to three-dimensional perturbations, periodical in azimuthal direction, was investigated. The finite differences method was used. The structure and stability of pure vibrational, thermo-capillary, and combined flows at different frequencies and amplitudes of vibrations and Prandtl numbers were studied. The stability maps for several the most dangerous perturbation modes were obtained. The possibility to counter-balance the capillary flow by the vibrational flow, reducing the intensity of the fluid motion in the zone and increasing its stability, was demonstrated.

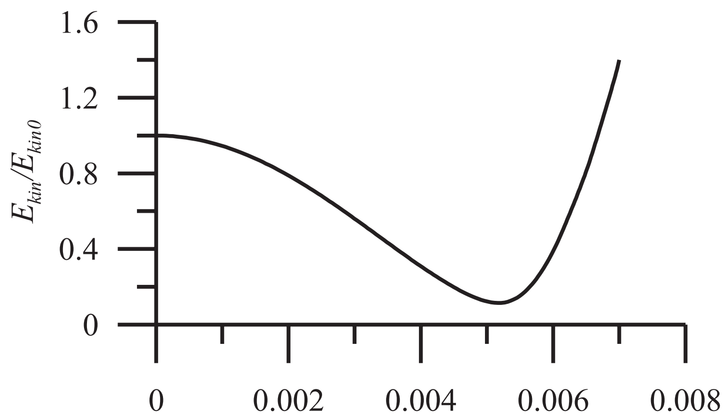

Fig. 1 The dependence of kinetic energy of the fluid motion on the dimensionless amplitude of vibrations for *Pr* = 0.02, *Re* = 2059, *We* = 17000

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Evaporation of pinned sessile microdroplets of water: computer simulations

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Evaporation of sessile liquid droplets is an interesting problem, which has many applications in industrial processes, such as painting, ink-jet printing, DNA analysis, particles deposition, up to the manufacturing of MEMS and complex functional materials.

In present work we study (numerically) the instantaneous distribution of heat and mass fluxes of a single evaporating droplet of pure water sitting on the top of a solid substrate in still air atmosphere. We assume the axial symmetry of the problem, sphericity of the droplet's cap, and quasi-steady regime of heat and mass transport processes.

Latent heat of vaporization is taken into account in the boundary condition for the heat flux discontinuity at the liquid-gas interface. Kelvin's equation [1] is used to account for the influence of curvature of the liquid-gas interface on the value of saturated vapor pressure immediately above the interface. The rate of droplet evaporation is limited by two processes: the rate of vapour diffusion into the ambient air (diffusion model) and the rate of molecules transition across the liquid-gas interface (kinetic effects). Both these phenomena are simultaneously incorporated into the present model. The rate of a molecular transition is calculated based on the Hertz–Knudsen–Langmuir formula [2].

It is shown that the effect of Marangoni convection in pure water is important only for droplets with size bigger than 10^{-5} m. Kinetic effects come into play for droplets with size less than 10^{-6} m.

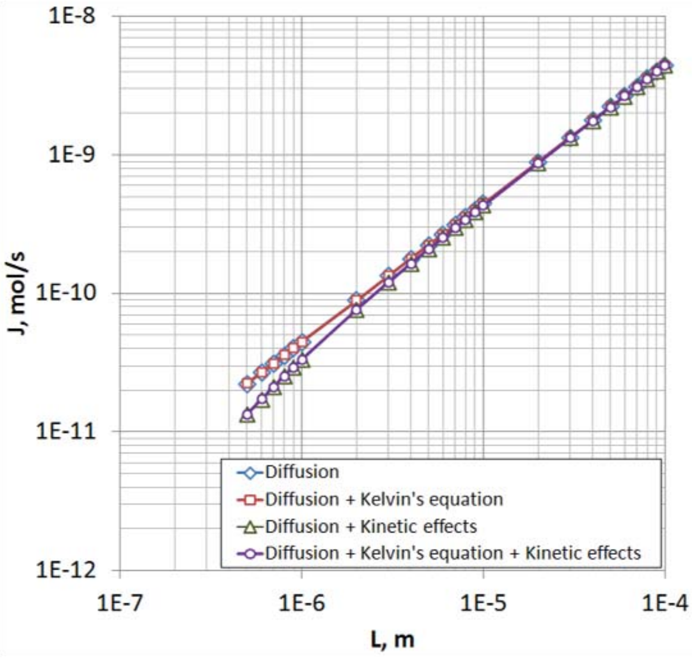

Fig. 1. Example of computer simulated dependence of evaporation rate, J, of a droplet on the contact line radius, L, in the case when contact angle is 90 deg. Parameters used: pure water droplet, copper substrate, air atmosphere, ambient temperature is 20°C, and relative air humidity is 70%.

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Numerical simulation of an evaporative meniscus on a moving susbtrate

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An hydrodynamic model based on lubrication theory has been recently developed to get a complete description of an evaporative meniscus in total wetting configuration, when evaporation takes place in air at atmospheric pressure [1]. Evaporation is thus driven by vapor diffusion in the gaz phase, then the coupling between liquid and gas must be explicitly taken into account, making the determination of the local evaporation flux a non local problem [2]. Although considering a total wetting situation, a non-zero effective contact angle can result from evaporation or substrate motion. A disjoining pressure approach is used to describe van der Waals interactions between the liquid and the solid substrate. The model allows the prediction of the effective contact angle, as well as the determination of the complete meniscus structure, from the bulk dominated by capillary pressure to the liquid film adsorbed on the substrate and governed by disjoining pressure. Scaling laws describing the different domains of the meniscus has been previously derived for a motionless substrate, and validated by numerical simulations. This study focus on conjugated effects of evaporation and substrate motion. Results show two distinct regimes when varying the substrate velocity on several orders of magnitude. At slow velocity, the meniscus structure is governed by evaporation and is independent of substrate velocity. On the contrary, at high velocity, evaporation turns to have a negligible effect on the meniscus macroscopic behaviour. A Landau-Levich regime is then obtained in the case of a receding contact line, and a Cox-Voinov regime in the case of an advancing contact line. Finally results are compared with simplifed models of the literature [3, 4].

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Thermal and solutal Rayleigh-Bénard-Marangoni convection induced by solvent evaporation in polymer solutions.

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During the drying of a solution with a volatile solvent and a non-volatile solute, the solvent evaporation has two main consequences at the upper free surface : 1) the formation of a temperature gradient due to the cooling induced by vaporization latent heat; 2) the formation of a density gradient of solvent due to the local evaporation flux. Each of these gradients might generate in turn several instability mechanisms producing convective cells: a) Buoyancy effects or b) Marangoni effects, due to thermal or solutal origin in both cases.

To analyse the respective part of these driving mechanisms, we have developed separately a thermal model [1, 2] and a solutal one. In this transient problem, comparison of instability thresholds is not sufficient to conclude on the dominant mechanism. The purpose of this paper is to perform a detailed comparison of the critical times and of the velocities to determine which phenomenon (thermal or solutal, surface tension or buoyancy driven convection) dominates and at what stage of the drying process. Numerical results are then compared to experiments performed on PIB/toluene [3] or PS/toluene [4] solutions, for various initial thicknesses and polymer concentrations. We show that numerical simulations are in agreement with experiments in order of magnitude. However, significant overestimation of fluid velocity predicted by simulations shows that more work is needed to improve model reliability.

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Mathematical modeling of the evaporating liquid films on the basis of the generalized interface conditions

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Modeling of the convective processes caused by impact of various forces on the fluid media is rather important nowadays. The additional tangential stresses on a thermocapillary gas-liquid interface and the evaporation effects should be taken into consideration in the case when the fluid flows are accompanied by the adjacent gas flows. The conditions to be applied at the interface between two interacting gas-liquid phases have been presented in [1]. The interface conditions result from the strong discontinuity relations as conservation laws of mass, momentum and energy. The additional relations concerning a continuity of some flow characteristics, laws of the heat and mass fluxes, of the dynamic, energy and phenomenological properties etc. are usually assumed to be fulfilled in order to obtain the closed problem statements. The generalized interface conditions allow to model the evaporative processes in the liquid and gas-vapor phases with interface in the full problem statement and in the long-wave approximation of the governing equations.

In [2] a detailed review of the problem statements, approaches for investigation and results of the liquid film flows subjected to action of the mechanical, thermal and structural factors have been presented. The evaporating or condensing liquid films have been also studied therein [2]. Further modeling of the liquid films flowing down the inclined heated substrates including evaporation effects has been performed in [3-5].

In the present research the results of scaling analysis and simplification features of the generalized interface conditions are presented. Non-dimensional analysis of these conditions gives a possibility to determine contribution of the various forces acting into dynamic and energetic processes at the interface. Construction of a hierarchy of the mathematical models of flows of the evaporating liquid films is carried out. The simplified mathematical models of the thin liquid films with evaporation and principal issues relating to well/ill posed initial boundary value problems are studied. Numerical investigations are carried out on the basis of the developed model in the two-dimensional case. The dynamics, heat- and mass transfer in the liquid under conditions of microgravity and zero-gravity demand special study, that can lead to refinement of the theoretical points of the classical convection theory and to application of the alternative convection models.

Acknowledgments. The research has been carried out in the frame of the scientific project "Investigation of the convection and heat transfer processes in the anisotropic domains and in the domains with moving boundaries" (Altai State University) and supported by the Russian Foundation for Basic Research (10-01-00007).

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Aspects of thermo-capillary and soluto-capillary instabilities in evaporating thin films

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Several aspects of thermo-capillary and soluto-capillary instabilities in evaporating thin films are considered and analyzed with the help of linear stability analysis and direct numerical simulations. Long-wave perturbations that deform the film interface, as well short waves in films with flat interfaces are considered.

The long-wave thermo-capillary instability of a film containing colloidal particles is discussed first [1]. The effect of particle concentration on the Brownian diffusivity and on film viscosity is accounted for. The instabilities lead to the development of lateral inhomogeneities in particle concentration. Depending on the magnitude of the Marangoni and particle Peclet numbers several types of defects in the final dried coatings may develop.

Secondly, a mechanism of long-wave Marangoni instability is presented, which has its origin on the effects of a soluble surfactant [2]. As the film thins due to evaporation, thickness perturbations lead to surfactant concentration perturbations, which in turn drive film motion and tend to enhance uneven film thinning. In the linear analysis a non-autonomous system is obtained for the film thickness and surfactant concentration perturbations, which shows that the instability will manifest itself provided that an appropriate Marangoni number is relatively large and the surfactant solubility in the bulk is large as well. On the other hand, low solubility in the bulk, diffusion and the effect of surfactant on interfacial mobility through the surface viscosity are found to resist disturbance growth.

Next, short wave disturbances are considered in flat films of constant viscosity. When thermo-capillary effects drive the fluid motion direct numerical simulations reveal interesting transitions between different wavelength patterns during film shrinkage. Similar soluto-capillary instabilities appear in two-component systems where one component is volatile. The analysis agrees with the experimental observation that instabilities develop only when the volatile component has a lower surface tension, according to a mechanism explained by de Gennes [3].

Finally, a linear stability analysis for the soluto-capillary instability is performed under the frozen base-state assumption, which takes into account the film deformation. The critical Marangoni number depends on the square root of a characteristic evaporation number, which determines the magnitude of concentration gradients in the evaporating film.

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Extremely Unstable Evaporative Bénard-Marangoni Systems: the Role of Transients in the Gas

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The present theoretical study is concerned with Bénard-Marangoni instabilities in horizontal liquid layers evaporating into the air, when possible extrinsic horizontal non-uniformities in the system are not essential. The vertical temperature gradients responsible for the instability here owe themselves entirely to the cooling occurring at the liquid-gas interface due to the latent heat of evaporation. In the case of a binary liquid, solutal gradients appear too in view of different volatility of the components. The solutal mechanisms of instability, for non-pure liquids, actually have a certain tendency to be predominant over the thermal ones as far as instability thresholds are concerned, or at least this is so in the examples considered here. The evaporation rate in the base state is determined by an effective transfer distance in the gas phase (typically, 1 mm ÷ 1 cm), at which the ambient conditions for the pressure, temperature and humidity are specified, and which appears in the model as an effective thickness of the gas layer [1]. Even though still a semi-empirical parameter, the transfer distance allows for a more precise and versatile description than merely the transfer coefficients often used in the literature, for it permits to explore a possible active role of the gas phase.

The feature we mainly focus upon in this presentation is the critical layer thickness for the onset of monotonic instability. The critical thickness turns out to be typically so small, well into a sub-millimeter range, that it is only the Marangoni mechanism (the thermal one for pure liquids, and the solutal one for binary mixtures) that is relevant in this context, the Rayleigh/buoyancy contributions being negligible. Furthermore, we focus our attention upon non-longwave modes of instability, for which the interface can be considered as undeformable, even for very small thicknesses, thanks to the action of the Laplace pressure (small capillary number). The role of the gas layer in the problem for perturbations proves to be well accountable for by means of a Biot number in the framework of a one-layer formulation, albeit this Biot number is here a function of the wavenumber of perturbations, which is a manifestation of the mentioned “activity” of the gas phase. All in all, the analysis we deal with can essentially be characterized as Pearson-like in a broad sense of the word.

Now the specific goal of the present study is to demonstrate that, under otherwise equal conditions, the critical thicknesses for transient regimes can actually be appreciably lower than those known for the corresponding (quasi-)stationary base states (towards which these transients evolve). Here we consider the transients resulting from initially putting in contact uniform (without temperature and composition gradients) liquid and gas phases that are not in phase equilibrium with each other so that evaporation and transient temperature and concentration profiles ensue. The key to this effect is that the system be sufficiently unstable (“extremely unstable”), with a sufficiently high Marangoni factor, so that the instability occurs well before a (quasi-)stationary state gets established in the effective gas layer. In fact, it turns out that systems with sufficiently volatile liquids (such as HFE-7100, or even ethanol, at normal conditions) or with binary mixtures possessing a strong solutal Marangoni factor (e.g. ethanol in water [2]) prove all to be extremely unstable in this sense, implying of course that the ambient relative humidity is well below 100%. The analysis for the transients is carried out using the frozen-time approach.

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Marangoni Instability of a Liquid Layer with Insoluble Surfactant under Heat Flux Modulation

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We consider a horizontal layer of an incompressible liquid bounded by rigid lower plane and free nondeformable flat upper surface. The layer is heated from below. The heat flux at the bottom of the layer is varying with time around a mean value. The rotational symmetry of the problem gives a possibility to consider only the 2D case in the linear stability analysis. The problem is governed by the following non-dimensional parameters: the Prandtl number, P, the Marangoni number, M, the Biot number, B, the Lewis number, L, the elasticity number, N, the non-dimensional frequency of the heat modulation, ω, and the ratio of the amplitude of the heat flux modulation to the mean value of the heat flux, δ.

Our previous investigation of the long-wavelength asymptotics of the problem [1] has showed the existence of two instability modes, monotonic and oscillatory ones. In this approximation, the vibration stabilizes the motionless state with respect to both instability modes. Here we consider the stability problem with respect to disturbances of arbitrary finite wave-number k. To solve the system of equations describing the stability of the equilibrium state the Fourier method was applied. Two types of the solutions were considered. The first one has a period of oscillation twice as the period of heat flux modulation (subharmonic mode) and the second one has the same period as the heat flux variation (synchronous mode). The calculation is performed for the typical Lewis number 10^{-2}, other parameters are subject to change.

The stability boundary (neutral) curves were obtained for different values of parameters B, P, ω, δ and N. Fig. 1 shows the neutral curves for a specific set of the parameters. As shown the most "dangerous" instability mode for given parameters is a subharmonic one, it is unstable only for some range of wave numbers. When the parameter δ decreases this mode disappears. The dependence of the critical value δ_c on modulated frequency was also investigated. In the case of $\delta \ll \delta_c$, the long-wave approximation is sufficient.

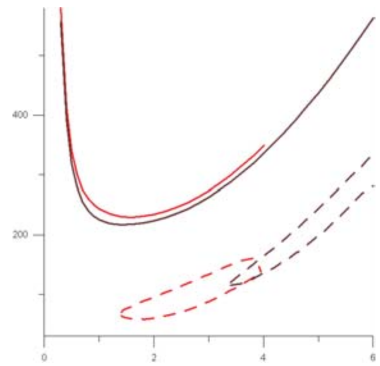

FIG. 1: Neutral curves for parametric Marangoni instability $M(k)$ for $\omega = 0.5$ (red color) and $\omega = 2$ (brown color). $P = 7, B = 0.2, L = 0.01, N = 0.1, \delta = 1$. Solid (dashed) lines correspond to synchronous (subharmonic) mode.

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Nonlinear Dynamics of a Thin Liquid Film on an Axially Oscillating Cylindrical Surface Subjected to Double-Frequency Forcing

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Investigation of the nonlinear dynamics of a thin axisymmetric liquid film on a horizontal circular cylinder subjected to harmonic axial oscillation was recently carried out in the isothermal [1] and non-isothermal [2] cases. It was found that it is possible to arrest the capillary long-time film rupture typical to the case of a static cylinder, if the substrate is forced with a sufficiently high amplitude and/or frequency.

In this research, we extend the study to the case of an axisymmetric liquid film subjected to axial forcing consisting of two components with different amplitudes, frequencies and with a phase angle shift. We have derived a nonlinear evolution equation describing the spatiotemporal dynamics of an axisymmetric liquid film subjected to the above-mentioned forcing using methods of the long-wave theory [3]. We have found the possibility of film rupture prevention even as the forcing parameters of each of the components correspond separately to the domain where rupture takes place.

We have investigated the variation of the critical forcing amplitude in the case of the equal forcing frequencies in the presence of a phase shift. The variation of the critical forcing amplitude as a function of the frequencies' ratio has a unique behavior that exhibits the emergence of spikes. The case of amplitude-modulated single- frequency forcing has been also addressed. In the case of commensurate forcing frequencies, the flow has been found to be quasi-periodic in the parameter range investigated.

The research was partially supported by the European Union via the FP7 Marie Curie scheme [PITN-GA-2008-214919 (MULTIFLOW)].

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Thin Film Behavior Under External Vibrations

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We study the dynamics of a thin liquid film on a horizontal or weakly inclined substrate. The film is parametrically excited by mechanical vertical and horizontal oscillations. Inertia effects are taken into account and the standard thin film formulation is extended by a second equation for the mean flow rate

$$q(x,t) = \int_0^{h(x,t)} v_x(x,t)\, dz \ ,$$

where h is the film thickness and v_x the horizontal velocity.

The set of two coupled PDEs for h and q allows for resonances and instabilities of the flat film due to external vibrations. For certain regions in the amplitude-frequency plane of the excitations we obtain rather involved spatial and temporal pattern formation.

Linear results based on a damped Mathieu equation as well as fully nonlinear results in the frame of long-wave approximation found numerically will be presented.

