Joint experiment “Relief”

THERMOCAPILLARY CONVECTION IN A MOVING THIN LIQUID LAYER

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Background
This project was submitted to the Russian Aerospace Agency in 1997. It is included in the long-term program of scientific and applied research and experiments planned on the ISS\(^1\). Program dated 1999, paragraph 2.1. This program was signed by director of RAA Y.N. Koptev and by president of Russian Academy of Sciences Y.S. Osipov.

Project "Relief" is very close to the project AO-99-110 “Convection and Interfacial Mass Exchange” CIMEX-1 “Evaporative Convection and Turbulence in Pure Fluids”, coordinated by Prof. J-C. Legros from the point of the onboard scientific equipment. Partners from Novosibirsk and MRC ULB have a long-term experience of cooperation. This cooperation has got the especially active form last two years within the framework of the Copernicus program of the European Commission. The obtained theoretical and experimental knowledge and know-how can be used for preparation of the joint space experiment on ISS.

Based on participation of Russian Aerospace Agency in the International Microgravity Strategic Planning Group and agreements between ESA and RAA\(^2\) the negotiation concerning joint realizations of this space experiment on ISS was carried out. The updated proposal “Relief” is explained in this document. Also the possible coupling of experiment “Relief” and CIMEX-1 is described.

Objectives:
- To investigate peculiarities of the liquid film dynamics driven by the gas flow in presence of intensive thermocapillary convection in microgravity conditions.
- To investigate instability mechanisms that induce three-dimensional rivulet patterns in non-uniformly heated films and to study the features of these patterns.
- To carry out measurements of the velocity, temperature and deformation fields at the interface of a locally heated moving liquid film following a spontaneous onset of periodic structures in order to validate the theoretical model and measure the enhancement of heat transfer due to these structures.
- To study the nonlinear dynamics of volatile thin liquid films flowing over a planar surface with localized heaters, resulting in film breakdown.

Motivation
The need to investigate the capillary flows, induced by nonuniformity of the temperature conditions along a phase interface, arises in the process of solving many scientific and technological problems. Such investigations were stimulated by experiments with liquids aboard space stations, by chemical

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\(^1\) Letter No. 93-F, dated 28.06.01, of Prof. B.G. Zakharov, Director of the Space Material Science Center, Vise Director of Science Material Department of Coordinating Engineering and Science Council, RSA.

\(^2\) Letter No. NTUI-174, dated 22.11.00 of academician N.A. Anfimov, Direktor of ZNIIMASH.
technology demand, and in recent years also by microgravity research. The importance of thin (<1 mm) liquid films in a variety of natural and industrial processes has led to intensive studies of their flow characteristics and stability against hydrodynamic waves and rupture. In recent years many related theoretical and experimental studies have been published.

The combination of falling films with Marangoni effect yields a new set of instabilities (Sreenivasan and Lin (1978)\(^5\); Kelly, Davis and Goussis (1986)\(^4\)). For uniformly heated falling films at low Reynolds number, thermocapillary instability acts to amplify the 2-D wave instability already present and may cause either wavebreaking or immediate rupture depending on the 2-D wavenumber. It has been shown in numerical simulations of three-dimensional heated layers that 2-D surface waves and thermocapillary instabilities interact nonlinearly and form undulations in the transverse direction, which leads to a rivulet structure and film breakdown (Joo, Davis & Bankoff (1991)\(^5\)). A review of various aspects of long-scale evolution of thin liquid films was given by Oron et al. (1997)\(^6\).

In experimental works by the authors of the project, a record temperature gradient along the free surface has been achieved. That poses a set of new problems against theoreticians: taking into account non-Boussinesq effects and variable transfer coefficients in thin layer flows; refinements of boundary conditions at the deformable interface; need to consider 3-D equation of heat transfer at large Peclet Number. Related experimental studies have focused on thin films falling down an inhomogeneously heated plate and have revealed the occurrence of novel instabilities forming a rivulet structure wave like in the transverse direction (Kabov \textit{et al.} (1995)\(^7\); Kabov (1998)\(^8\)). Since such an instability may drastically change the heat conductive properties of a thin film, it is essential to understand when and why instabilities onset may break the film. It was found that in the terrestrial conditions the wavelength of the instability is a function of the Bond number. **Experiments in the microgravity condition will allow varying the capillary scale of the liquids and verifying the gravity effect.**