Parametrically excited Marangoni convection in a locally heated liquid layer

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The results of the numerical simulation of weakly-supercritical thermocapillary convection in a thin layer of liquid with free deformable upper boundary and the inhomogeneous nonstationary source of heat (a pulsatory thermal spot, localized in the space and periodically modulated in time) are represented. Interest to this problem is connected to the capabilities of control of Marangoni flow stability and structures, shown in the case of the infinite liquid layer with spatially homogeneous modulation of the temperature of the interface [1–3]. Furthermore some experimental observations show effects of the onset of localized oscillations of surface and temperature of the liquid layer, heating locally in the near-surface region, followed by appearance of concentric and spiral surface waves in the course of a change in the characteristics of the thermal source [4].

The long-wave approximation is assumed, based on the existence of long-wave instability in a problem with homogeneous heating [2, 3], and assumption that horizontal spatial scale of the flow is much larger than its vertical scale. The heat inhomogeneity is treated as compatible with long-wave approximation, slightly exceeding the critical value of homogeneous heat flux inside the localized hot spot, and having subcritical value outside it, as in the case of a constant localized heat flux [5, 6]. Two limit cases are considered, of low and high frequencies of heat flux modulation respectively. In both cases the problem is reduced to the system of two-dimensional nonlinear equations for the amplitudes of the disturbances of temperature, vorticity and deviation of free surface from the flat undeformed state, generalizing those for the homogeneous heating [3, 7]. In the first case evolution equation is written only for temperature disturbances, and in the second one - also for the surface deformation. The flat and axisymmetrical versions of the horizontal inhomogeneity of thermal spot are examined. The basic non-stationary localized solutions of the system, preserving the spatial symmetry of inhomogeneous heat flux and changing in time with the same period, are determined, their dependence of amplitude and frequency of modulation, parameters of the heat flux inhomogeneity and physical parameters is obtained on the basis of the Galerkin method. The linear stability of the periodic solutions is investigated on the basis of the Floquet method and nonlinear development of 2D disturbances - by pseudo-spectral method. Numerical results show that beyond the limits of the stability region disturbances of the basic solutions with the same (synchronous) or with the doubled period (half-integral) can develop, like in the spatially homogeneous case [1, 2]. The spatial structure of noinlinear regimes is defined either by the localized disturbances of another symmetry (in the flat case - with the odd profiles of the dependencies of the amplitudes of temperature and of surface deformation, in the axisymmetrical case - of dipole structure), or by the disturbances, forming global cellular structures in entire space, occupied with liquid.

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Long wave Rayleigh-Benard-Marangoni instability of a fluid layer with deformable free surface

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The paper deals with the investigation of the buoyancy effect on the onset of thermocapillary instability in a horizontal fluid layer. The lower boundary of the layer is rigid; it is maintained at constant temperature. The upper boundary is free and deformable, at this boundary the heat transfer law characterized by the Biot number is imposed. Since the deformations of the free surface cannot be properly accounted for in the framework of the Boussinesq approximation, to describe the buoyancy effect we implement the model where the density variations are taken into account not only in the volumetric force but also in the mass balance equation and in the inertial terms of the momentum equations. For temperature dependence of the density the exponential law providing the positive values of the density at any temperature difference is accepted. Analysis is restricted by the long wave perturbations and is carried out by the expansions of increments and all hydrodynamic fields into the series with respect to the wave number.

The calculations show that the long wave instability is of the monotonous type. The critical value of the Marangoni number is found to be proportional to the Galileo number and linear function of the Biot number. In the case when buoyancy is absent the result obtained in [1] is reproduced. The buoyancy effect on instability threshold obtained in our paper in non-Boussinesq approximation is qualitatively different than the result obtained in the framework of Boussinesq approach: in the non-Boussinesq model, for any values of the Biot number including zero value, accounting for the buoyancy effect results in the lowering of the instability threshold whereas in the Boussinesq model at zero Biot number the buoyancy does not make any influence on the long wave instability threshold.

The surface tension effect on instability threshold is characterized by the capillary parameter (inverse Crispation number). In real situations this parameter is large such that the surface tension is able to make significant influence even for the long enough waves. To study this behavior we analyze the asymptotics taking into account the capillary parameter and found that the surface tension leads to the sharp stabilization at non-zero wave numbers such that the range of existence of the long wave instability is limited by very large wavelength values and in the limit case of non-deformable free surface it vanishes in spite of the fact that at zero wave number the critical Marangoni number does not depend on the capillary parameter. Thus, there is a crossover – in the limit case where wave number tends to zero and capillary parameter tends to infinity the result depends on the order of limit transitions.

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Pattern formation and mixing in three-dimensional film flow

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The effect of inertia on gravity-driven free surface flow over different three-dimensional periodic corrugations is considered analytically, numerically and experimentally. To validate the theoretical and experimental methods we consider a first experimental system, where the topography is weakly corrugated and we find that the analytical results of the free surface shape and free surface velocity agree perfectly well with the numerical and experimental results. Next, we investigate the flow along a strongly undulated topography over a wide range of film thicknesses. We show that two qualitatively different regimes are possible: for thick films the liquid flows over the topography while for thinner films the liquid film breaks up, shows dry patches and flows around the topography peaks. In the limit of very thin films the flow degenerates to a rivulet flow which concentrates around the minima of the topography only. Apart from the complex free surface distortion we find that the topography induces a flow reversal perpendicular to the main flow direction. For increasing Reynolds number the eddy size grows, reaches a maximum and decreases until the eddy vanishes completely. The complex flow structure motivates us to consider the mixing within the bulk flow. Numerical and experimental results show that the periodic topography shape enhances the laminar mixing within the bulk flow.

Coherent accumulation structures formed by small inertial particles in periodic flows.

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The effect of formation of spiral-like coherent particulate structures in thermocapillary flows in liquid bridge was first observed experimentally more than a decade ago [1]. It occurs in the far supercritical oscillatory regimes of the flow characterized by a hydrothermal wave running in the azimuthal direction. Although the particles are small (with the characteristic Stokes number of the order of 10^{-5}) and in other settings would generally be expected to follow the flow, in certain regimes they organize in stable accumulation structures (PAS). These structures are dynamic and rotate azimuthally together with the wave.

Recently, it was shown that formation of spiral-like PAS takes place in a wide class of time-periodic incompressible flows [2]. Small inertial particles have a tendency to spontaneously align in one-dimensional dynamic coherent structures. From the dynamical systems perspective, this process is accompanied by a dramatic reduction of the degrees of freedom of the system, which indicates on the synchronization as a mechanism behind PAS formation. It was proposed, based on experimental [3] and numerical [2] observations, that this process is comprised of two distinct steps: the migration of the particles from the bulk toward a 'toroidal shell' and the breaking of the the azimuthal symmetry of the shell.

We report the results of our further numerical studies of the coherent structures formation. In particular, in certain regimes we observe formation of *toroidal* coherent structures closely resembling the 'toroidal core' described in experimental studies [4]. We show that formation of these structures can be interpreted as emergence of quasi-periodic attractors in the particle phase space.

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On the different manifestations of particle accumulation structures (PAS) in thermocapillary flows

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The accumulation of particles in thermocapillary flows (PAS) has been a puzzling phenomenon since its discovery by D. Schwabe and co-workers [1]. This is partly due to the difficulties of numerically modeling the phenomenon. As a remedy, a model system will be considered which allows a comprehensive qualitative study of PAS. Using this modeling approach the key factors leading to PAS can be identified and various features of PAS can be elucidated. It is shown how the different types of PAS depend on the flow topology, in particular on the presence of certain closed (invariant) streamtubes. Moreover, PAS is able to explain certain features of flow visualization which were not previously recognized as a manifestation of PAS. There is ample evidence that PAS, as observed in the experiments (see e.g. [2–5]), is primarily due to the finite-particle-size effect discovered by [6]. Curiously enough, inertia plays a minor role in most of the experiments to date.

Support from ESA under contract number 4000103003 is gratefully acknowledged.

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Hybrid Continuum-molecular Modeling of Filtration Flows in the Transition Flow Regime

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For micro- and nano- fluids including motion of particles and fluids in fibrous filters the $Re<1$ and $Kn>0$. The boundary singularity methods (BSM) are advantageous compare to traditional finite-volume methods because they eliminate the need to mesh complex 3-D geometry of flowfield between irregular fibers. Using BSM, only surface of fibers need to be meshed. For nano-scale filtration, flows typically are in transitional molecular-to-continuum regime and, therefore, traditional no-slip boundary conditions are no longer valid. Modeling of flowfield to predict particles' dynamics and material adsorption in fibrous structures is of significant interest. While cell models for predicting the capture efficiency and pressure drop of fibrous media are available, more detailed models of flowfield are currently needed, for example, to predict the position of the adsorbed particles within the multi-modal non-structured fiber web.

A novel hybrid method [1-3] combining the continuum approach based boundary singularity method (BSM) and the molecular approach based direct simulation Monte Carlo (DSMC) is developed and then used to study viscous fibrous filtration gas flows in the transition flow regime, $Kn > 0.25$. First, the flow about a single fiber confined between two parallel walls is used to test the proposed hybrid method. The DSMC is applied to an annular region enclosing the cylinder and the BSM is employed to the entire flow domain. The parameters used in the DSMC and the coupling procedure, such as the number of simulated particles, the cell size and the size of the coupling zone are determined by inspecting the pressure drop obtained. It is observed that in the partial-slip flow regime the results obtained by the hybrid BSM-DSMC method match the ones from the BSM combined with the heuristic partial-slip boundary conditions. For higher Knudsen numbers, the difference in pressure drop and velocity is significant. The developed hybrid method is then parallelized by using MPI and extended for multi-fiber filtration flows. The multi-fiber filter flows considered are in the partial-slip and transition regimes. For $Kn \le 0.25$, the difference in pressure drop between the BSM and hybrid method appears to be less than 10%. For $Kn = 0.75$, the difference in pressure drop approaches 20%. The computed velocity near fibers changes even more significantly with the increase of the Knudsen number, which confirms the need of molecular methods in numerical evaluation of the flow in filters.

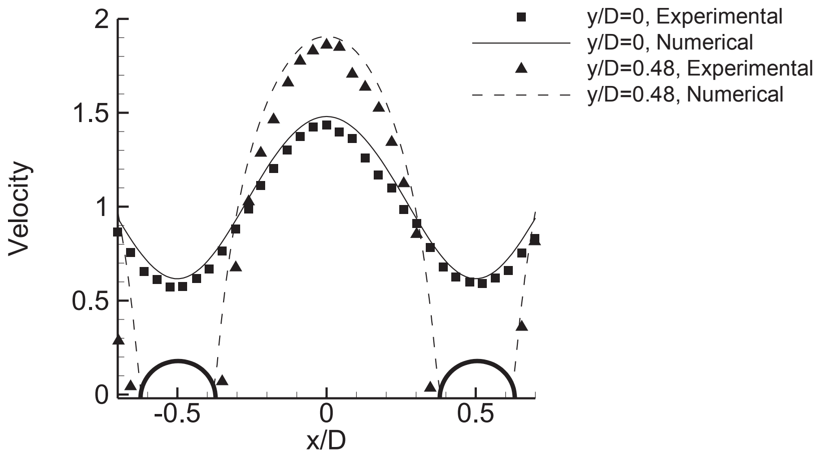

Fig. 1 Comparison between numerical and experimental results

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On the transitions from cellular into a wave-like patterns during the mass transfer of weakly surface-active substances in liquid-liquid systems

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Mass transfer across liquid interfaces is frequently accompanied by solutal Marangoni convection with complex and irregular flow structures. This so-called interfacial turbulence, first studied in the pioneering work by Sternling & Scriven [1], is of considerable importance in chemical engineering. Interfacial turbulence is known to evolve progressively from small to large length scales by a cascade-like process. This hierarchical evolution displays a characteristic sequence of flow structures before it is repeated on a significantly larger length scale. The details of this evolution and the characteristic properties of the various flow structures and their transformations are only poorly understood.

To provide more detailed insights into selected aspects of interfacial turbulence we use a liquid-liquid system in which the mass transfer of a surface-active species leads to a buoyantly stable situation. This system is studies in a set of three-dimensional cuvettes of different geometry which impose constraints on the degrees of freedom. At the beginning, each cuvette is completely filled with one of the solvents. In a second step both cuvettes are superimposed to each other by means of a special experimental setup. The system is studied by shadowgraphy in transmission to follow the evolution of the patterns and their length scales. In parallel, particle image velocity (PIV) is applied to measure the underlying flow fields.

We show that first Marangoni cells of different scale, i.e. order, are developed which may embed a sub-structure of smaller cells. After a while, however, the forcing of this type of cells is too low to sustain them longer and they undergo a transition into a wave-like pattern which may also appear in different orders. In this work we study such waves in lowest order by parallel use of shadowgraphic imaging and PIV which allows to unravel both the mechanism underlying this transformation and the particular features of such waves.

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Faraday wave dynamics of immiscible systems in finite cells

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The motivation of this work is to produce an immiscible Faraday wave system with minimized sidewall stresses, permitting a comparison to available theory for parameter spaces where wavenumber selection is governed by sidewall boundary conditions. The invsicid model of Benjamin and Ursell[1] provides substantial insight into the fundamental physics of the instability, but is insufficient for making predictions in physical systems, in part due to its offering of instabilities arising from perfect resonance for infinitesimal forcing amplitudes. Linear damping has been incorporated into this model to aid matching with experiment, but this requires a phenomenological parameter and can't be used to make predictions a priori. The viscous model of Kumar and Tuckerman[2] treats the viscous effects of the system rigorously, and its predictions have been validated for conditions where sidewalls do not effect wavenumber selection. Prediction of threshold amplitudes where the excited wavelength is of the order of the lateral cell dimensions is much more challenging due to wetting and contact non-idealities at the sidewalls.

In these experiments the s formation of a sidewall film of the upper fluid allows for an apparent free motion of the bulk phases and interface. Minimization of the upper fluid viscosity shows the thickness of this film decrease and in turn the no-stress limit is approached. Making the stress-free assumption, threshold amplitudes for a cell mode and its bounding co-dimension 2 points are well predicted by the Kumar and Tuckerman model, with slight deviation due to residual sidewall effects. Experiments near the threshold suggest a forcing frequency-dependent transition from subcritical to supercritical bifurcations. In the subcritical parameter space, unbounded growth and wavebreaking is common, while saturation to standing waves is more common in the supercritical space. In the saturation to standing waves, it is seen that the linear spatial form of the mode is well preserved for forcing amplitudes near the instability threshold, and sufficient increase promotes the development of secondary instabilities that serve as higher order system damping. This behavior helps explain the differences of what can be expected in a two liquid system versus a single liquid system, a central question to this work.

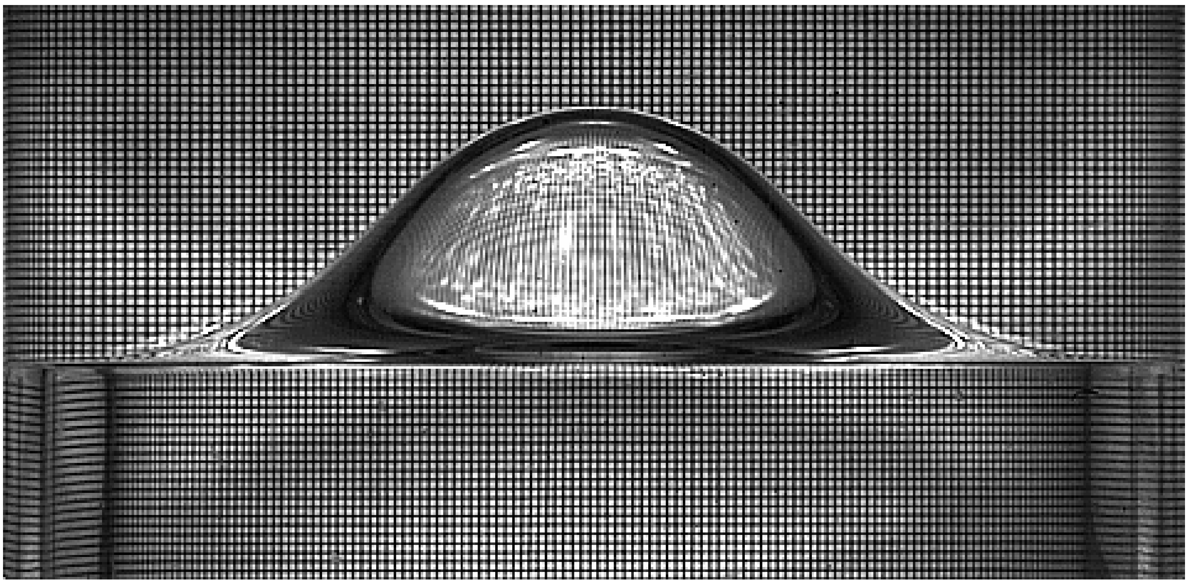

Fig. 1 Experimental excitation of (0,1) cylindrical mode in an immiscible liquid system

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Model-based estimation of nonlinear dissipation mechanisms in free and modulated surface flows

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The focus of this investigation is on model-based estimation of nonlinear dissipation mechanisms in free and modulated surface flows. The identification of damping mechanisms is straightforward for linear processes governed by exponential decay or response to external harmonic excitation. However, processes governed by self-excited modulation or parametric excitation require an intimate knowledge of nonlinear damping, without which response may spuriously grow without bound. Examples include parametrically excited Faraday waves [1], trapped waves in confined domains [2], parametrically excited liquid films [3], and scattered pressure waves due to acoustic fluid-structure interaction [4]. We employ a spline-based methodology where controlled measurements of surface flow growth are decomposed into slowly-varying amplitude and phase, which in-turn enable construction of nonlinear frequency and damping backbone curves [5]. The latter enable estimation of nonlinear damping mechanisms from models that can be reduced to their equivalent normal forms by temporal multiple-scale asymptotics. Validation of the nonlinear model-based damping mechanism is obtained by comparison to independently obtained data (figure 1). We consider nonlinear damping mechanisms estimated from both a small-scale Faraday wave experiment, a numerical model for thin film evolution, and scattered pressures wave from an acoustically excited panel. Results shed light on the significance of nonlinear damping mechanisms that govern complex and chaotic-like dynamics.

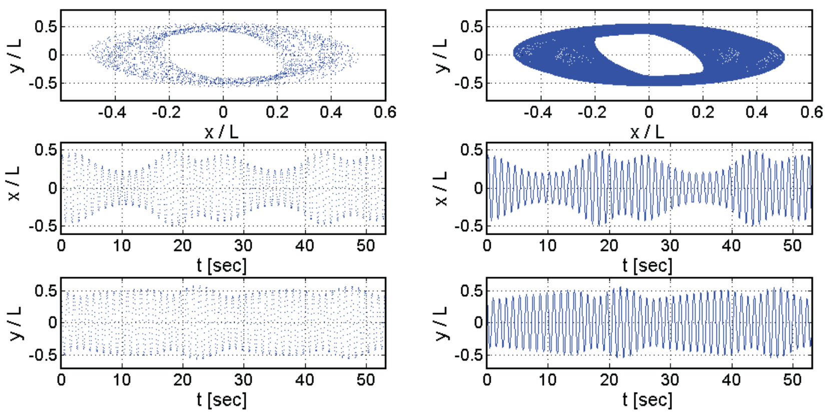

Fig. 1 Quasiperiodic modulation [5]: experiment (left) and model-based numerical simulation (right)

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Nonlinear dynamics of a liquid film on an axially oscillating cylindrical surface in the high-frequency limit

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Thin films exist in nature as membranes of red blood cells, lining of the alveoli of lungs, enclosures of microorganisms and as mucus films in the human eye. In the industry, they appear in paints, coatings, insulating layers in micro-circuitry, emulsions, and adhesives. An effective method for investigation of the dynamics of thin liquid films is based on the study of the pertinent evolution equation derived using the long-wave approximation [1]. It has been found, both experimentally and theoretically, that vibration may dramatically affect the behavior of a physical system and lead to its stabilization or destabilization [2],[3],[4],[5].

In this research, we investigate the nonlinear dynamics of a thin liquid film coating a horizontal cylindrical surface subjected to fast axial harmonic vibration via the evolution equation derived here for the averaged film thickness. The method used in this work is based on multiple-scale asymptotic expansions for the Navier-Stokes equations and the relevant boundary conditions, and on separation of the fields into averaged and pulsating parts, similar to what was done by [6] who investigated the behavior of films on a flat substrate.

Linear stability and weakly-nonlinear analyses are carried out based on the nonlinear evolution equation derived here. Depending on the choice of the parameter set, namely the forcing amplitude and the frequency, linear stabilization of the system is observed in certain ranges of the ratio between the mean film thickness and the cylinder radius. Furthermore, external forcing can be also destabilizing in other parameter domains. This interesting response of the system provides a tool for a premeditated change of the width of the instability domain with respect to the unforced case and for a control of the system.

Weakly-nonlinear analysis carried out based on the evolution equation derived here, shows the emergence of either supercritical or subcritical bifurcation from the equilibrium depending on the choice of the parameter set. In the case of supercritical bifurcation, saturation of the pattern and the emergence of a nontrivial steady state are expected slightly beyond criticality. On the other hand, in the case of subcritical bifurcation we expect rupture of the film. The numerical investigation of the strongly nonlinear dynamics of the film based on the aforementioned evolution equation is now underway.

The research is partially supported by the European Union via the FP7 Marie Curie scheme [PITN-GA-2008-214919 (MULTIFLOW)].

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Thermocapillary Pumping by Periodical Heating

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We use direct numerical simulations of the full Navier-Stokes equations and a long-wave theory to examine the two-dimensional fluid flow in a thin layer of viscous fluid placed on a solid substrate. The substrate is heated in a non-uniformly manner, such that the substrate temperature profile exhibits a sinusoidal shape. Furthermore, the sinusoidal temperature distribution can propagate along the substrate with a constant speed, thereby forming a steady traveling thermal wave.

Using the two models, we examine the film deformation and emerging flows in a thin liquid film for different values of the Marangoni number, thermal wave amplitude, and thermal wave speed. Specifically, we demonstrate that the film has a stable steady-state solution with a non-flat interface when the thermal wave is stationary. A good agreement between the models is found in predicting the shape and time evolution of an initially flat liquid film. However, when the Marangoni number is sufficiently large the solution of the Navier-Stokes equations indicates the formation of circulatory rolls in the thicker part of the film which cannot be predicted using the long-wave analysis. These short wave rolls suppress the film deformation and stabilize it.

When the thermal wave moves along the substrate with a constant speed, a unidirectional fluid flow emerges in the liquid film, thereby creating a pumping effect. The pumping direction coincides with the direction of the traveling wave. The film deformation decreases when the wave speed increases. The flow rate increases with the magnitude of the Marangoni number until the continuous film breaks down and form a train of separate droplets. An increase of the wave speed also enhances the pumping. However, when the wave speed exceeds a critical magnitude the film exhibits a chaotic behavior and the pumping rate drops.

The results of our study open a new way for regulating fluid flows in open microfluidic devices in which fluids are exposed to the surrounding air. Thus, our results will be useful for such applications as bio-sensing, molecule manipulation, explosives detection, and microchip cooling. Furthermore, manipulating fluid flows using thermal waves in open microfluidics allows to design adaptive devices in which the operational pattern can be widely adjusted during device operation.

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Oscillatory instability of thermocapillary convection in a bilayer liquid system

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The linear instability analysis of thermocapillary convection in a bilayer system of Silicon oil 10cs and Fluorinert FC70 liquids is discussed[1]. The bilayer system is bounded below by a rigid plate and above by a free surface with a passive gas, and the two immiscible liquids are separated by an interface. The system is subjected to a constant temperature gradient $\partial_x T = -b, (b > 0)$ parallel to the substrate[2,3], so we defined a Marangoni number $Ma_1 = \gamma_1 b h_2^2 / \rho_2 \nu_2 \kappa_2$, where $\gamma_1 = -\partial_T \sigma$, σ is the surface tension of the liquid-gas interface, $h_2, \rho_2, \nu_2, \kappa_2$ are the depth, density, kinematic viscosity, and heat diffusivity of FC70 respectively. In this study, we consider a micro-gravity environment and neglect the buoyant effect. By using the fully numerical method to study the linear stability problem, two typical cases are studied, including steamwise homogenous disturbances (the streamwise disturbance wave number *α*=0, results is shown in Fig.1), and spanwise homogenous disturbances(the spanwise disturbance wave number *β*=0). When *α*=0, it is found that convection in the two layers may occur in the form of stationary mode (Mechanical Coupling (MC) mode and Thermal Coupling (TC) mode) or oscillatory mode. And the oscillatory mode takes the form of traveling wave that propagates in either spanwise direction. When *β*=0, convection in the two layers occurs in the form of oscillatory mode, and this mode takes the form of traveling wave propagating in the same direction as base flow. Furthermore, discussion of the three dimensional disturbances to the system suggests that the spanwise disturbance is the most dangerous mode to the system.

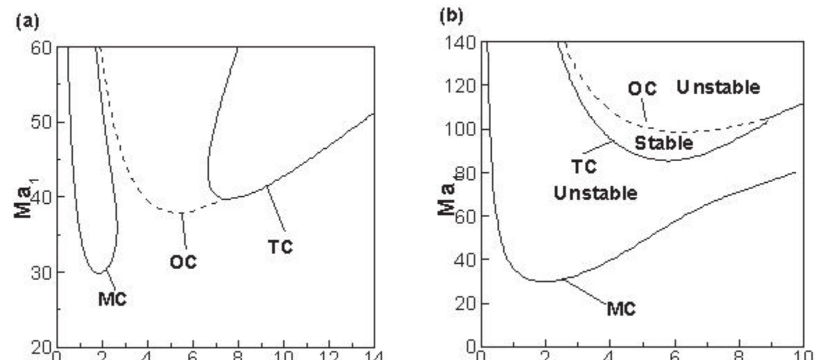

Fig. 1 Marginal curves of the system in *Ma-k* plane for Different Biot numbers: (a) *Bi*=30 and (b) *Bi*=300, at same depth ratio *h* (h_1/h_2)=0.5, and streamwise disturbance wavenumber *α*=0. The dashed lines correspond to the oscillation mode and the solid lines represent the stationary mode.

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Parametric instability of a Marangoni convection in a thin film

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We study parametric excitation of a Marangoni convection in a thin layer atop a solid substrate of high thermal conductivity. The layer is subject to the vertical vibration of the amplitude large in comparison with the mean layer thickness. The vibration frequency is assumed low, such that the vibration period is comparable to the evolution time of a layer. Stability of the oscillated layer against the Faraday waves is guaranteed by the restriction on the amplitude [1].

We demonstrate that under these conditions the vibration results only in a gravity modulation within the conventional amplitude equation derived in [2]. Linear stability analysis based on the Floquet theory shows that the stability threshold is independent of the amplitude of the gravity modulation. However, when noise is present in a real system, the critical Marangoni number should depend on both the vibration amplitude and the noise intensity; in the limit of high noise levels this guess is confirmed and the layer destabilization occurs.

Computations are performed in order to investigate the nonlinear dynamics of the system. It is shown that the layer loses its stability subcritically within the Floquet theory, which again reaffirms the layer destabilization in a noisy case. A limit cycle emerges as a result of instability. A perturbation grows at such phases of the vibration, when the vibration diminishes the modulated gravity and even changes its the direction; a strong spike-like impulse emerges. When the gravity starts increasing, this perturbation decreases fast and the layer returns to the almost undeformed state. Calculations are carried out in the wide range of the problem parameters. In particular, the longitudinal length of the computational domain proves very important; no spatially periodic regimes are found as this length increases.

We also carry out an asymptotical analysis of the amplitude equation in the limit of high rescaled frequency. This analysis allows partial reduction of this model to the averaged description of the system [3]. To that end an intermediate asymptotics is derived, which matches both the discussed modulation effects and the oscillatory motion studied in [3].

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The buoyancy effect on oscillatory Marangoni instability in liquid layer with a deformable surface

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We study an oscillatory instability of horizontal flat liquid layer with deformable surface. The liquid is considered to be isothermally incompressible. Lower rigid boundary is heat-insulated. Upper free boundary is deformable and the Newton law for heat transfer is formulated here. Surface tension coefficient is assumed to be linearly dependent on temperature. Exponential density dependence on temperature is assumed.

We do not use the Boussinesq approximation in the problem statement. The density dependence on temperature is included not only in the buoyancy force term but everywhere in the Navier-Stokes equation, the continuity condition and boundary conditions. This very model is supposed to be appropriate for investigation of systems with a deformable surface.

The two-dimensional perturbations of equilibrium state is examined numerically. Maps of stability and neutral curves are obtained for different parameters (Prandtl number, Galileo number, capillarity parameter, Boussinesq parameter). Also the linear analysis of instability revealed an additional oscillatory instability mode with zero Marangoni number and zero gravity (see Fig.1). The main mechanism of this instability is supposed to be determined both by surface deformability and strong density dependence on temperature. The influence of diferent factors such as gravity, capillarity on an additional instability is investigated. The parameter region of soft instability excitation is detected by weakly nonlinear analysis of a new mode.

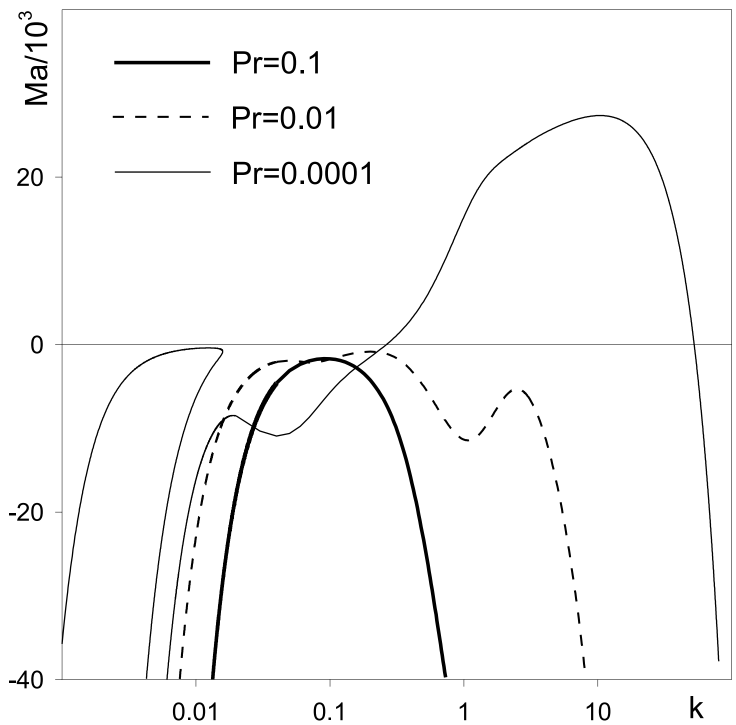

FIG. 1: Neutral curves of Marangoni instability for different Prandtl numbers

Bénard-Marangoni instability in a viscoelastic ferrofluid

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Ferrofluids are magnetic fluids formed by a stable colloidal suspension of magnetic nanoparticles dispersed in a carrier liquid. Without an applied external magnetic field the orientations of the magnetic moments of the particles are random resulting in a vanishing macroscopic magnetization (magnetic disorder). An external magnetic field, however, easily orients the particle magnetic moments and a large (induced) magnetization is obtained. There are two main features that distinguish ferrofluids from ordinary fluids, the polarization force and the body couple [1]. In addition, when a magnetic field is applied, the ferrofluid can exhibit additional rheological properties such as magneto-viscosity, adhesion properties, and non-Newtonian behavior, among others [2]. In the last decades much efforts have been dedicated to the study of convection mechanisms in ferrofluids. In addition, heat transfer through magnetic fluids, in particular, has been one of the leading areas of scientific study due to its technological applications [3].

Finlayson [4] studied the convective instability of a magnetic fluid for a fluid layer heated from below in the presence of a uniform vertical magnetic field. He discussed the cases of both, shear free and rigid horizontal boundaries within the linear stability method. Recently, the thermal convection in viscoelastic magnetic fluids was studied for idealized and rigid boundary conditions [5,6].

On the other hand, the Marangoni instability is a good example of a surface tension driven instability. If a temperature gradient is applied to a layer of a fluid with a free surface, the heat conducting state becomes unstable, and convection starts, beyond a certain critical temperature gradient, when the heating is done from below. The linear analysis of the convection in a magnetic fluid with deformable free surface was studied in Refs. [7,8], while the linear and weakly nonlinear analysis in the case of viscoelastic pure fluids was performed in Refs. [9,10].

In this work, we report theoretical and numerical results on the Bénard-Marangoni convection of a magnetic fluid in a viscoelastic carrier liquid. The viscoelastic properties are given by the Oldroyd model. The lower boundary is rigid, while the upper one is free, giving rise to a Marangoni number describing surface tension effects and a Biot number due to heat transfer effects. We calculate numerically the convective thresholds using a spectral method. The effects of the Kelvin force and the rheological properties on the instability thresholds are emphasized.

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Movement of composite microcapsules in a viscous liquid

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Microcapsules are of importance for modern nanotechnologies and are characterized by diverse values of their parameters. Centrifugation is a production stage of microcapsules; therefore, information on their hydrodynamic behavior is not only of mathematical interest, but may appear to be useful for their production and fractionation, as well as the targeted formation of their sediments.

In this work, we consider a viscous liquid flow around a capsule. The capsule is modeled as a permeable spherical shell, the characteristics of which are the parameters of the problem. Assume that the interior of the capsule is free of foreign bodies and filled with the liquid that flows around it.

Let us consider a flow around a spherical capsule with radius $\tilde{a}$ that represents a droplet with radius $\tilde{R}$ coated with a porous layer having thickness $\tilde{\delta}$ with the flow having preset velocity at infinity, direct $\tilde{z}$ axis along velocity vector $\tilde{\mathbf{U}}$ and specify spherical coordinate system ($\tilde{r},\theta,\varphi$) with the origin located at the center of the capsule.

At small Reynolds numbers, the motion of the liquid inside ($0<\tilde{r}<\tilde{R}$ - region no. 1) and outside ($\tilde{a}<\tilde{r}<\infty$ - region no. 3) the capsule will be described by the Stokes and continuity equations as follows:

$$\tilde{\nabla}\tilde{p}^{(i)}=\tilde{\mu}\,\tilde{\Delta}\tilde{\mathbf{v}}^{(i)};\;\; \tilde{\nabla}\cdot\tilde{\mathbf{v}}^{(i)}=0. \qquad (i=1,3) \qquad (1)$$

The motion in the porous layer ($\tilde{R}<\tilde{r}<\tilde{a}$ - region no. 2) will be determined by the Brinkman and continuity equations presented below:

$$\tilde{\nabla}\tilde{p}^{(2)}=\tilde{\mu}^{(2)}\tilde{\Delta}\tilde{\mathbf{v}}^{(2)}-\tilde{k}\tilde{\mathbf{v}}^{(2)};\;\tilde{\nabla}\cdot\tilde{\mathbf{v}}^{(2)}=0, \qquad (2)$$

where the tilde refers to dimensional values; superscript (*i*) denotes the number of a region to which a value is relevant; $\tilde{\mu},\tilde{\mu}^{(2)}$ are the viscosity coefficients of the liquid flowing around and the Brinkman medium, respectively; $\tilde{p}^{(i)}$ refers to pressures; $\tilde{\mathbf{v}}^{(i)}$ refers to velocity vectors; and $\tilde{k}$ is the Brinkman constant, which is proportional to the specific permeability of the porous layer.

At the porous layer–liquid interfaces ($\tilde{r}=\tilde{R}$ and $\tilde{r}=\tilde{a}$), the continuity conditions of velocities, normal stresses $\tilde{\sigma}_{rr}$, and jumps in tangential stresses $\tilde{\sigma}_{r\theta}$ are imposed as follows:

$$\tilde{\mathbf{v}}^{(i)}=\tilde{\mathbf{v}}^{(2)};\;\tilde{\sigma}_{rr}^{(i)}=\tilde{\sigma}_{rr}^{(2)};\;\tilde{\sigma}_{r\theta}^{(i)}-\tilde{\sigma}_{r\theta}^{(2)}=\mp\beta\tilde{v}_{\theta}^{(i)}\sqrt{\tilde{k}_0\tilde{\mu}},\;(i=1,\,3) \qquad (3)$$

where β>0 is a parameter characterizing the jump in the tangential stresses, which varies in the range of 0 to 1.

The following continuity condition of a uniform liquid flow is imposed in the distance from the capsule:

$$\tilde{\mathbf{v}}^{(3)}\to\tilde{\mathbf{U}},\tilde{r}\to\infty\,. \qquad (4)$$

The system of equations (1, 2) with boundary conditions (3, 4) was solved analytically. Velocity and pressure distributions were determined.