Thermocapillary flow instabilities in thin liquid layers may lead to dry spot formation. Dynamics of their evolution can be investigated with the help of a precise experimental technique only. This problem also demands development of new theoretical approaches based on variable geometry of the flow and moving triple contact line, under the condition when evaporation must be taken into account. Majority of the published data, devoted to film breakdown, was obtained for extended heaters with the length of more than 200 mm along the flow and for developed waves structure. There are four different causes of film breakdown 1) minimum wetting flow rate, 2) Marangoni effect (film breakdown is determined by local temperature and concentration gradients), 3) nucleate boiling and 4) evaporation. Review of the literature has revealed that there is a lack of information regarding multicomponent effects. Last experiments in this area (Kabov (2000)\(^9\)) have shown essential influence of heater size on breakdown of the film. **No experiments on the breakdown of the moving liquid film were performed in the microgravity condition.**

**Inputs:**


\(^9\) O.A. Kabov, Breakdown of a liquid film flowing over the surface with a local heat source. Thermophysics and Aeromechanics, 7, No. 4, 513-520 (2000).
The emergence of regular structures in flowing liquid films was first revealed (Kabov (1994)\textsuperscript{10}, Kabov \textit{et al.} (1995,1996)\textsuperscript{11}), in the Institute of Thermophysics. These structures allowing a substantial increase of the heat flux density were observed in the experiments with heaters of small linear size. In fact, a new phenomenon of the emergence of spatial self-organizing structures in gravity-driven thin locally heated liquid films under was identified. The mechanism of this phenomenon is not completely understood to date. The formation of these regular structures was studied experimentally in various regimes by infrared thermography and optical Schlieren Technique (Scheid \textit{et al.} (2000)\textsuperscript{12}, Kabov \textit{et al.} (1999\textsuperscript{13}, 2001\textsuperscript{a,14}, 2001\textsuperscript{b,15}) in ITP and ULB. A model describing the formation of the regular structures based on the reverse flow of the liquid in the bump in the presence of the transverse (to the basic flow) surface temperature gradient was proposed and a general expression for the critical heat flux resulting in the regular structures onset was obtained (Kabov, (1998)\textsuperscript{10}). Further this approach was extended to describe the distance between the rivulets on the film surface at the moment of their occurrence and to derive a generalized relationship taking into account the effect of surface tension, the Reynolds number of the flow and the plate inclination angle (Chinnov \textit{et al.} (2001)).

2-D theoretical studies of the liquid film flow with a local heating were performed with a thin-layer approach (Marchuk and Kabov (1998)\textsuperscript{16}, Kabov \textit{et al.} (1999), Kuznetsov (2000)\textsuperscript{17}). In some of the particular cases numerical and analytical solutions were derived. These models taking into account gravity, surface tension, thermocapillarity and viscosity effects predict the emergence of a horizontal bump. A preliminary asymptotic analysis of a combined flow of the incompressible liquid and low-viscosity gas along the plate with a localized heater was carried out by Kuznetsov (2000). It was found that even the flow of a low viscosity gas exerts a tangential stress on the free surface of the liquid that can cause a flow of the latter\textsuperscript{18}.

\textbf{Expected results:}

- The relative importance of capillary, thermocapillary, gravity and viscous forces in the development of instability of locally heated liquid films will be found experimentally with specially chosen ratios of the physical properties of the liquids.
- The velocity field at the interface for the flows with periodic structures will be measured. Experimental data on the film thickness profile and the surface temperature distribution will be obtained, and the results of numerical calculations will be compared with the experimental data. The most extensive data will be acquired in the domain of the film thickness where the long-wave theoretical approach is applicable (film thickness 50-150 µm).
- The instability mechanism that induces three-dimensional rivulet patterns in the case of periodically and locally heated moving liquid films will be described in detail. The related critical Marangoni number for the onset of the instability will be specified in terms of other parameters of the problem.