An important characteristic of the problem under consideration is force $\tilde{F}$ applied to the capsule by the external liquid as follows:

$$\tilde{F}=\oiint_S\left(\tilde{\sigma}_{rr}\cos\theta-\tilde{\sigma}_{r\theta}\sin\theta\right)ds\,. \qquad (5)$$

Dimensionless force Ω is determined by the ratio of force $\tilde{F}$ to the Stokes force $\tilde{F}_{\rm st}=6\pi\tilde{a}\tilde{\mu}\tilde{U}$. Force $\Omega(\delta,m,s_0,\beta)$ is a function of four arguments. Parameter $\delta=\tilde{\delta}/\tilde{a}$ is the dimensionless porous layer thickness, $m=\tilde{\mu}^{(2)}/\tilde{\mu}$ is the ratio between the viscosities of the liquid flowing around and the Brinkman medium, $s_0=\tilde{a}/\sqrt{\tilde{\mu}/\tilde{k}}$ is the dimensionless Brinkman coefficient characterizing the drag of the porous medium, and parameter β characterizes the tangential stress jump at the porous medium–liquid interface.

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Thermocapillary Instability of Three Immiscible Phases Flowing Through a Channel

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Previous studies considering thermocapillary convection in symmetrical multilayer systems assume the interface is rigid (non-deflecting) and the fluids are stationary. This paper re-examines the Marangoni-Bénard instability for a three-layer system with deflecting interfaces undergoing planar Poiseuille flow. Linear stability analysis shows that at small and large wave numbers a deflecting interface has a different linear stability than a non-deflecting interface. At intermediate values of wave number both cases have the same stability point. Furthermore, considering a deflecting interface reveals that a base planar Poiseuille flow affects the linear stability of the system. The dependence of the linear stability analysis on the viscosity ratio and depth ratio are also presented.

Instability in the presence of evaporation for binary liquids

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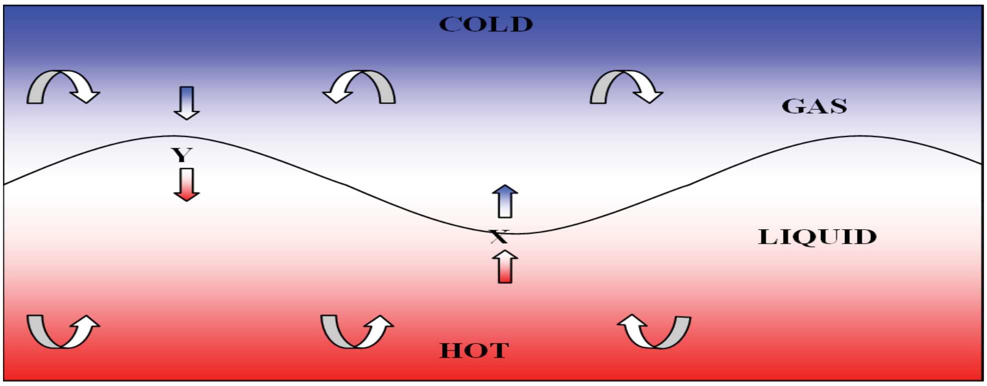
There are several applications in chemical engineering in which convection phenomena play a very important role, ranging from crystal growth and the coating of films to the casting of alloys and the space processing of glasses and semiconductors and in most of those applications involve mixtures of fluids. Common to, many of these problems is the occurrence of an interface such as a fluid-fluid or fluid-solid interface and when there is an interface there often occurs a form of interfacial instability wherein a sudden change in interfacial pattern occurs as system control variable crosses a critical value.

In this study, evaporative convection accompanies the classical Rayleigh and Marangoni convection phenomena. Having two or more fluids introduce solutal effect into the system such as concentration dependence of density and concentration dependence of surface tension. Due to these new effects binary mixtures behave different than pure ones.

Pure evaporative convection, in the absence of gravity and surface tension, can occur if the system is bounded by impermeable walls and there is a temperature gradient at the interface. The closed system guarantees zero total evaporation rate. Note that in the closed system the liquid which evaporates at the trough has to condense at the crest. As a result of evaporation there will be an upwards flow at troughs and a downward flow at the crest as shown in Fig 1 ,which is an indication of convection.



In this work the effect of mass fraction, vapor dynamics and heating arrangement (heating from below or above) are investigated. Calculations are done for a deflecting interface both in the presence and absence of gravity.

The results show that the deeper the liquid layer, the more unstable the system becomes. However, a similar statement does not hold for the vapor layer height. For the vapor layer height, there is a trade off between the buoyancy-driven convection and the stabilizing effect of vapor flow of phase change even when buoyancy is ignored. Thus there is a turning point of stability for the vapor height where the destabilizing effect of the buoyancy overcomes the stabilizing role of vapor flow arising from phase change itself.

On the interaction between Marangoni cells and double diffusive fingers in a reactive liquid-liquid system

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We study a novel kind of coupling in chemo-hydrodynamic pattern formation driven by a neutralization reaction along a plane interface separating two immiscible liquid phases [1]. The neutralization reaction, during which a surface-active carboxylic acid is converted into a surface-active salt, gives rise to numerous cycles of relaxation oscillations between a fast cellular Marangoni convection with parallel-acting density plumes and a slow finger convection, cf. Fig. 1. By means of particle image velocimetry the dynamics of the sub-structured Marangoni cells are characterized while their geometrical aspects are analysed using shadowgraphy for different concentration ratios between acid and base. Based on concentration-dependent density measurements and further experiments with miscible solutions, the finger convection could be clearly identified as a double-diffusive phenomenon with the base and salt as the quickly and, respectively, slowly diffusing species. Furthermore, the interaction of the sub-structured Marangoni cells with the density effects is examined. The behavior found is compared with other experiments using slightly different chemical species [2]. The comparison allows to draw interesting conclusions with respect to the problem of interfacial turbulence.

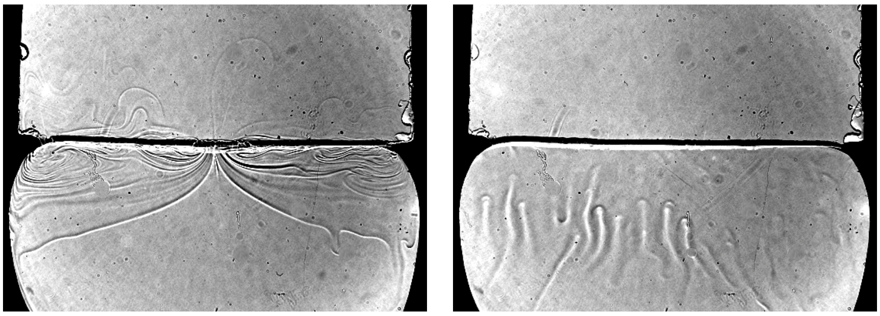

FIG. 1: Marangoni cells (left) and double diffusive fingers (right) which couple during the mass transfer of carboxylic acid undergoing a neutralization in the aqueous phase [1].

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The influence of thermocapillary effect on the stability of fluid interface subjected to the horizontal vibrations

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The influence of thermocapillary effect on the onset of instability of fluid interface subjected to the gravity and horizontal vibrations of finite frequency and amplitude is studied. Two-layer system of horizontal layers of immiscible fluids of different densities (lower fluid is more dense) subjected to the vertical temperature gradient is considered. In the absence of heating, parametric waves can be excited on the interface under the action of finite-frequency vibrations. For horizontal vibrations the excitation of parametric waves was studied in [1] for inviscid fluids and in [2] for viscous fluids and, differ from well-known Faraday ripple, only synchronous resonance instability zones were found. Additionally to the parametric instability, fluid interface subjected to the horizontal vibrations can become unstable due to the development of Kelvin-Helmholz instability [3,4]. For thin layers this instability is of the long-wave type and for the layer thickness exceeding certain critical value the perturbations with finite wavelength are most dangerous such that a frozen wave develops on the interface [3].

In the presence of vertical temperature gradient, two-layer system can become unstable due to the development of thermocapillary instability. The interaction of parametric and thermocapillary instability mechanisms was studied for the case of vertical vibrations in [5]. It was found that thermocapillary effect makes significant influence on the Faraday instability threshold. The present work deals with the investigation of thermocapillary effect on the onset of instability of fluid interface subjected to the horizontal vibrations. Two-layer system of thin horizontal layers of viscous incompressible immiscible fluids is considered. The buoyancy effect is neglected. The problem allows the solution which corresponds to the plane-parallel flow with flat interface where only horizontal component of velocity is non-zero; it depends on time and transversal coordinate. For the case of low viscosity stability of this basic state is studied analytically. It is found that, depending on the fluid properties, the thermocapillary effect can make either stabilizing or destabilizing influence. For finite values of viscosities stability of fluid interface is studied numerically. The transformation of neutral curves with the increase of Marangoni number is investigated. Numerical results well correspond to the conclusions made on the basis of the analytical investigation.

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Stability of an evaporating falling film

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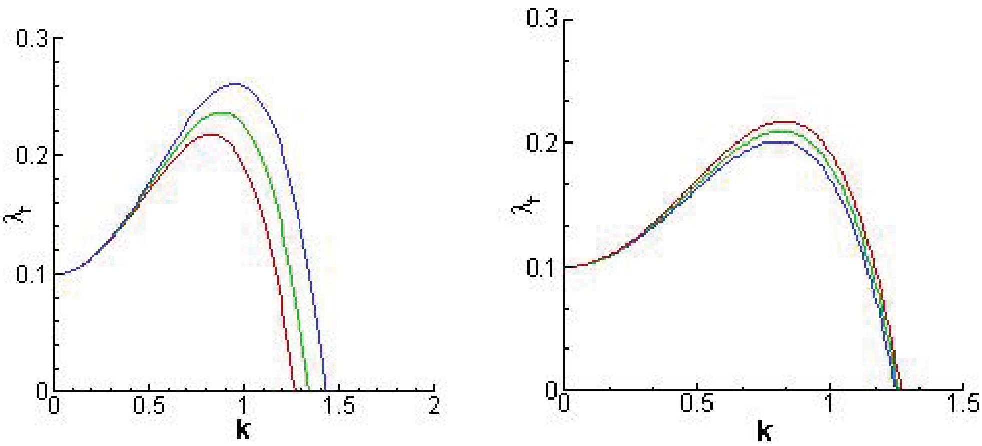
We use a newly developed set of interfacial conditions[1,2] to revisit the problem of a falling film driven by gravity on a uniform heated inclined plate. Instead of using the Hertz-Knudsen-Langmuir relation[3], we consider a more general equation expressing the balance of configuration momentum at the interface, and derive a Benney-type equation governing the film thickness h. Two new terms are introduced into the governing equation. One accounts for the energy flux along the interface which is measured by a dimensionless parameter $\overline{N} = \varepsilon T_s \nu \eta_s / \kappa \Delta T h_0$, and the other is referred as effective pressure, and the magnitude of which is measured by a dimensionless parameter $A_2 = T_s \nu^2 / L \Delta T h_0^2$, where T_s is the saturation temperature, ν is the kinematic viscosity, η_s is the interfacial entropy density, κ is the heat diffusivity, ΔT represents the temperature between the temperature of substrate and the saturation temperature, L is the latent heat, and h_0 is the initial depth of the liquid film, ε is a small parameter which is defined by h_0 / l_0 (l_0 is proportional to a typical wave length). Linear stability analysis shows that the effective pressure and energy transport along the interface is stabilizing. Results are shown in Fig.1. Nonlinear evolution study shows that rupture time of the film increases with increasing the effective pressure effect or energy transport effect obviously, when the vapor recoil effect is present.



(a) (b)

Fig. 1 Effective growth rate λ_r versus the disturbance wave number k.
(a) for different effective pressures: $A_2 = 0.04$ (red line), $A_2 = 0.02$ (green line), and $A_2 = 0$ (blue line) ; (b) for different energy flux: $\overline{N} = 0$ (red line), $\overline{N} = 0.15$ (green line), and $\overline{N} = 0.3$ (blue line). Both the two figures are plotted under the same evaporation number $\overline{E} = 0.1$, and Reynolds number $\mathrm{Re} = 5\sqrt{2}/2$.

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Creeping motion and coalescence of droplets in a tube flow

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Creeping motion of droplets in a tube flow is expected to be useful for fluid handling technique, controlling chemical reaction and so on. In the case of motion of droplets with suspended particles, DDS (drug delivery system) can be cited as one of applications. The problem is also underlying basis on analyzing the flow of multiphase fluids through porous media. Such phenomena can be seen, for instance, in enhanced oil recovery, breaking of emulsions in porous coalescers and so on.

Regarding study examples of creeping motion of droplets in a tube flow, Hetsroni et al. [1] considered motion of a droplet and bubble with small d/D(d:undeformed diameter of droplet or bubble, D: tube diameter)theoretically. Higdon et al. [2] obtained resistance functions for spherical particles, droplets and bubbles numerically. Olbricht et al. [3,4] investigated mainly coalescence time of coalescence phenomena of droplets. There exists little information, however, on induced flow in coalescing droplets and effects of suspended particles in the droplets concerned on their coalescence.

In this experiment, a glass tube of 2.0 mm in inner diameter, 7.0 mm in outer diameter, and 1500 mm in length is used as a test tube. Silicones oil of 50, 1000 and 6000cSt are employed as the test fluid for the droplet. Mixture fluid of glycerol and pure water is used for a surrounding fluid in the tube flow. The density of the droplets is matched to that of the surrounding fluid by adding carbon tetrachloride. An over flow tank is used to keep the flow in the tube steady at a designated averaged velocity V. The test tube is surrounded by a tank filled with a temperature-controlled water to keep the temperature of the system constant. Droplets are injected into the test tube using micro-syringes in front of inlet of the tube. Behaviors of droplets and suspended particles are monitored by a digital video camera, CCD cameras and high speed cameras placed on a sliding stage. The motion of the stage is electrically controlled to follow the travelling droplets in the tube. Motion of single droplet is examined. Coalescence time of two droplets is measured and the time is compared with semi-theoretical equation obtained by reference to semi-theoretical equation by Aul et al. [4]. Induced flow of coalescing droplets is investigated using colored droplets and droplets with suspended particles.

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Thermocapillary Levitation of Nanoliter-Volume Single- and Compound-Phase Droplets

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A novel method of droplet transport developed by Nagy and Neitzel [1] utilizing a thermocapillary levitation technique and applied to microliter-volume droplets of silicone oil is desirable for application to lab-on-a-chip (LOC) architectures. The levitation technique exploits the permanent nonwetting phenomenon studied by Dell'Aversana et al. [2] which drives a layer of lubricating gas between the droplet and substrate. A silicone-oil droplet levitated using this technique is shown in Fig. 1. As illustrated in the cartoon of Fig. 2 and demonstrated by Nagy and Neitzel, an asymmetry in the surrounding flow field generated by off-center heating yields a propelling force driving the droplet in the direction of the heater. One benefit of this levitation technique compared with other, more traditional mechanisms of LOC transport (e.g. large pressure gradients, capillary pumping, or electrokinetics [3]) is a complete lack of contact between droplet and substrate, thereby reducing friction and preventing sample cross-contamination when employing multiple-use chips. In order to apply the technique to LOC systems, it must be shown to work with nanoliter-volume droplets. It has been suggested that a minor amount of squeezing (to alter the spherical shape of a droplet whose diameter is much less than the liquid's capillary length) may be necessary to provide enough surface area over which the pressure within the lubricating layer can act to support the droplet's weight. Preliminary experiments suggest otherwise, however, and the experiments presented within this study will explore whether there is a need for squeezing of droplets of $O(nl)$ volume. Additional studies on oil-encapsulated-water (compound) droplets will be attempted. This will provide further impetus for the technique's application to LOCs, given the fact that many bio-processing applications (e.g. DNA testing) utilize aqueous samples that may not be as suitable for thermocapillary processes due to the possibility of surface contamination interfering with the driving thermocapillary surface flows.

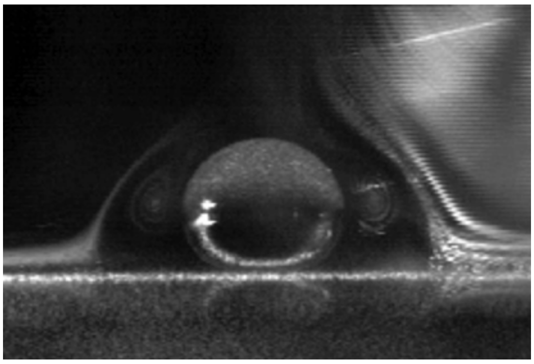

Fig. 1 Image of levitated microliter-volume silicone oil droplet with visualization of surrounding flow field

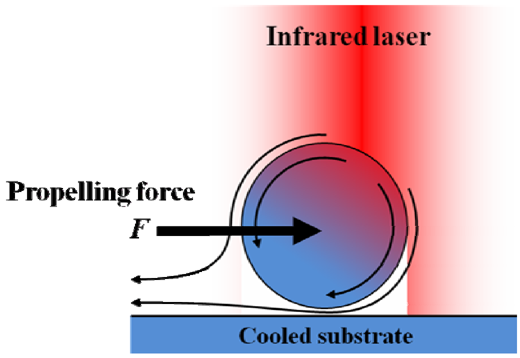

Fig. 2 Illustration of a levitated nanoliter-volume silicone oil droplet with resulting propelling force caused by asymmetric heating

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Droplet actuation induced by coalescence: experiments and modeling

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Microfluidic devices play an ever increasing role in nano- and biotechnologies. An emerging area of research in this technology-driven field is digital microfluidics which is based upon the micromanipulation of discrete droplets. Microfluidic processing is performed on unit-sized packets of fluid which are transported, stored, mixed, reacted, or analyzed in a discrete manner. An obvious challenge however is how to displace the sessile droplets on a substrate. This work investigates a little explored driving mechanism to actuate droplets: the surface tension gradient which arises during the coalescence of two droplets of liquid having different compositions and therefore surface tensions. The resulting surface tension gradient gives rise to a Marangoni flow which, if sufficiently large, can displace the droplet. This mechanism is, in a sense, analogous to the well-studied thermo-capillary actuation.

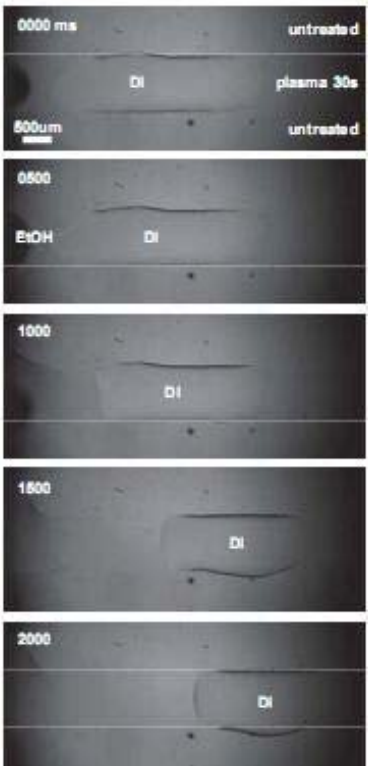

Fig. 1: Droplet actuation on a hydrophilic stripe.

In order to understand, the flow dynamics arising during the coalescence of droplets of different fluids, a model has been developed in the lubrication framework. This model builds on earlier work from Sellier and co-workers, [1,2]. The numerical results confirm the existence of a self-propulsion window which depends on two dimensionless groups representing competing effects during the coalescence: the surface tension contrast between the droplet which promotes actuation and species diffusion which tends to make the mixture uniform thereby anihilating Marangoni flow and droplet motion.

In parallel, experiments have been conducted to confirm this self-propulsion behaviour. A range of fluid combinations on different substrates has been tested. The expected self-propulsion behaviour was indeed observed as illustrated in Figure 1. In this figure, a droplet of distilled water is first deposited on a “hydrophilc highway”. This stripe was obtained by plasma-treating a piece of PDMS which is shielded in some parts by glass coverslips. This surface functionalization was found to be the most convenient way to monitor in a controlled manner the coalescence. When a droplet of ethanol is deposited near the “water slug”, coalescence occurs and a rapid motion of the resulting mixture is observed. For the case of Figure 1, the droplet velocity was in the order of 0.8 mm/s and displacements in excess of 5 times the initial droplet size were repeatedly observed. This phenomena is the open flow analogue of the one reported by Bico and Quéré [3] in closed capillaries.

The observed phenomena could offer an attractive alternative to other droplet actuation mechanisms currently in use which rely on sophisticated micro-fabrication techniques.

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Translation of Droplets in Viscoplastic Fluids

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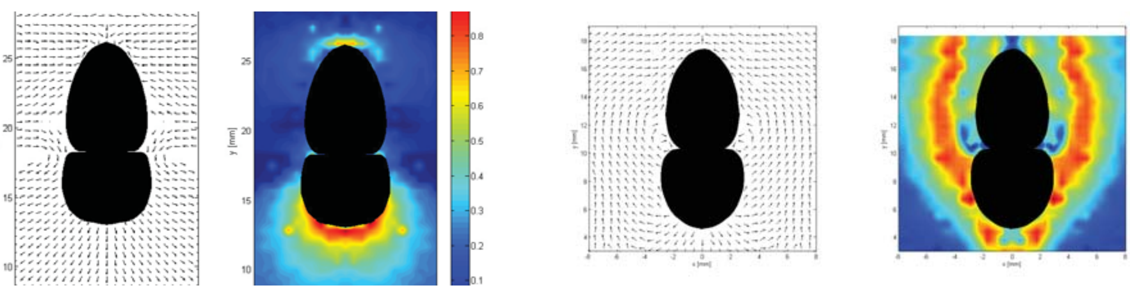
We report on an experimental study of the motion of viscous drops in an otherwise quiescent yield stress material. The focus of the study is the determination of the yielded region around the inclusion and the flow field there, making use of flow visualization techniques, Particle Image Velocimetry (PIV) and Particle Tracking Velocimetry (PTV). The drops move under the action of gravity either in an unbounded domain or in the presence an adjacent vertical wall or a neighbor drop. Low concentrated aqueous gel of Carbopol 940 (0.07% w/w) was used as the yield stress material. Newtonian drops (R ~ 2.8mm) of various densities having similar viscosity and interfacial tensions were used. Heavier and faster drops move with velocity of O(0.1 mm/s) when isolated, while lighter ones move an order of magnitude slower, with velocity of drops of O(0.01 mm/s). The measured velocity data are results averaged for 5 experimental runs, with at least 40 image pairs in each run.

For the motion in unbounded domain, it was demonstrated that the yielded region extends more vertically than horizontally. The vertical extent does not significantly change with the drop speed, but the horizontal dimension at the equator expands considerably for drops with higher velocity.

When the drops settle in the proximity of a vertical solid wall, their settling speed is augmented. This behavior is contrary to what is known for Newtonian or viscoelastic domains. In addition, it is demonstrated that, when close to the wall, the drops drift slowly toward it, again opposite to what is anticipated for Newtonian systems. The increase in settling speed can be attributed to the dynamic formation of a thin clear solvent layer providing effective wall slip.

When two equal-side drops are released at some distance from each other, the trailing drop moves considerably faster than the leading one. As a result, the drops approach each other and eventually coalesce. We have visualized flow field around a system of two slow drops from the beginning of their motion until the process of the coalescence is completed. When the trailing drop reaches the leading one, the drop doublet moves ensemble a relatively long time before the coalescence begins (the doublet travels about approximately three drop sizes). The flow field around the doublet during this stage of interaction process is presented in Fig. 1 (a). At the beginning of the coalescence process the flow field around the drop doublet changes drastically. The drops elongate, the flow field becomes more intensive and a small vortex develops near the boundary between the two drops. Figure 1 (b) presents the flow field and the flow intensity after the onset of the coalescence process. The time interval between states in (a) and (b) is less than 0.2 s.



(a) (b)

Fig.1. Flow field (left subplots) and flow intensity (right subplots) around a coalescing doublet system during its quasi-static motion. (a) The trailing drop reached the leading one, but coalescence has not yet begun; (b) Immediately after coalescence starts. Frames are taken 0.2 s apart.

Effect of the Direction of the Electric Field on the Interfacial Instability between a Newtonian Fluid and a Viscoelastic Polymer

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Electrohydrodynamics is shown to be an effective method for inducing interfacial instability between two immiscible fluids flowing in a microchannel. In this study, we perform linear stability analysis of the interface between a Newtonian fluid and an Upper Convective Maxwell fluid. The fluids are assumed to be immiscible and leaky dielectric. The electric field is either parallel or normal to the flat unperturbed interface between the two fluids. A comparative study of the effect of the Weissenberg number, the physical system such as depth ratio of the fluids, and the fluid properties is conducted.

Experimental investigation of 3-dimensional wavy liquid films under the coupled influence of thermo-capillary and electrostatic forces

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The wave topology of falling liquid films under non-isothermal conditions is strongly influenced by the presence of thermo-capillary (Marangoni) forces at the interface which leads to destabilization of the film flow and to appearance of rivulets, as presented by Lel et al., 2008 [1]. As a consequence film rupture might occur, possibly damaging the heater or temperature sensitive fluids. The strong coupling between flow and temperature field complicates the investigation of Marangoni driven flows, for which reason an alternative or additional surface force can be imposed by the presence of an electric field for the case of dielectric working fluids, also showing a destabilizing effect on the film topology. Investigations of the sole influence of this force have been presented in Rohlfs et al, 2011 [2]. In the present study, new experimental results of the coupled influence of both surface forces on regularly excited three-dimensional surface waves will be shown. Figure 1 (top) illustrates the employed measurement section, whereby the streamwise excitation is realized by way of an upstream loudspeaker (not shown), and the spanwise wavelength, λ_z, by equidistantly spaced needles. The resulting falling film is exposed to an electric field established between a heatable copper plate ($\dot{q}''$) and a glass plate coated with a thin electrically conductive Indium-Tin Oxide (ITO) layer, thereby allowing optical access for different measurement techniques. Film thickness measurements performed by the confocal-chromatic imaging technique will be presented for isothermal and non-isothermal cases with and without an applied electric field. Due to the good repeatability of these surface waves, three-dimensional pictures where reconstructed from the pointwise measurements consecutively gathered in spanwise direction. Figure 1 (bottom) shows a typical three-dimensional surface wave as presented in [2]. For isothermal conditions, the electric field leads to a local increase of maximum film thickness and can cause a breakup of the wave front. Under heating, the wave topology is expected to form rivulets, leading to an accumulation of the fluid in the colder regions, which will be further intensified by the destabilizing character of the electric surface force.

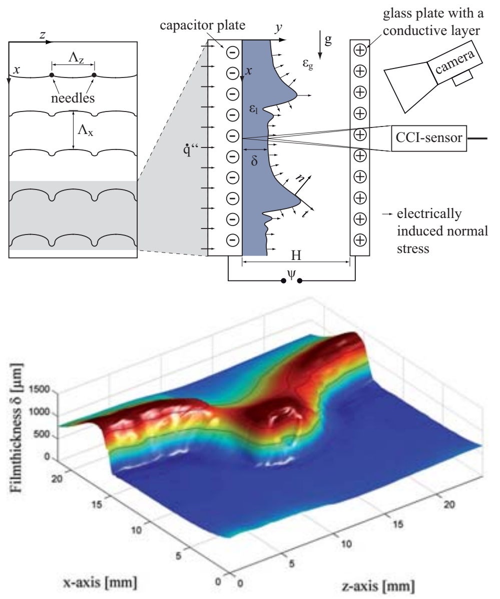

FIG. 1: Top: schematic drawing of the experimental setup: front view (left) and side view (right); Bottom: reconstructed three-dimensional plot from the surface waves with contours shown for 900μm, 1200μm.

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The continuous separation of molecules on the basis of their polarizability using optical electric fields

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We introduce a new and revolutionary way to separate macromolecules. The principle is to use light to selectively retain some molecules over others depending on their differential interaction with optical fields. We call the method Photonic Waveguide Chromatography (PWC), as it combines photonic waveguides and a flow channel that constitutes a ”column” of conventional liquid chromatography. This presentation will focus on the underlying physics and our current theoretical efforts to characterize the parameter space of this process: considering both the design of the optical electric fields and the fluid dynamics needed to effectively separate molecules. This new method has a higher selectivity than traditional techniques and avoids the problem of fouling. The theoretical separation efficiency and resolution of PWC will be compared to other chromatographic techniques for various macromolecular and biological systems.

Effect of the influence of *slow* rotation to stability of thermocapillary incompressible liquid flow in infinite layer in microgravity situation

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The stability of thermocapillary flow arising in a rotating thin infinite liquid layer in microgravity situation is investigated. Both borders of a layer are free and also they are considered as plane, the thermocapillary tangent Marangoni force acts on them and a convective heat exchange on a Newton's law is present on the boundaries. The axis rotation is perpendicular to a liquid layer. The rotation is slow enough and allows neglecting centrifugal force [1].

Then the bound temperature is linear function of horizontal coordinates x, y the considered thermocapillary flow is described by analytically, being the exact solution of Navier-Stokes equations [2]. There are two horizontal components of velocity: $u_0(z)$ and $v_0(z)$, which profiles are depend on the Taylor number (*Ta*), the Grashof number (*Gr*) and temperature $Ax+By+\tau_0(z)$, which profile is depend on *Ta*, *Gr*, the Prandtle number (*Pr*) and the Biot number (*Bi*).

According to the linear theory of stability the neutral curves depict the dependence of a critical Marangoni number (*Mn*) on a wave number at different small values of the Taylor and the Grashof number for $Pr=6,7$ and $Bi=0,1$. It was used the technique of small perturbation [3, 4] for calculations. The behavior of perturbation of finite amplitude in the supercritical region for the Marangoni numbers large than critical ones was investigated by a grid method on the bases of nonlinear system.

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Effect of system rotation on thermocapillary convection and stability of silicon melt in differential heated annular pools

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Abstract In order to understand the effect of system rotation on the thermocapillary convection and its stability, the numerical analysis was conducted for the rotation-thermocapillary convection of silicon melt in differential heated annular pools rotating about its center axis with inner radius of 20 mm, outer radius 40 mm. The axisymmetric steady rotation-thermocapillary convections under rotation rates ranging from 0 to 2.09 rad/s were simulated numerically. The critical Marangoni numbers for the incipience of oscillatory flow and the dissipative structures of flow were determined by linear stability analysis, as shown in Fig.1. The results indicate that the weak pool rotation with low rotation rate destabilizes the axisymmetric steady thermocapillary convection, whereas the rotation with high rotation rate stabilizes the flow. The wave pattern of dissipative structure under critical conditions propagates azimuthally in the same direction as pool rotation direction. The vortex comes out at the bottom of layer when the pool rotates with high rotation rate, which destabilizes the convection slightly.

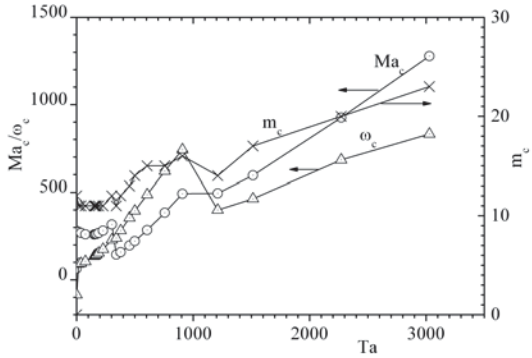

Fig. 1 Critical Marangoni number, critical wave number and critical phase velocity (Ma_c, m_c and ω_c) for the onset of oscillation flow as a function of Ta number

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Investigation of Instabilities in a Thermocapillary-Driven, Low Prandtl Number Liquid Bridge with Magnetic Stabilization Using Three-Dimensional Simulations and Linear Stability Theory

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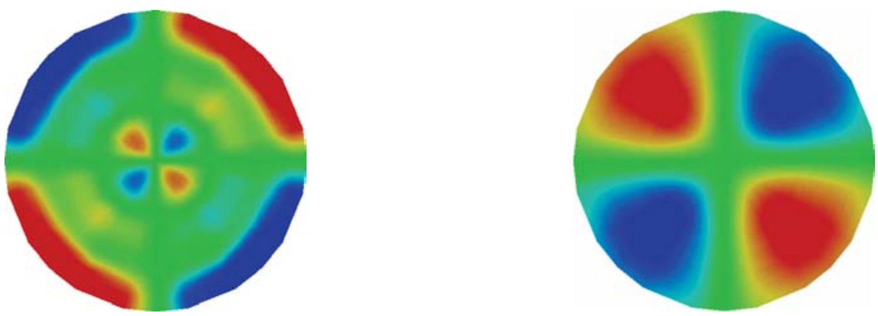
Instabilities in a Full-Zone, thermocapillary-driven liquid bridge with magnetic stabilization are investigated at Prandtl number 0.02 with height-to-diameter aspect ratio 1. Results of three-dimensional, time-dependent spectral element simulations are in good agreement with linear stability theory. Without magnetic stabilization there is competition between two steady modes of opposite symmetries at a thermocapillary Reynolds number, Re_{FZ}, near 1750. This is just above the value of the critical instability, predicted by three-dimensional simulations to occur between 1600 and 1650 and by linear stability to transition at $Re_{FZ,cr} = 1546.58$. In three-dimensional simulations the perturbation alternates between symmetric and anti-symmetric modes. Linear stability theory verifies that these two modes exist as unique steady modes [1].

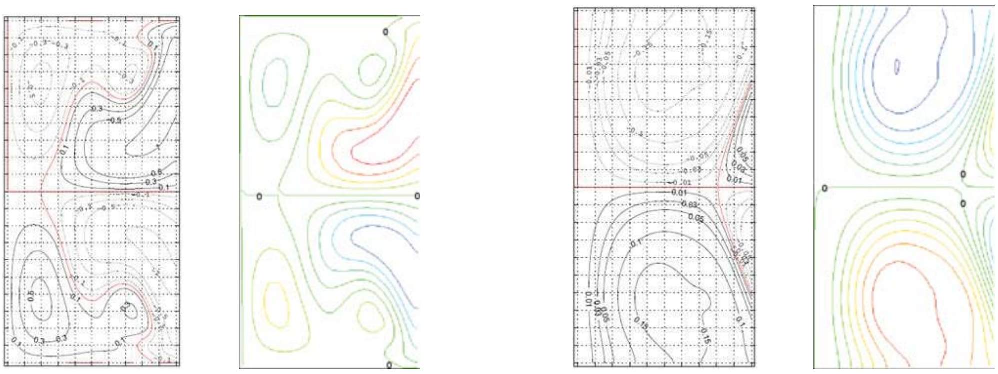
A common practice in crystal growth processes is to apply a magnetic field to avoid the onset of instabilities, which can lead to microstructure defects and compositional nonuniformity. A constant, uniform, axial magnetic field, measured by the Hartmann number, is applied to the Full-Zone and flow instabilities are investigated with field strengths up to $Ha = 50$. Instabilities predicted by three-dimensional numerical simulations are compared to those predicted from linear stability theory by Huang and Houchens [2]. For each value of Ha, flow simulations are computed for a range of Re_{FZ} near the predicted critical value and the flow dynamics are monitored for modal competition. Figure 1 shows the azimuthal velocity (a) and the electric potential (b) found with three-dimensional simulations for the $Ha = 5$ case, confirming the $m = 2$ mode. Figure 2 shows good agreement of the azimuthal velocity (a,b) and electric potential (c,d) between eigenfunctions predicted via linear stability theory ($Re_{FZ,cr} = 1842.97$) and three-dimensional numerical simulations.



(a) (b)

FIG. 1: The stationary $m = 2$ mode for $Ha = 5$ at $Re_{FZ} = 1950$ shown by a) the azimuthal velocity and b) electric potential at $z/b = 0.5$.

[1] Davis, K., Huang, Y. and Houchens, B., *Physics of Fluids*, under review.
[2] Huang, Y. and Houchens, B., *European Physical Journal - Special Topics*, **192**, pp. 47-61, 2011.



(a) linear stability

(b) 3D simulation

(c) linear stability

(d) 3D simulation

FIG. 2: The stationary $m = 2$ mode for $Ha = 5$ at $Re_{FZ} = 1950$ shown by comparison of three-dimensional simulations to linear stability theory via contours of the azimuthal velocity (left) and the electric potential function (right) over the domain $1 \leq z/b \leq -1$ and $0 \leq r \leq 1$ in the θ plane where each reaches its maximum.

Effect of interfacial shear on the longwave Marangoni instability in a locally heated falling film

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We consider the motion of a liquid film falling down a locally heated planar substrate. The flow is driven by gravity and a unidirectional 'wind' shear $\boldsymbol{\tau}$ is applied to the free surface. The problem is studied in the framework of longwave theory. Marangoni effect due to the local temperature gradients at the free surface induces a horizontal bump in the vicinity of the upper edge of the heater and results in an instability in the form of a rivulet structure periodic in the transverse direction. We focus on the effect of shear $\boldsymbol{\tau}$ on the two-dimensional steady-state solutions of longwave equations. Further we analyse the linear stability of this bump with respect to disturbances in the spanwise direction. Our computations show that the shear in streamwise directions will decrease the hight of the bump. We also studied the influence of $\boldsymbol{\tau}$ on the dispersion relations between growth rate of the fastest growth mode and the wavenumber. It is shown that the increase of $\boldsymbol{\tau}$ significantly damps the growth rate of the most unstable mode. Three-dimensional simulations have been performed to investigate the influence of shear on development of the rivulet structure beyond the instability threshold.