\textsuperscript{12} B. Scheid, O.A. Kabov, C. Minetti, P. Colinet, J C Legros, Measurement of free surface Deformation by reflectance-Schlieren method, 3\textsuperscript{rd} European Thermal-Sciences Conference, Heidelberg, 2, 51 (2000).
\textsuperscript{17} V.V. Kuznetsov, Dynamics of locally heated liquid films. Russian Journal Engineering Thermophysics. 10, № 2, 107-120 (2000).
\textsuperscript{18} O.A. Kabov, V.V. Kuznetsov, I.A. Marchuk, V.V. Pukhnachov, E.A. Chinnov, Regular structures at thermocapillary convection in a driving liquid layer, Poverkhnost, rentgenovskie, sinkhronnie i neitronnie issledovanija in Russian, No. 5, pp. 84-90 (2001).

Joint experiment “Relief”, Thermocapillary convection in a moving thin liquid layer
J-C. Legros (Brussels), Oleg A. Kabov (Novosibirsk), Vladislav V. Puchnachev (Novosibirsk), 10.07.03, Page 3 of 10
• Development of a three-dimensional numerical code capable to simulate the temporal evolution of the rivulet instability and comparison between the numerical and experimental results. The results will naturally lead to the ways of control of the instability onset so that the film breakdown can be prevented.

• A mathematical model and numerical algorithms of the film flows will be developed taking into consideration body and surface forces, convective and diffusive heat transfer, evaporation and the gas flow influence.

Participants:
• Microgravity Research Centre of the Free University of Brussels, Brussels, Belgium.
• Kutateladze Institute of Thermophysics of the Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia.
• Lavrentyev Institute of Hydrodynamics of the Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russia.

Methodology: We will study the stability of low Re flows on a plate containing a three localized heaters at the upper edge of which a temperature jump will be imposed. Surface tension is known to decrease with increase of the temperature of the fluid surface. The concomitant surface tension gradient produces a Marangoni flow opposed to the gas-driven flow. The competing flows will produce a 2-D band of a relatively large film thickness, or "bump", which can become unstable and develop rivulets in the direction parallel to the flow. Fig. 1 shows the regular structures in the locally heated liquid film moving by gravity in terrestrial condition. We will solve the evolution equation numerically to compute these profiles and study the dependence of the system on the Marangoni number, which measures the surface-tension gradient, on the Bond number measuring the curvature pressure, and on the Biot number measuring the heat transfer from the film to the gas flow. The temperature of the gas flow will be varied.

The patterns of a bump and of rivulet structures will be measured experimentally by a surface deformation measurement technique (Schlieren technique)[12]. This technique allows two-dimensional deformation measurements using an algorithm that will be developed. It will also provide relative three-dimensional profiles of the film thickness. Fig. 2 (a) shows the Reflectance-Schlieren set-up. Film thickness will be measured in several points at inlet and outlet of the cell. An optical fiber probe of reflective type can be used. The method of measurements of the film thickness is based on the dependence of intensity of reflected light on the distance between the probe end and the reflecting surface. In Fig. 2 (b) the scheme of the light flows is shown[19]. These measurements also will allow controlling the spanwise non-uniformity of the thickness of the film.

The rivulet-like structure will be also computed by simulating the appropriate nonlinear evolution equation. The results are expected to be quantitatively coherent with the experiments what will allow us to understand the instability mechanisms. For this purpose, the energy method (Spaid and Homsy (1996)[20]) is expected to be useful to reveal the physical meaning of the eigenfunction problem arising from the linear stability analysis. The instability mechanisms will be analyzed for the bump and for the heated liquid film on the heater separately. The source of the developing rivulet structures will be identified. For the moment it is supposed that two various types of structures can be generated by the bump and by the wavy liquid film (Fig. 3).

At the present time, there are a large number of publications studying thin films flows where the governing flow equations are derived under various assumptions. This multiplicity of approaches is explained by the diversity of the phenomena described, among them convective and diffusive heat-mass transfer, the thermocapillary effect, hydrodynamic waves on the free surface, the instability evolution, temperature-dependence of liquid properties, and others. The traditional

approach is based on simplifying the continuity, momentum and energy equations using the lubrication approximations and integrating them across the film. This allows to reduce the problem to one (or more) evolution equation in terms of the film thickness. However, in recent experiments performed by Kabov et al. (1996\textsuperscript{11}, 1999\textsuperscript{13}), the appearance of a large temperature drop both in the streamwise and spanwise directions was found (gradients up to 15 K/mm). The latter causes substantial deviations of dynamic viscosity of the liquid from its value at the initial conditions. Moreover, using liquids with the large Prandtl number of order ten, neglecting convective heat transfer with respect to conductive heat transfer is not justified in the framework of the long-wave theory. Therefore it is impossible to exactly integrate the equations across the film, as it is done in the long-wave approach.