Consider a thin liquid film falling down an inclined substrate with inclination angle θ with respect to the horizontal direction. A heater is embedded in the substrate and produces the temperature field $T_0(x)$ at the plate surface, and the thickness of film far away from the heater is uniform. The coordinate system is constructed with x in the streamwise direction, y the spanwise direction and z normal to the substrate. For the present problem, an appropriate choice of the length scale and the time scale is based on a balance of viscous and gravitational forces. the dimensionless variables (primed) are defined by

$$\begin{aligned} x = Lx',\ \ y = Ly',\ \ z = Hz', \\ u = \frac{g\cos\theta H^2}{\nu}u',\ \ v = \frac{g\cos\theta H^2}{\nu}v',\ \ w = \frac{g\cos\theta H^3}{\nu L}w', \\ p - p_\infty = \rho g L\cos\theta p', \tau = \rho g H\cos\theta\tau',\ \ t = \frac{\nu L}{g\cos\theta H^2}t', T - T_\infty = \Delta T T', \end{aligned} \tag{1}$$

where H is the height of the film, L is the length scale in the streamwise direction over which temperature varies, p_∞ is the ambient pressure, ΔT is the temperature jump at a heater and T_∞ is the ambient temperature. We obtain the evolution equation of the thickness of the film,

$$\frac{\partial h}{\partial t} + \boldsymbol{\nabla}\cdot\left(\frac{h^3}{3Bo}\boldsymbol{\nabla}\nabla^2 h - \frac{h^2}{2}Ma\boldsymbol{\nabla}T_i\right) + \frac{1}{2}\boldsymbol{\nabla}\cdot(\boldsymbol{\tau}h^2) + \frac{1}{3}\frac{\partial h^3}{\partial x} = 0. \tag{2}$$

In figure 1, we present the influence of interfacial shear on the profiles of the film thickness at different Marangoni number for several typical cases. It is shown that the increase of interfacial shear will decrease the hight of bump near the vicinity of the local heater.

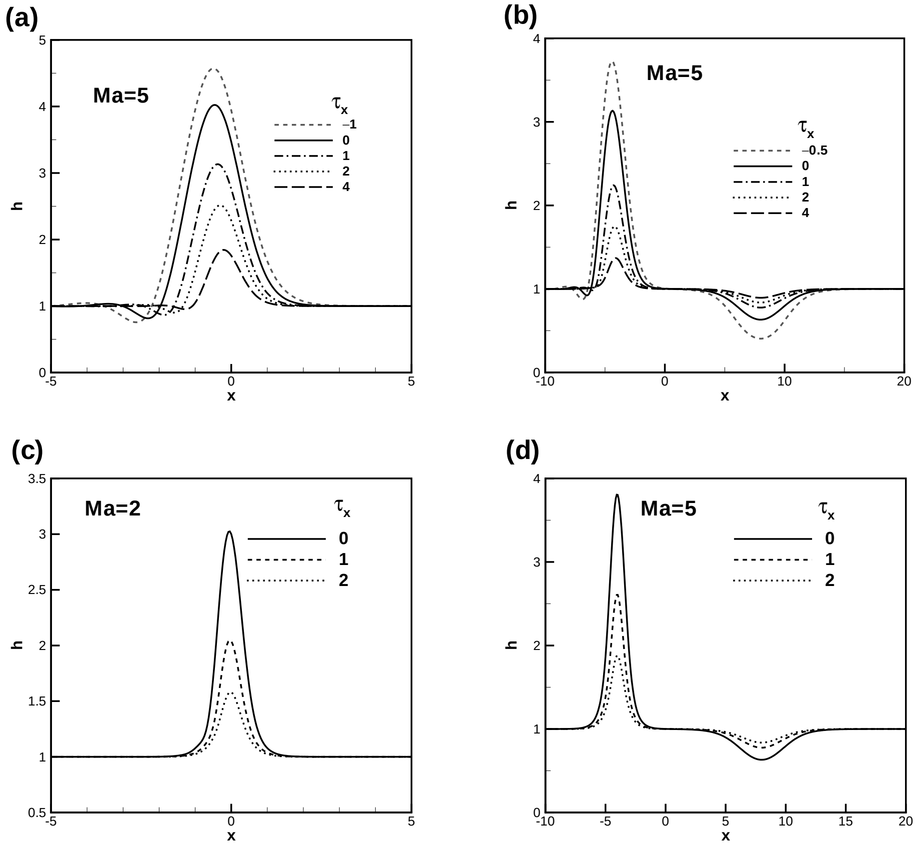

FIG. 1: Effect of interfacial shear on the film profiles for the steady solutions at $Bi = 0$. (a),(c) for semi-infinite heater with $l = 20L$ and the wavelength $\lambda = l/L$, (b),(d) for finite length heater with the wavelength $\lambda = 40$. $Bo = 10$ for (a) and (b), and $Bo = 1000$ for (c) and (d).

Thin film flow: rivulet formation, evolution and merger

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The motion of a thin liquid film, either perfectly or partially wetting, of asymptotic thickness H_0, down a planar substrate inclined at an angle θ to the horizontal can result in complex behaviour and interesting dynamics at the associated advancing front which becomes unstable as the flow evolves. Huppert [1] was the first to make a detailed study of the same, showing the critical wavelength of the emerging instability, when scaled with the capillary length for the liquids considered, to be captured by a linear fit. In the present work, this three-dimensional flow is revisited, requiring a numerical solution of the associated governing equations.

The liquid is considered to be incompressible with constant density, ρ, viscosity, μ, and surface tension, σ. Under the assumption that H_0 is small compared to the capillary length, $L_0 = H_0/(6Ca)^{\frac{1}{3}}$, where $Ca\ O(\epsilon^3) << 1$ is the capillary number (= $\mu U_0/\sigma$), that is $H_0/L_0 << 1$, taking $U_0 = 3Q_0/2H_0$ (Q_0 being the volumetric flow rate per unit width) and adopting appropriate scalings, the governing Navier-Stokes and continuity equations reduce to a coupled system of partial differential equations for the film thickness, h, and pressure, p [2]. At time zero, the system is perturbed with a superposition of N modes with random length, l_j, and differing wavelength, $\lambda_{0,j}$, as in [3] via $h(x,y) = 0.5\left\{1 + h^* - (1-h^*)\tanh\left[x - x_f(y)\right]\right\}$; $x_f(y) = x_u - \sum_{j=1}^{N} l_j \cos(2\pi y/\lambda_{0,j})$, where x_u is the position of the unperturbed front.

Despite the simplifying assumptions made, the associated computational challenges are significant given the extent of the solution domain involved and the long-time solutions required; the case of partially wetting films further adds to computational effort required. Accordingly, a key feature of the methodolgy adopted to solve the discretised governing equations accurately is one based on a strategy employing automatic error controlled adaptive time stepping and mesh refinement/derefinement within an efficient multigrid framework. Noting that sufficiently far away from the advancing front, the film thickness remains constant, provides another avenue for exploitation, in that judiciously removing nodes in such regions has a dramatic effect in terms of further reducing the solution time required without loss of accuracy.

In the case of both perfectly and partially wetting films, the predicted rivulet pattern at long times is found to be in very good agreement with observations made experimentally, for example [4]; for a perfectly wetting film Huppert's [1] suggested linear fit is recovered exactly. Similarly, the shape and dynamics of the rivulets change with inclination angle. In addition, from the resulting long-time solutions generated it is possible to construct a map of rivulet wave length versus inclination angle (up to and including a vertically aligned substrate) which can be used to predict whether, as a particular film flow evolves with time, neighbouring rivulets will merge.

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Preliminary Results of the Influence of Thermo-capillary Forces on Two-Dimensional Wavy Falling Films of Water

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Heat exchangers employing falling films are a well-known method that is often coupled with phase or mass transfer in industrial applications. These applications may consist of water-based or water-soluble substances, and as such water presents a relevant liquid. However, within the field of falling films, pure water is one of the most difficult liquids to work with, due to its high surface tension and relatively low viscosity, leading to: surface wetting problems, increased growth of disturbances and a strong influence of boundary conditions. These problems make it very hard to obtain two-dimensional wavy flows, for comparison with and for validation of numerical and analytical solutions. The last comprehensive experimental study on high-waves in falling films of water was conducted by Nosoko and Miyara, 2004 [1], in which photography was employed in order to establish wave shape and length. Although well-defined waves were generated in that work, the analysis of these was somewhat limited.

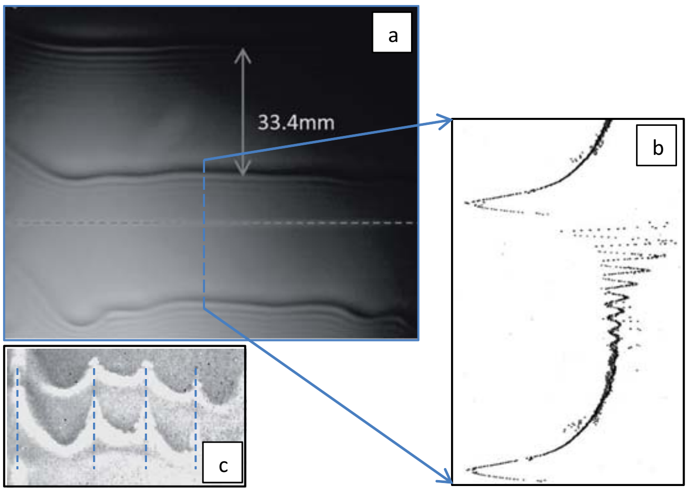

FIG. 1: Typical two-dimensional waves in water falling films, 140mm downstream of the inlet (dashed line in a)): a) averaged-image of 30 waves; b) CCI film thickness measurement; c) with high heating - dashed lines indicate hot-streaks

In the present study, great efforts were made in order to produce stable two-dimensional waves in water (see Fig. 1), these were photographed and in addition wave topology (film thickness) was measured with high accuracy by the CCI optical method. The present study proposes a criterion for two-dimensionality of the waves, under which an extended range of Reynolds numbers and frequencies, for the occurrence of two-dimensional waves, is identified. From the film-thickness measurements that were performed, the waves and their development were characterized in a detailed quantative manner.

Once, the range of conditions over which two-dimensional waves could be obtained was established, it was examined how the waves are destabilized by the addition of heating (see Fig. 1c). For example, in the work of Lel et al., 2008 [2], spanwise-periodic hot-streaks were observed in heated silicon-oil wavy films , due to thermocapillary (thermal Marangoni) effects. In the present study, similar hot-streaks were observed and analyzed in water films, an observation that has not previously been reported.

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Modulation instability for a longwave oscillatory Marangoni convection

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Selection of wavy patterns is known to be a complicated issue, which is far from being fully understood. Most studies in this field deal only with the selection of stable oscillatory patterns on a fixed lattice, either square or hexagonal. Near the stability threshold, appropriate sets of Landau (ordinary differential) equations were studied in [1, 2]. However, these regular, periodic in space, patterns also can exhibit instability with respect to spatial modulation. In order to describe such instability, a set of Ginzburg-Landau (partial differential) equations should be investigated.

Applying the multiscale-expansion technique, we derive a set of Ginzburg-Landau equations valid for an analysis of longwave oscillatory convection. The model is based on two assumptions, namely: (i) the dispersion relation is quadratic with respect to the wavenumber; and (ii) only gradients of the amplitude functions, not the functions themselves, appear in the amplitude equations. Examples of the phenomena satisfying these conditions are buoyancy [3] or Marangoni [4] convection in a layer of a binary fluid.

Analyses of the regular patterns found in [1, 2] based on this set of amplitude equations demonstrate that depending on the pattern, up to four types of perturbations exist corresponding to different types of modulation of standard patterns. For each pattern and each type of perturbations the stability conditions are obtained.

We apply these conditions to the particular problem of the Marangoni instability in a binary mixture. In the case of Alternating Rolls, the only stable pattern on a square lattice [5], the domain of stability substantially diminishes due to modulation perturbations. Among the patterns that belong to a hexagonal lattice [6], no patterns stable with respect to modulation are found. In both cases, the instability mode is qualitatively similar to that leading to a self-focusing in nonlinear optics.

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[6] Shklyaev, S., Nepomnyashchy, A. A. and Oron, A., *Phys. Rev. E*, **84**, 056327, 2011.

Thermocapillarity instabilities in a free liquid film.

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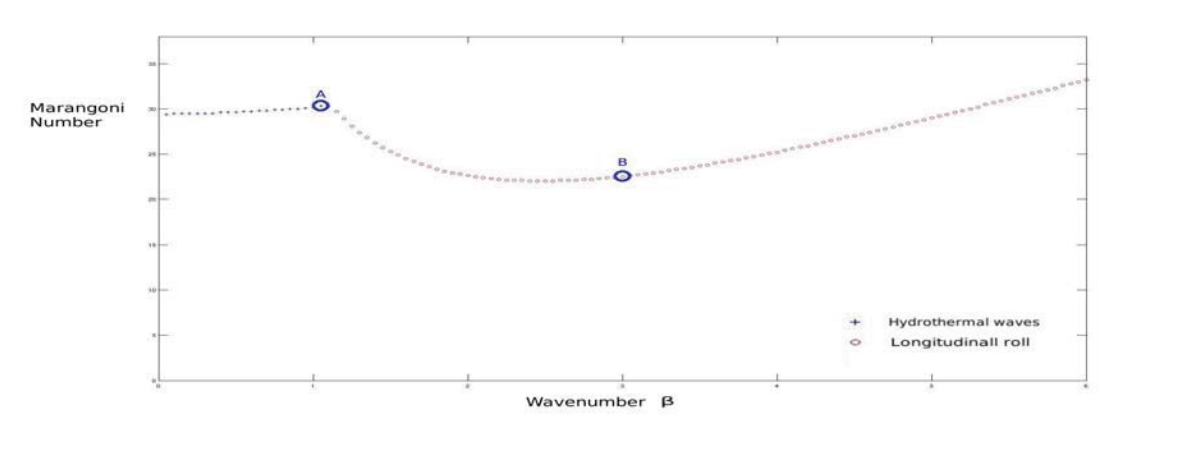
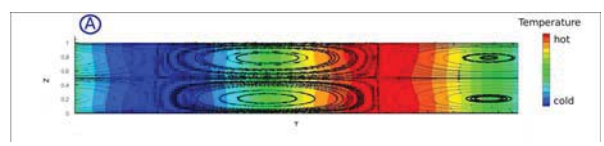
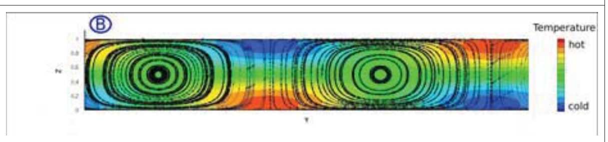
This talk is about the generation of thermocapillary instabilities in a three dimensional liquid film that is subject to a horizontal temperature gradient on two surfaces. A temperature gradient along the layer is imposed which then generates a steady shear flow that is driven by thermocapillarity. Using linear-stability, Smith and Davis [1] predicted two kinds of instabilities: steady longitudinal-rolls and oscillatory hydrothermal waves. The occurrence of these have been demonstrated by experiments and numerical calculations. This phenomenon has importance in the field of semiconductor crystal growth, where these instabilities create "striations" that can alter the material properties. While the applications often involve more than one free surface it appears that there is little knowledge about the thermocapillarity driven flow in a free liquid with two free surfaces [2]. One of the advantages is that the fluid is not bounded by walls along its large free surfaces so that during processing there will be less contamination by the container. A linear stability for a free liquid film with two velocity profiles ("linear flow" and return flow), is presented with different Prandtl and Biot numbers. A comparison with the work of Smith and Davis is made. The figure below shows the stark transition from a double roll structure with oscillatory flow to a single roll steady structure. The physics of the transition and its experimental implications are discussed.



Neutral curves for longitudinal rolls and hydrothermal waves
in the "linear flow" for the free liquid film with Bi=0 and Pr=1





The projected streamlines at a constant x-location

A) is for the longitudinal hydrothermal waves in the "linear flow" for the free liquid film at β=1

B) is for the longitudinal rolls in the "linear flow" for the free liquid film at β=3

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Dynamic interface deformation under the actions of Marangoni convection and coaxial gas stream.

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Heat/mass transfer on the moving gas-liquid interface is an important subject directly related to many industrial applications from crystal growth to cooling of electronic devices. In the present study, the attention is focused on the dynamics of the gas/liquid interface in the system with cylindrical symmetry. A cylindrical liquid bridge is co-axially placed into an outer cylinder with solid walls. The internal column consists of solid supports at the bottom and top, while the central part is a liquid zone filled with viscous liquid and kept in its position by surface tension. Gas enters into the annular duct and entrains initially quiescent liquid. Besides, the temperature difference may apply between the two rods which causes thermocapillary flow. This study is concerned to future space experiment JEREMI (Japanese European Research Experiment on Marangoni Instabilities) which aims at the examination of the influence of an coaxial gas flow on the Marangoni convection in liquid bridges with a final target to control the threshold of instability.

Static deformation is unavoidable in the experiments, performed in ground conditions. Flow inside liquid bridge causes additional dynamic deformation, which could be stationary or oscillatory depending on the type of flow. The flow patterns caused by co-axial gas or thermo-capillary convection have been studied previously [1], [2]. In the earlier experimental studies the dynamic deformation caused by thermocapillary flow have been analysed [3]. Here we analyze experimentally the dynamic surface deformation caused by coaxial gas stream and compare with numerical simulations. The study is performed in liquid bridges of different initial volumes and various aspect ratios.

We will also present a numeral study of the dynamic interface deformation under simultaneous action of Marangoni force and coaxial gas stream. Comparison with available experimental results will be provided.

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Onset of Oscillatory Thermocapillary Convection in Liquid Bridge with various Pr Numbers

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Thermocapillary convection is thermo-fluid phenomena, therefore Prandtl number (Pr) which is a ratio of kinematic viscosity and thermal diffusivity is very important parameter affecting on flow and temperature fields. In thermocapillary flow, a driving force to induce flow exists on only surface. So, temperature distribution on free surface is quite different in each Pr number and it directly affects the flow motion. As a result, the onset of oscillatory convection should have a feature in each range [1]. In case of the low Pr number fluid, the first bifurcation to three-dimensional steady convection occurs initially, the transition to oscillation is observed in a higher temperature difference. In contrast, for the high Pr number, oscillatory flow appears from axisymmetry steady one above certain critical value.

Many experiments to determine the critical Marangoni number at the onset of oscillatory flows for high Prandtl number (Pr) fluids have showed dependence of the diameter of the liquid bridge, although the aspect ratio of the column is the same. To confirm the size dependency on critical values, experiment with large liquid bridge of silicone oil with 50 mm in diameter was performed under microgravity condition onboard the ISS (Fig.1).

In order to obtain more accurate and detailed results than the past experiments for low Pr, a liquid bridge experiment with molten tin (Pr = 0.009) was conducted in high vacuum chamber (Fig. 2). For the first time an experimental proof of this first transition is provided by means of very precise measurements of temperature at different azimuthal positions. And onset of oscillatory flow was determined.

The effect of Pr with widely ranging from 0.009 to 113 on the critical Marangoni number could be summarized. Critical value of moderate Pr of acetone liquid bridge (Pr=4.3) was also taken into account [2]. Critical Maragoni number increased with the proportional to 2/3 of Pr experimentally.

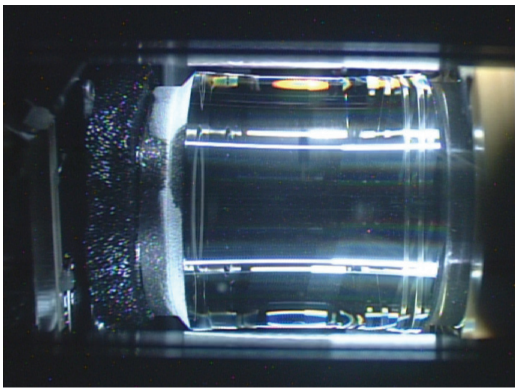

Fig. 1 Liquid bridge of silicone oil (Pr=113) with 50mm diameter and 60 mm length in microgravity

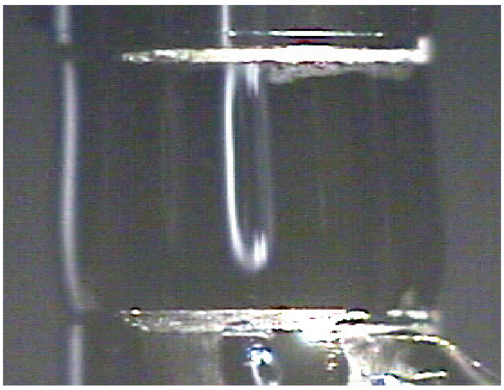

Fig.2 Liquid bridge of molten tin (Pr=0.009) with 6 mm diameter and 4.2 mm length

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Flow and Temperature Field Associated with Hydrothermal Wave of Marangoni Convection in Liquid Bridge under Microgravity

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Marangoni Experiment in Space (MEIS) [1] has been conducted as the first science experiment in the Japanese Experiment Module 'Kibo' in the International Space Station (ISS). Four series of experiments were performed in 2008(MEIS-1), 2009(MEIS-2), 2010(MEIS-4), and 2011(MEIS-3), respectively. The aim of MEIS is to clarify the instability mechanism of Marangoni convection and associated flow and temperature fields in large liquid bridges that can be generated only in a good-quality, long-duration microgravity environment.

A liquid bridge of silicone oil is formed between two coaxial disks heated differently. The disk diameter is 30mm in MEIS-1, 2 and 3, while 50mm in MEIS-4. Silicone oil with the kinematic viscosity of 5cSt is used as the working fluid in MEIS-1 and 2, while silicone oil with the kinematic viscosity of 20cSt is used in MEIS-3 and 4. The Prandtl number of former liquid is 67, while that of latter one is 207 at 25°C.

Both flow and temperature fields are visualized and measured by using three-dimensional particle tracking velocimetry [2, 3] and infrared camera. Figure 1 shows the time-series plots of the particle trajectories, where the temperature difference between heated and cooled sides is 11°C. This value is substantially higher than the critical temperature difference, therefore, the flow is oscillating in a fixed radial direction. This result exhibits that the vortex near the left and near heated side grows with time and it propagate to the cooled side. Figure 2 shows the time-series plots of the gray-scale image of surface temperature fluctuation. In these results, higher and lower temperature regions are seen as white and black regions, respectively. It is observed that the hydrothermal wave with an inclined angle propagates with same direction and same speed as the vortices shown in Fig. 1. More details of the characteristics of hydrothermal waves will be discussed in conjunction with their role in the instability mechanisms in long liquid bridges.

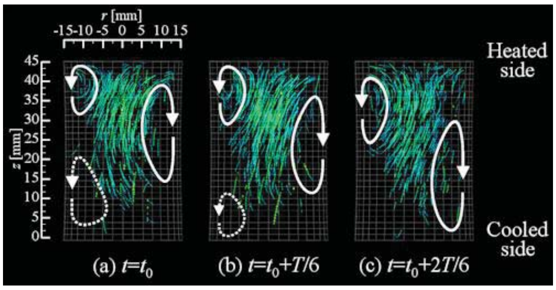

Fig. 1 Flow fields measured by 3-D PTV.

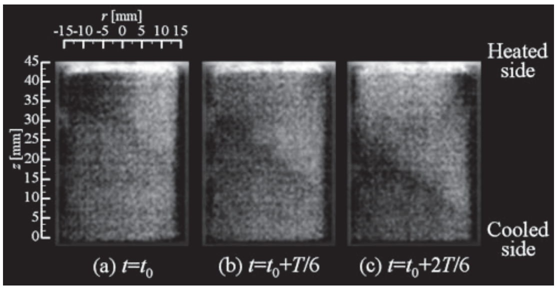

Fig. 2 Temperature fields measured by IR camera.

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Hydrothermal wave instability in $\Gamma \geq 2.0$ liquid bridge of high Prandtl number fluid

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The long-duration fluid physics experiments on a thermocapillary-driven flow have been carried out on the Japanese experiment module 'Kibo' aboard the International Space Station (ISS) since 2008. In these experiments, various aspects of thermocapillary convection in a half-zone (HZ) liquid bridge of high Prandtl number fluid over 200 have been examined under the advantages of the long-duration high-quality microgravity environment. In 2010, the authors succeeded to realize nonlinear convective fields in the HZ liquid bridge of rather large aspect ratio Γ ($\equiv$ height/radius) $\geq$ 2.0[1] (Fig. 1). The special attention was paid upon to the complex convective fields, especially the behaviors of the hydrothermal waves (HTW)[2] over the free surface visualized by an infrared camera. In order to evaluate the characteristics of the nonlinear convective behaviors and their transition processes, the authors indicate the fabricated images describe the time evolution of HTW, the spatio-temporal diagram, the Fourier analysis and the pseudo phase space reconstructed from the time series of the scalar information of the liquid bridge, that is, surface temperature variation. In this paper, the authors introduce the signature of complex HTW behaviors observed at the long-duration on-orbit experiments (Fig. 2), and make comparisons with some previous terrestrial and microgravity experiments.

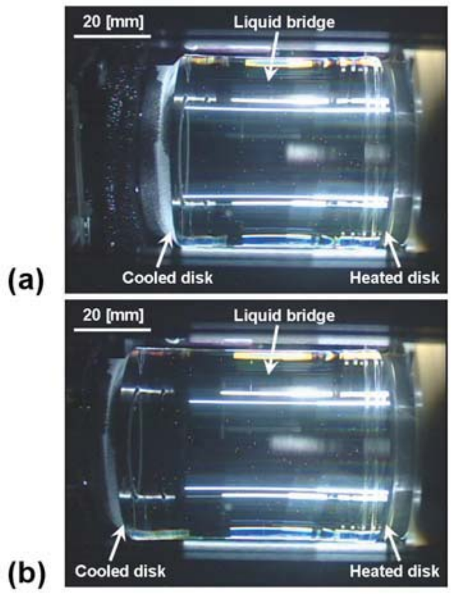

Fig.1. Side view of liquid bridge of 25 mm in radius and of Pr = 206.8 (at 25 °C); (a) Γ = 2.0 and (b) Γ = 2.5.

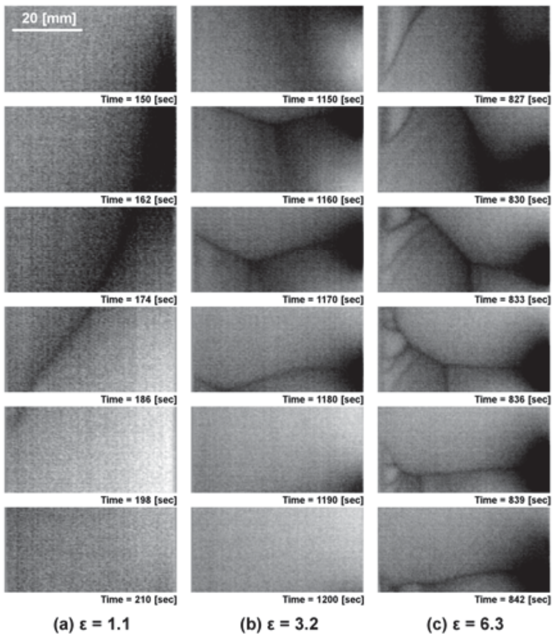

Fig.2. Time series of temperature deviation on the liquid bridge surface of 1/6 region in azimuthal direction evaluated by IR images in the case of Γ = 2.0; (Ma, ε) = (a) (4.2×10^4, 1.1), (b) (8.5×10^4, 3.2) and (c) (1.5×10^5, 6.3).

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The internal fluid motion within highly viscous adherent droplet

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Liquid droplets adhering to a solid substrate under an imposed shear flow appear in a variety of engineering and bio-medical problems. We focus on the limit of large droplet viscosities typical of those occurring in the upper respiratory tract of CF or chronically ventilated patients with the goal of estimating the shear force resulting from the interaction between the internal fluid motion and the solid substrate.

Owing to the large viscosity ratio, continuity of the tangential traction across the liquid surface implies that the external (air) flow effectively satisfies a no – slip condition there. To further simplify the problem we assume asymptotically small Bond and capillary numbers and consider a hemispherical (non-deformable) droplet. Under these approximations the problem decouples into (i) the external problem of an imposed shear flow over a planar solid wall with a hemispherical protuberance, which is numerically simulated by means of a commercially available volume – of – fluid code (ACE) over the interval of Reynolds numbers between 0.05 – 50, and (ii) the inner Stokes flow animated by the (now prescribed) shear – traction distribution over the drop surface. The latter problem is analised through use of series expansions in spherical harmonics (as in Lamb's (1932) solution). Following Brenner (1964) the dynamic conditions on the droplet surface are implemented in terms of the divergence and curl of the shear – traction distribution.

The resulting caterpillar – like internal fluid motion gives rise to a wall shear force adding to the hydrodynamic drag of the external flow. Figure 1 presents the variation with the external – flow Reynolds number of the relative contribution of the wall shear force to the resultant force in the downstream direction. We see that, while it is slowly decreasing, throughout the entire range of Reynolds numbers considered the wall shear contributes over one third of the total force acting to dislodge the droplet from the solid substrate. This contribution is thus significant to the prediction of the critical conditions for the aerodynamic removal of the adherent droplet.

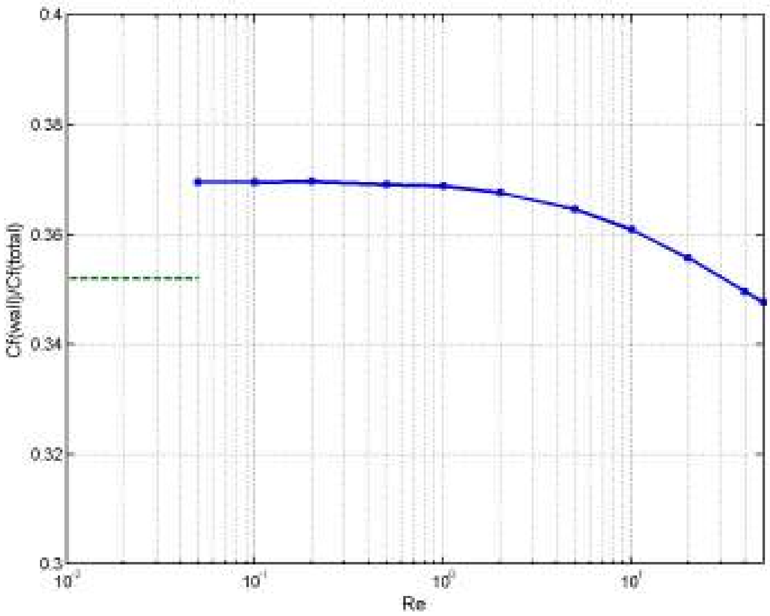

Fig. 1 Variation with the Reynolds number of the relative contribution of the wall shear force.

[1] Brenner, H., *Chemical Engineering Science*, pp. 519-539, 1964.

Moving contact lines: diffuse-interface model and applications

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A three-phase contact line forms when a gas-liquid interface intersects a solid substrate, and a moving contact line presents a well-known singularity that cannot be computed using the conventional Navier-Stokes formalism. I will discuss the use of a diffuse-interface model for computing moving contact lines. The Cahn-Hilliard diffusion is known to regularize the singularity and makes possible a continuum-level computation. But relating the results to physical reality is subtle. I will show numerical results that suggest a well-defined sharp-interface limit, with a finite contact line speed that can be related to measurements. Then I will discuss two applications: enhanced slip on textured substrates and propulsion of water striders on the air-water interface. In each case, the diffuse-interface model provides new physical insights into the hydrodynamics underlying novel phenomena.

Deformation of a Viscous Drop in Compressional Stokes Flow

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The dynamics of deformation of a drop in axisymmetric compressional viscous flow is addressed. Although countless studies of the corresponding extensional flow appeared in the literature in the past, the opposite case of a drop in compressional flow received only limited attention so far (see e.g., Stone and Leal, 1989) and we present here an expanded systematic report. We obtain and compare exact and approximate analyses and results. The dynamics and shapes are obtained for a variety of capillary numbers, *Ca*, and viscosity ratio, λ. The critical *Ca*, below which a steady drop shape exists, is established for various λ. Exact analytic solutions are obtained for oblate spheroidal drops employing generalized analytic function conformal technique. For the case of equal viscosity of the phases, $\lambda = 1$, we employ the integral representation suggested by Zabarankin and Nir (2011), where steady shapes are expresses in terms of Chebyshev polynomials.

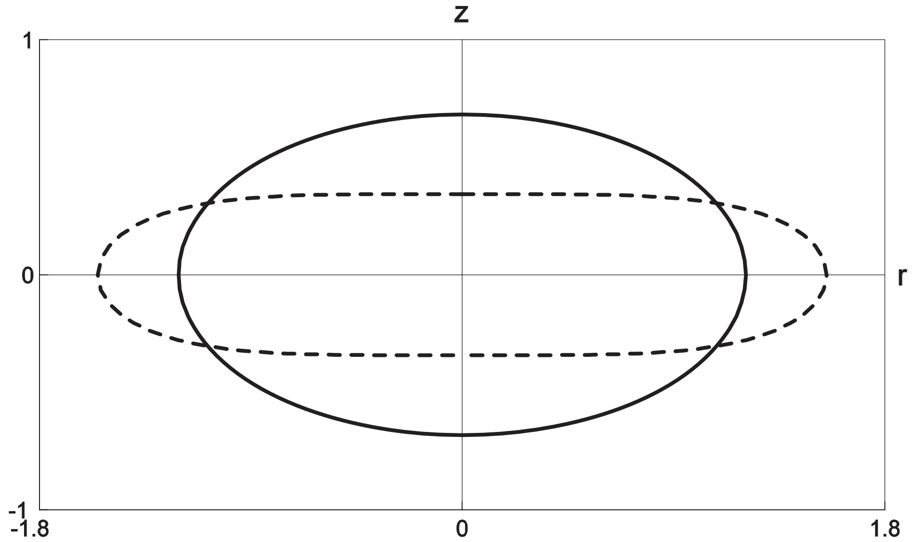

Fig. 1.The cross-section of the steady-state shapes of the drop two-parametric for equal viscosity, $\lambda = 1$. Ca = 0.15 (solid line) and Ca =0.193 (dashed line).

The general case of arbitrary viscosity ratio is solved numerically using the BI presentation previously employed by Toose et al. (1996) and Smagin et al. (2011). It was demonstrated that while at relatively low *Ca* the drop shape resembles that of an oblate spheroid (see solid shape in Fig.1), for capillary numbers close to the critical one the deformed drop assumes the shape of a flat disk with rounded edge (see dashed shape in Fig.1). Similarity to and difference from the deformation of a drop in axisymmetric extensional flow are discussed.

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Thermocapillary motion of a slender viscous droplet in a channel

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(Dated: December 19, 2011)

We extend the previously developed low-capillary-number asymptotic theory of thermocapillary motion of a long bubble and a moderately viscous droplet in a channel [1, 2] toward droplets with an arbitrary viscosity. A generalized modified Landau-Levich-Bretherton equation, governing the thickness of the carrier liquid film sandwiched between the droplet and the channel wall in the transition region between constant thickness film and constant curvature cap, is derived and solved numerically. The thermocapillary velocity of the droplet translation is shown to be a function of two dimensionless parameters: the modified capillary number, $\Delta\sigma^*$, equal to the surface tension variance over a distance of channel half-width scaled with the mean surface tension, and the inner-to-outer liquid viscosity ratio, λ. It is found that the velocity of the droplet decreases with the increase in its viscosity, as expected, while this retardation becomes more prominent at higher values of $\Delta\sigma^*$.

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Influence of Density Stratification on Stability of a Two-Layer Binary-Fluid System with a Diffuse Interface

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A two-dimensional layer of a quasi-incompressible binary fluid below the phase-separation point in the presence of gravity force is considered. The dependence of the density on the mass fraction is taken into account, which is significant under the action of gravity. The layer is bounded by a planar solid substrate from below and by a gas phase from above. The system is assumed to be isothermal. The deformable liquid-gas interface is considered as a sharp boundary, whereas the different phases of the binary liquid are separated by a diffuse interface. A mathematical model consists of the continuity, Navier-Stokes and modified Cahn-Hilliard equations governing the motion of quasi-incompressible fluid. To study this problem, the diffuse interface approach is applied.

We investigate the stability of two-layer base solutions with respect to long-wave disturbances in the framework of the linear stability analysis in the case of small density ratio (E) and large Galileo number (G). A two-layer base configuration is described by a subset of solutions that are monotonic (increasing or decreasing) functions. The solutions of this problem in the form of asymptotic series in powers of small wavenumbers corresponding to the long-wave limit are considered. The dependence of the growth rate on the parameters is found. This expression depends on the Cahn and Marangoni numbers, and parameter EG.

The stability of the system is investigated in absence and in presence of the density ratio and the Marangoni effect, and Korteweg stresses. It is shown the existence of stable equilibrium for negative values of E. The stabilization of solution at negative E can be explained by a stable density stratification.

Decomposition and interface evolution in films of binary mixtures

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Model-H describes the coupled transport of concentration and momentum in binary mixtures such as polymer blends. Films of polymer blends are used in technological applications that involve coatings or the creation of structural functional layers.

We use an extended version of the model-H for free evolving surfaces [1] to analyze the stability of vertically stratified base states of polymer blends on a solid substrate. We determine the bifurcation diagram of the films by studying their free energy, and L2-norms of surface deflection and concentration field. We provide results for selected mean film thickness with and without energetic bias at the free surface and discuss the role of composition in extended and laterally bounded systems.

In addition, we show that the inclusion of convective transport leads to new mechanisms of instability as compared to the purely diffusive case [2, 3].