In the present project it is planned to extend the thin film theory to be valid for the flows with such features. When constructing simplified models, methods of asymptotic analysis, perturbation theory and group methods are used. The planned theoretical research will be based on the analytical as well as on the numerical approaches. In this connection, methods of the stability theory, dynamic-systems theory, finite-difference and spectral numerical methods will be used. The advantage of the suggested complex of methods is the ability to simulate the evolution of the film surface in 3D flow-mode on the basis of 2D computations. Some preliminary results in this directions are already obtained by Kuznetsov et al.\textsuperscript{21,22} (Fig. 4).

From the experimental point of view, in addition to the above-mentioned surface deformation measurements, we will measure both the velocity and temperature fields at the interface. The basic element of the experimental set-up is a flat plate with three flush-mounted heaters of various sizes. The heat sources of two types will be used, which will allow us to maintain a constant temperature or the heat flux on the substrate. In the second case the heat sources will measure simultaneously the local heat flux. The heat flux density will be determined in several points via the temperature drop through a stainless steel plate 2-3 mm thick. A mixture with the thermal conductivity around 100 times less than that of stainless steel will fill the surface around the heaters.

The liquid interface temperature measured at the frequency up to 30 frames per second will allow to visualize the distribution of the tangential force on the interface and to measure the wavelength of the structures. The velocimetry method based on a high-speed camera system and talc powder or a ceramic microspheres with an average size of 1-10 µm will be implemented. Particles will be blown on the interface and tracked by adequate software. Fig. 5 shows concept of experimental cell.

**Coupling with experiment CIMEX-1**

Fig. 6 shows a preliminary concept of the loop for CIMEX-1 experiment “Evaporative Convection and Turbulence in Pure Fluids”. It is supposed to use four liquids for CIMEX-1 experiment (table 1). Values of the most important parameters are presented in the table 2.

Fig. 7 shows a preliminary concept of the loop for “Relief” experiment. The same four liquids are suitable for “Relief” experiment. 25 % mixture of ethanol in water also will be used. Parameters of the flow for “Relief” experiment are shown in the table 3. To perform experiment “Relief” it is needed to change the experimental cell only. All other equipment in the experimental container will be practically the same. More extended gas-liquid separated system will be needed.

\textsuperscript{21} V.V. Kuznetsov, O.A. Kabov and J.C. Legros, Free surface deformation in a falling thin liquid film locally heated, Physics of Fluids (in preparation).

\textsuperscript{22} Kabov O.A., Scheid B., Kuznetsov V.V., Kabova I.O. and Legros J.C., Free surface deformation in a locally heated falling thin liquid film with the temperature dependent viscosity, 12th International Heat Transfer Conference, Grenoble, 18-23 August, 2002 (in preparation).

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Fig. 1. “Regular horseshoe-like structures” in the locally heated liquid film moving by gravity in terrestrial condition, 25% solution of ethyl alcohol in water, $T_0=20^\circ\text{C}$, Re=1, heater 6,7 ×68 mm, $q=4.2 \text{ W/cm}^2$ (image on the left).

Fig. 2 (a). Reflectance-Schlieren set-up: 1-Light source, 2-Diffuser, 3-Coding filter, 4-Collimating lens, 5-Beam splitter, 6-Sampling surface, 7-Schlieren lens, 8-Schlieren stop, 9-Camera lens, 10-CCD camera.

Fig. 2 (b). Film thickness measurements by the optical fiber probe.
Fig. 3. “Regular rivulet structures” in the locally heated **wavy liquid film** moving by gravity in terrestrial condition, Water, $T_0=20\, ^\circ\mathrm{C}$, Re=10.4, heater 150×150 mm$^2$, $q_v=0.64\, \text{W/cm}^2$.