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[3] S. Madruga and U. Thiele. *Eur. Phys. J. S.T.*, **192**, pp. 101-108, 2010.

Stability of a condensing liquid film of a binary vapor mixture

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We study stability of a condensing liquid film of a binary vapor mixture. When a zeotropic binary vapor mixture is cooled on a substrate, it condenses and a liquid film emerges. If the surface tension of a one component of the mixture having a higher boiling point is stronger than that of the other component, the liquid film takes an inhomogeneous form such as a droplet one due to the solutal Marangoni effect. In order to investigate such a phenomenon, we apply the long-wave approximation to the condensing liquid film and derive a nonlinear partial differential equation describing the spatio-temporal evolution of the film thickness. Here we adopt interfacial boundary conditions taking account of effects of mass gain of the liquid film during the condensation and temperature dependence of the mass transfer coefficient of the vapor phase derived from the mass conservation of the one component of the mixture, which were not considered in the earlier theoretical work [1].

Based on this model, we performed a linear stability analysis around a flat-film solution. We found that there exists a certain critical thickness below which the liquid film is stable and above which it is unstable. The effect of mass gain stabilizes a disturbance and dominates over the destabilizing effect of solutocapillarity in the stable region. The critical thickness depends on the temperature derivatives of both the equilibrium vapor concentration at the liquid-vapor interface and the mass transfer coefficient, the latter having been ignored in Ref. [1]. We plot the values of the critical thickness as a function of the wall temperature for a water-ethanol system in the left panel of Fig. 1. It is observed that if the effect of the temperature dependence of the mass transfer coefficient is included into the model the values of the critical thickness significantly change.

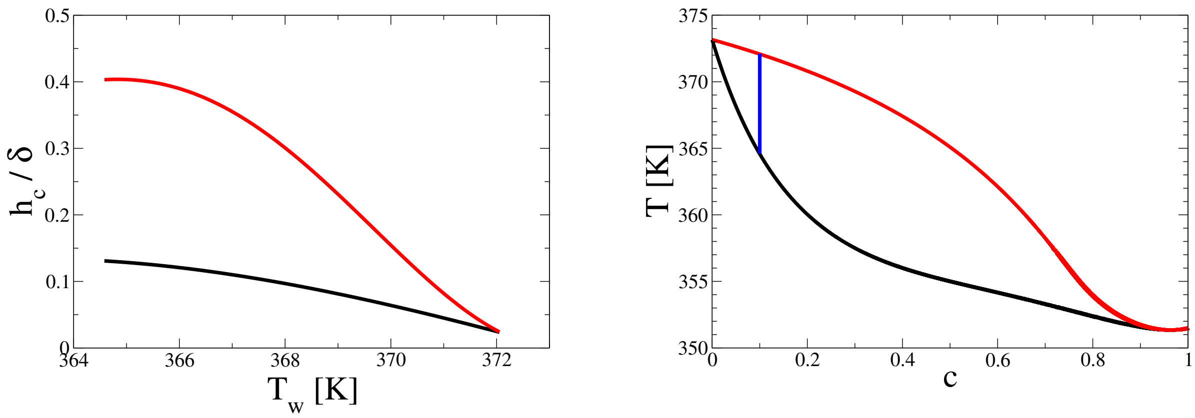

FIG. 1: Left: The critical thickness h_c versus the wall temperature T_w for a water-ethanol system. The parameter δ is a constant of dimension of length determined from the ambient-vapor condition. The black curve indicates the case where the temperature dependence of the mass transfer coefficient is ignored as in Ref. [1], which is independent of the ambient-vapor concentration. The red curve corresponds to the case where the mass concentration of ethanol of the ambient-vapor mixture is 0.1. Both curves are plotted in the temperature domain indicated by the blue line in the right panel. Right: Vapor-liquid equilibrium for water-ethanol mixture. The black and red curves are the liquid and vapor lines. The composition c represents the mass fraction of ethanol.

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Marangoni convection in binary fluids with soluble surfactant

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Marangoni convection in a binary-liquid layer with deformable interface in the presence of the Soret effect was studied earlier in the case of a prescribed temperature at the substrate [1, 2], a prescribed heat flux at the substrate [3–5], and for arbitrary heat conductivity of the substrate [6]. In the above-mentioned papers, surface tension was assumed to be a function of temperature and solute concentration at the interface. However, in reality surface tension is determined by the composition of the interface. If the characteristic time of adsorption/desorption processes is small (that is typical for relatively small surfactant molecules), the concentration of a surfactant adsorbed at the interface is close to its equilibrium value, hence, it is nearly proportional to its bulk concentration, which leads to the model used in the works mentioned above. Otherwise, the adsorption/desorption kinetics and the surfactant advection along the interface have to be taken into account for finding the surfactant surface concentration and the local value of the surface tension.

We study the stability of the base state of the system, described above, by means of long-wave asymptotic expansions. A special attention is paid to the case of a small Galileo number, where the instability mechanism connected with the surface deformation prevails. Also, the Lewis number is assumed to be small. Linear stability analysis carried out in earlier work revealed a competition between the monotonic and oscillatory modes of instability, as well as between long-wave and short-wave types of instability. A significant influence of the surfactant adsorption on the stability criteria was found. Parameter domains for different kinds of instability were obtained, and transitions between them, taking place with the change of the mean surfactant concentration, were investigated.

Nonlinear analysis of the problem yields a set of nonlinear evolution equations in terms of the layer thickness and solute concentration. Conservative forms of these equations have been derived. Numerical investigation of the evolution equations has been carried out based on both the Newton-Kantorovich method and method of lines. In the case without adsorption/desorption, the results agree with the weakly-nonlinear theory [5]: bounded solutions were observed, namely standing and traveling waves. However, significantly far from the instability threshold long-wave theory fails and evolution equations become ill-posed. The latter can be attributed to the presence of unbalanced backward diffusion terms.

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Cahn-Hilliard Equation and Anomalous Marangoni Effect

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It is known that for a pure liquid the surface tension σ is a monotonically decreasing function on the temperature θ. But in some solutions the dependence $\sigma(\theta)$ is non-monotonic with a minimum point θ_* [1]. Anomalous Marangoni effect in two-layer system was investigated on the basis of the full Navier-Stokes equations in [2]. In the thin film approximation we have investigated the Rayleigh-Benard problem with the condition $\theta = \theta_*$ on the free surface. We assume that the characteristic disturbance amplitude of free surface $u(x, y, t)$ is much less than the average layer thickness. In this case its evolution can be described in terms of Cauchy problem solutions for the Cahn-Hilliard equation

$$u_t + \Delta^2 u + \Delta(u^2 - \beta u) = 0; \quad u = u_0(x, y), t = 0, \tag{A}$$

where β is the Bond number. The sufficient condition of the global solution existence of problem (A) and its collapse for a finite time for the periodic function u_0 has been formulated. Realization of both possibilities at rapid decreasing of u_0 at infinity in two-dimensional and axisymmetrical cases is numerically modeled.

The equation (A) is reduced to the case $\beta = 0$ by substitution $u = u' + \beta/2$. In this case the equation has self-similar solutions. The "mass" conservation law takes place for Cauchy problem (A)

$$\int_{\mathbb{R}^2} u dx dy = \int_{\mathbb{R}^2} u_0 dx dy = c, \tag{B}$$

where the value c can be negative. In the axisymmetrical case self-similar solutions are compatible to the conservation law (B). Analytical and numerical research shows that axisymmetrical self-similar solutions exist at small values of $|c|$, and they do not exist for large and positive c. For negative values of c there were found two branches of self-similar solutions with various qualitative behavior. The self-similar solutions of the two-dimensional problem satisfying the conservation law exist only for $c = 0$. The role of self-similar solutions is that they often give the leading order of asymptotic solution of Cauchy problem (A) as $t \to \infty$. In our case it is so for axisymmetrical solutions, where $u = O(t^{-1/2})$. For the self-similar solution of two-dimensional problem at $c = 0$ an order of decrease is the same as in the axisymmetrical case, while the Cauchy problem solution with small initial data has a decrease order $t^{-1/4}$ as $t \to \infty$.

The equations (A) have numerous stationary solutions. There are cnoidal waves, Korteweg and de Vries solitons, and axisymmetrical solitons among them. Open questions are stability of stationary solutions, collapse structure.

This work is supported by the Russian Foundation for Basic Research (Grant No. 10-01-00007).

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Micro- and nanoscale pattern formation in Langmuir-Blodgett transfer: Control mechanisms and bifurcation analysis

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The coating of solid substrates with regularly patterned surfactant monolayers is exemplary for the purposeful utilization of self-organized pattern formation. The withdrawal of a solid plate from a water-filled trough covered by a monolayer of the phospholipid DPPC endues the solid with a highly regular pattern with periods down to a few hundred nanometers. This phenomenon results from phase decomposition in the monolayer triggered by an interaction with the substrate at the contact line. It can be understood in terms of a model describing a receding contact line of a surfactant covered liquid film in the vicinity of a monolayer phase transition [1, 2].

On the basis of this model, we discuss possibilities to control the properties of the transferred patterns. Chemically prepatterned substrates can be applied to yield structures of higher complexity, resulting from synchronization between the natural frequency of the system and a perturbation due to a periodic prestructure [3]. Furthermore, the patterns can be tuned by adjusting the water temperature as has been found in a combined theoretical and experimental study [4].

The bifurcations resulting in the pattern formation are analyzed by use of an amended Cahn-Hilliard equation [5]. By combination of numerical simulations and continuation methods, we find that the onset of spatiotemporal pattern formation results from a homoclinic and a Hopf bifurcation at small and large substrate speeds, respectively. Furthermore, the critical velocity corresponding to the Hopf bifurcation is calculated analytically by means of the marginal stability criterion for pattern formation behind propagating fronts. In the regime of low transfer velocities, the stationary solutions exhibit snaking behavior.

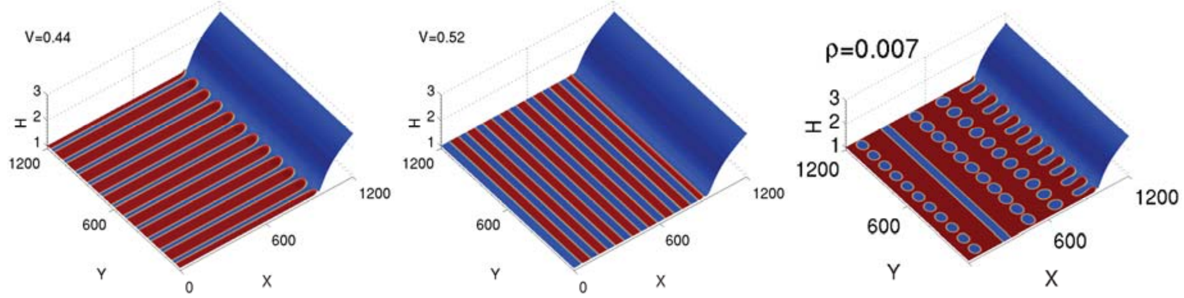

FIG. 1: Examples of patterns generated by monolayer transfer: Stripes oriented perpendicular (left) and parallel (center) to the contact line are observed for low and high pull velocities, respectively. Using prepatterned substrates, more complex structures can be realized (right).

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Instability of Marangoni flow in the presence of insoluble surfactant. Experiment

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A presence of surface tension gradient or a viscous entrainment of a liquid surface by a volume flow results in appearance of a surface (or capillary) flow. A structure of such flows is as rule easily predictable and can be simply modeled in theoretical and numerical investigations. However there are a few experimental studies where the structure of observed surface flows is much altered from that predicted by a theory or followed from symmetry considerations. The most probable cause of the obtained discrepancies is a presence (often uncontrolled in experiments) of surface-active impurities which form an adsorbed layer at an interface. In this case the surface flow develops under boundary conditions which are different from those at a free liquid surface. From this point of view the additional study of development and stability of the surface flows in presence of surfactant films is needed for the formulation of the boundary conditions suitable for such problems.

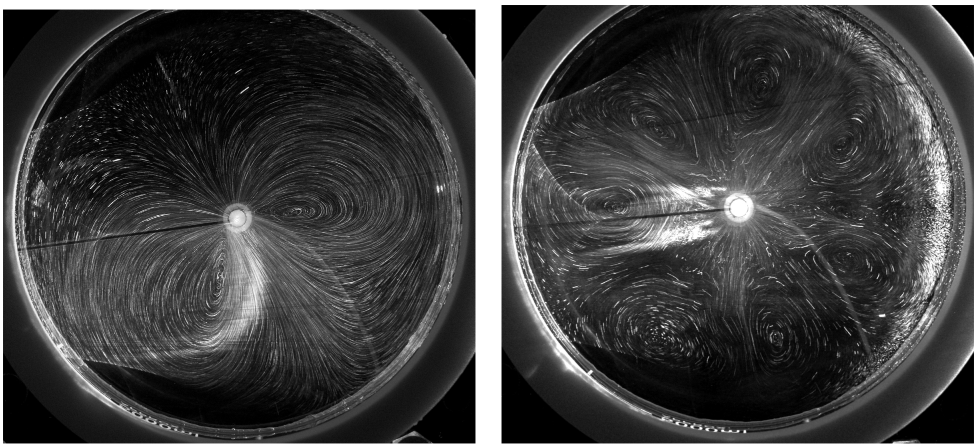

FIG. 1: The surface flow structure under $Ma = 2 \cdot 10^6$ and surfactant surface density Γ/Γ_e=0.35 (left picture) and 0.3 (right picture). Γ_e - surface density of monolayer.

The results of the experimental study of interaction between a solutocapillary axisymmetric surface flow, induced on a water surface by a localized source of a weak ethanol solution, and an adsorbed film of an insoluble surfactant (oleic acid) are presented in the presentation. It's found that in case of clean water surface the main axisymmetric flow remains stable under any Marangoni number realizable in the experiment. Addition of any amount of the surfactant on the water surface leads to breaking of symmetry by the main flow. As a result a multivortex flow structure (Fig. 1), which is periodic in azimuthal direction, forms on the interface. The azimuthal wavenumber of such structure essentially depends on Marangoni number (defined through the consumption and concentration of the ethanol solution) and surface density of the surfactant. It's found out that the wavenumber increases with increase of Marangoni number and decrease of surface density. It's shown that there is a critical surface density (depending on Marangoni number) above which the solutocapillary convection doesn't arise at all.

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Surfactant transfer enhancement between the drop connected to the reservoir and the surrounding fluid due to Marangoni convection

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The character, intensity and duration of the soluto-capillary convection largely depend on the intensity of the surfactant source and its location in a multi– fluid system with the interface. As an example we refer to the case of surfactant diffusion from a drop of the binary mixture to a surrounding liquid under microgravity conditions [1]. The droplet is coupled with the reservoir filled with the source mixture through a long thin tube (needle). A decrease of surfactant concentration in the drop was found to provoke its diffusion from the needle. The ejection of the surfactant initiated a capillary flow, which, in turn, contributed to the formation of a large-scale structure of the fluid motion in the drop.

The paper presents the results of studying the interaction between the capillary and gravitational mechanisms of motion in a similar problem treated under terrestrial conditions. Visualization of the flow patterns and concentration fields has shown that surfactant diffusion from the needle in the normal gravity leads to the onset of the oscillatory mode of the capillary convection in the drop. It has been found that the frequency of the Marangoni convection outbursts, the lifetime of the oscillatory flow modes and the amount of the initial mixture involved in the process of mass transfer depend on the drop size and initial concentration of the surfactant. The obtained results are compared with the case of surfactant diffusion from the secluded drop. We also consider the case of surfactant diffusion from the solution to the drop, which is connected with the reservoir filled with source fluid.

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Marangoni Convection in Liquid Films on Heated Structured Walls at Normal and Reduced Gravity

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The Marangoni convection in heated liquid films can be controlled by using structured substrates [1] and by using substrates with non-uniform thermal properties [2]. The substrate structures and non-uniformities lead to development of Marangoni vortices, to the deformation of liquid-gas interface and to controlled film dryout over the structure crests. It has been expected that the gravity level significantly affects the Marangoni convection. In the terrestrial gravity conditions the hydrostatic pressure opposes the interface deformation and can prevent the film dryout. Moreover, the Marangoni vortices coexist with the vortices induced by buoyancy which have the same direction as the Marangoni-induced vortices.

In the present work, the Marangoni convection in liquid films on heated structured walls has been studied experimentally in a lab and in a parabolic flight. The geometry of the wall structure and the properties of the liquids have been varied. Both non-volatile and volatile liquids have been tested. The velocity field in the liquid films has been determined using the PIV technique. The deformation of the liquid-gas interface has been measured using the phase-shifting schlieren technique.

Figure 1 shows the phase-shifting schlieren images of the surface of an evaporating HFE 7500 film in terrestrial conditions at different time instances after the film application. The wall structure is comprised of longitudinal grooves with approximately sinusoidal cross-section. The period of the structure is 10 mm, and the amplitude is equal to 140 μm. Immediately after the film application the development of interfacial instabilities is observed in the regions around the structure crests (the elongated structures ordered normal to the groove axis direction, see Fig. 1a). Three minutes after the film application, when the average film thickness is reduced due to evaporation, the interfacial instabilities can be observed in the regions around the structure troughs (branch-like structures, see Fig. 1b). At this time instant the nucleation of dry spots over the structure crests can be observed. Four minutes after the film application the structure crests are completely dry, and the liquid remains in the structure troughs in the form of rivulets as predicted in [1] (see Fig. 1c).

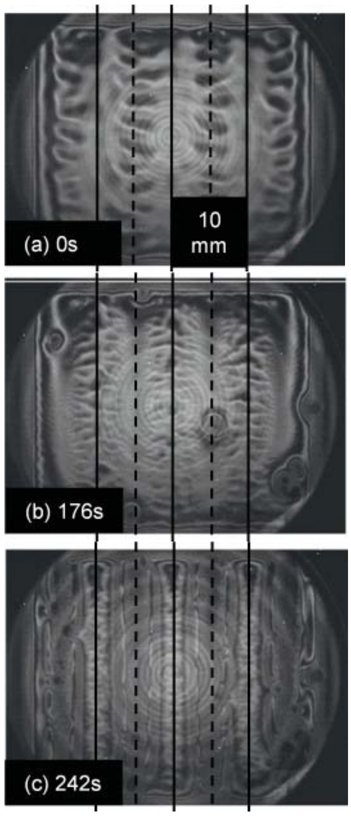

Fig. 1. Phase-shifting shlieren images of an evaporating film of a fluorinert liquid HFE 7500 on a heated structured wall. Solid line: structure trough; dashed line: structure crest.

The Marangoni vortices in liquid films on heated structured walls have been also observed and quantified in parabolic flight experiments. Different techniques for controlling the stability of the liquid-gas interface during the parabolic flight have been tested, and the results of the tests are presented.

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