Fig. 4. Deformation of the film surface, 10 % solution of ethyl alcohol in water, $T_0=20\, ^\circ\mathrm{C}$, heater 6.7×68 mm, thickness of the film 100 µm, $q=0.1\, \text{W/cm}^2$. 

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Fig. 5. Concept of experimental cell.
Table 1. Liquids for CIMEX-1 experiment.

<table>
<thead>
<tr>
<th>TS = 30°C, Liquid</th>
<th>Water</th>
<th>Ethanol</th>
<th>FC-72</th>
<th>?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_S$, bar</td>
<td>0.04</td>
<td>0.1</td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>$r$, kJ/kg</td>
<td>2261</td>
<td>879</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>$\lambda$, W/mK</td>
<td>0.6</td>
<td>0.2</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>$\sigma \times 10^3$, N/m</td>
<td>71.2</td>
<td>21.5</td>
<td>11.6</td>
<td></td>
</tr>
<tr>
<td>$-\frac{\partial \sigma}{\partial T} \times 10^3$, N/mK</td>
<td>0.19</td>
<td>0.13</td>
<td>0.099</td>
<td></td>
</tr>
<tr>
<td>$\mu \times 10^3$, Nc/m²</td>
<td>0.8</td>
<td>1</td>
<td>0.65</td>
<td></td>
</tr>
<tr>
<td>$\rho \times 10^3$, kg/m³</td>
<td>1</td>
<td>0.78</td>
<td>1.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Parameters of the flow for CIMEX-1 experiment.

<table>
<thead>
<tr>
<th>Title</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_{gas}$</td>
<td>Gas flow rate</td>
<td>up to 10 ml/s</td>
</tr>
<tr>
<td>$U_{GS}$</td>
<td>Superficial gas velocity (radius of condenser tube, $R_c=2.5$ mm)</td>
<td>0.5-0.05 m/s</td>
</tr>
<tr>
<td>$G_L$</td>
<td>Evaporation rate</td>
<td>0.01-0.0001 g/s</td>
</tr>
<tr>
<td>$U_{LS}$</td>
<td>Superficial liquid velocity in condenser tube</td>
<td>0.3-0.003 mm/s</td>
</tr>
<tr>
<td>$P_{Cond}$</td>
<td>Pressure in the gas line</td>
<td>0.4-1.3 bar</td>
</tr>
<tr>
<td>$T_{WB}$</td>
<td>Temperature of cooling water</td>
<td>4-50°C</td>
</tr>
</tbody>
</table>
Fig. 7. Two-Phase Loop for “Relief” Experiment.

<table>
<thead>
<tr>
<th>Title</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$</td>
<td>Maximum heat released on the heaters</td>
<td>20 W (H2, H3)</td>
</tr>
<tr>
<td>$q_{max}=q_{bd}$</td>
<td>Maximum heat flux density on the heaters</td>
<td>5.8 W/cm$^2$ (H3)</td>
</tr>
<tr>
<td>$G_{gas}$</td>
<td>Gas flow rate</td>
<td>up to 400 ml/s</td>
</tr>
<tr>
<td>$U_{GCell}$</td>
<td>Superficial gas velocity in the experimental cell (120×4 mm)</td>
<td>up to 0.8 m/s</td>
</tr>
<tr>
<td>$U_{GCond}$</td>
<td>Superficial gas velocity in condenser tube, radius of condenser tube, $R_c=5$ mm</td>
<td>up to 5 m/s</td>
</tr>
<tr>
<td>$G_L$</td>
<td>Evaporation rate</td>
<td>0.1(FC-72)-0.008 (water) g/s</td>
</tr>
<tr>
<td>$U_{LS}$</td>
<td>Superficial liquid velocity in condenser tube for FC-72, radius of condenser tube, $R_c=5$ mm</td>
<td>0.75 mm/s</td>
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<tr>
<td>$P_{Cond}$</td>
<td>Pressure in the gas line</td>
<td>0.4-1.3 bar</td>
</tr>
<tr>
<td>$T_{TB}$</td>
<td>Temperature of cooling water</td>
<td>4-50°C</td>
</tr>
</tbody>
</table>