Alexander Mialdun, Valentina Shevtsova

Influence of Interfacial Heat Exchange on the Flow Organization in Liquid Bridge

The appearance and development of thermoconvective oscillatory flows in a cylindrical column with a free lateral surface (so-called liquid bridge) filled with 5 cSt silicone oil are investigated experimentally. The experiments were carried out under terrestrial conditions for a wide range of volumes of liquid bridges. Heat transfer from the interface changed the threshold of oscillatory instabilities. The sensitivity of thermo-convective flows to the interfacial heat exchange was found to be strongly depending on the liquid bridge volume. Slender liquid bridges (under filled zone with respect to the straight cylinder) are rather stable to external disturbances. On the contrary, fat liquid bridges are extremely sensitive to the thermal environment in the gas phase.

Authors

Alexander Mialdun
Valentina Shevtsova
Microgravity Research Center
Université Libre de Bruxelles
Chimie-Physique EP - CP165/62
Avenue F.D. Rossevelt, 50
B-1050 Bruxelles
Belgium

Correspondence

Valentina Shevtsova
Tel.: +32-2-6503024
Fax: +32-2-6503126
E-mail: vshev@ulb.ac.be

1. Introduction

During the last few decades, convective flows in systems with free boundaries attract much attention from both fundamental and industrial aspects, especially in microgravity-related science. In the terrestrial environment, buoyancy and thermocapillary forces are coupled to cause convection. In addition the motion of ambient gas is very different in terrestrial and microgravity conditions.

Although the majority of ground-based experiments were performed in small liquid bridges with silicone oils, it is rather confusing to compare quantitatively the results of different researchers. The discrepancy between critical parameters is quite large. There are several reasons for this: difficulties in precise detecting of the onset of oscillations, difficulties in accurate determination of the relative volume of liquid bridge, which leads to additional deformation of free surface and, of course, different experimental conditions. It covers anti-wetting agents, temperature regime around the set-up, the temperature of cold rod (as usually heating from above is studied), the heat exchange from the free surface, etc.

Our results [1, 2], as well as results of other researchers [3, 4], indicate extreme sensitivity of the liquid bridge to environmental conditions. However, a deep understanding of the physical mechanism of these effects is still missing and is the target of proposed study in the frame of forthcoming ESA program.

2. Experiment

The experimental apparatus used in present work is similar to the one utilized in our past experiments, see Ref. [1]. The general view of the setup is shown in Fig. 1. The length of liquid zone was constant in all experiments $d = 3.6$ mm and radius is $R_0 = 3.0$ mm; the resulting aspect ratio is $\Gamma = d/R_0 = 1.2$. The 5 cSt silicone oil (Pr = 68.4) was used as working liquid. To establish a fluid zone the precisely defined amount of liquid was injected from a dedicated push syringe into the gap between rods. The dimensionless (relative) volume of the liquid bridge with deformed interface V is measured with respect to the volume of straight cylinder $V_0=\pi R_0 2d$: conventionally the LB with $V/V_0 < 1$ is slender LB (under-filled) and with $V/V_0 > 1$ is fat LB (over-filled). In current experiments the volume was varied in large limits $0.7 \le V/V_0 \le 1.2$.

The upper rod was constructed in such a way that three-dimensional movements are possible. A heating element Thermofoil™ was mounted around the upper rod to heat the fluid from above. The lower rod was kept at a constant temperature using thermo-regulated water-cooling system.

Temperature oscillations due to time-dependent convection were measured by inserting five shielded thermocouples (*D=0.25 mm*) inside the liquid at the same radial and axial positions and different azimuthal angles. These thermocouples were embedded into the liquid through the upper rod to prevent disturbing of the free surface.

A typical experimental run is carried out as follows. The temperature of cold rod T_C is fixed at desired value (usually 293…298 K) and temperature of hot rod rises up by large step ΔT_0 by increasing heater power, and then the flow regime is stabilized during 20 min. The following stepwise increasing of ΔT is performed by smaller steps, $\Delta T_i < \Delta T_0$, but with the same stabilization time. Starting from some ΔT, close to the critical one, on each step at least 2048 thermocouples readings are recorded with sampling frequency of 10 Hz. The ΔT_{cr} is defined by the appearance of the temperature oscillations on thermocouples. The analysis of flow regimes involved determination of the critical temperature differences ΔT_{cr}, oscillation amplitudes, Fourier spectra, phase planes and peak-to-peak diagrams for all thermocouples.

The experiments were carried out under two different conditions of the surrounding gas. First was an open air (non-shielded LB). In second case the LB was enclosed within thermo-stabilized pipe (shielded LB), see Fig.1.

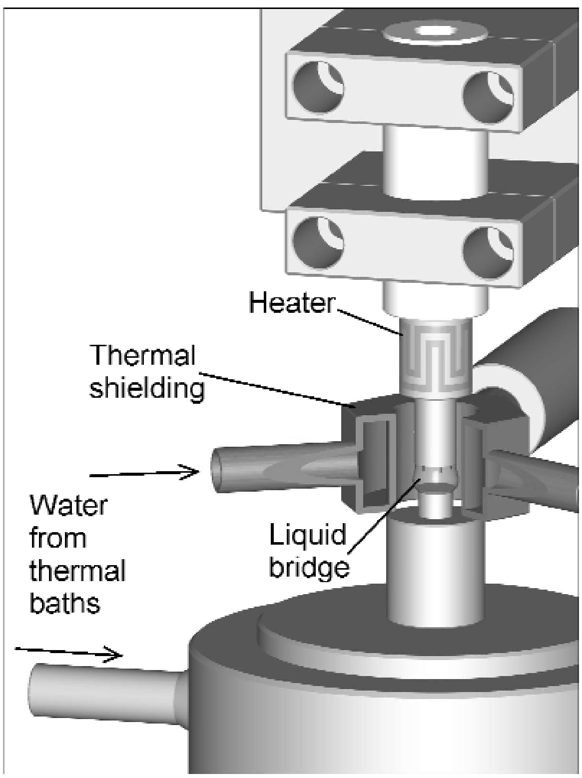

Fig. 1: General view of experimental setup with thermal shielding block installed (sliced in the figure to show a central part).

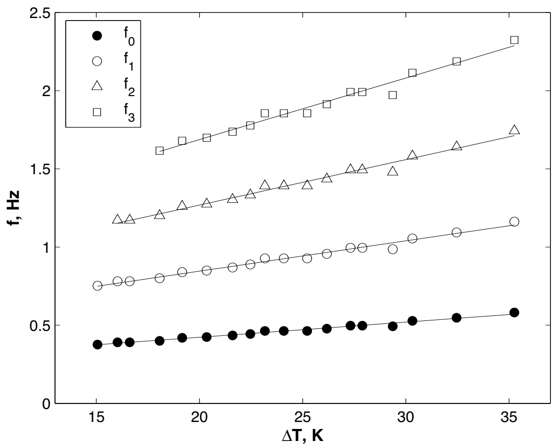

Fig. 2: Evolution of fundamental frequency and three first harmonics with the increase of ΔT (non-shielded LB).

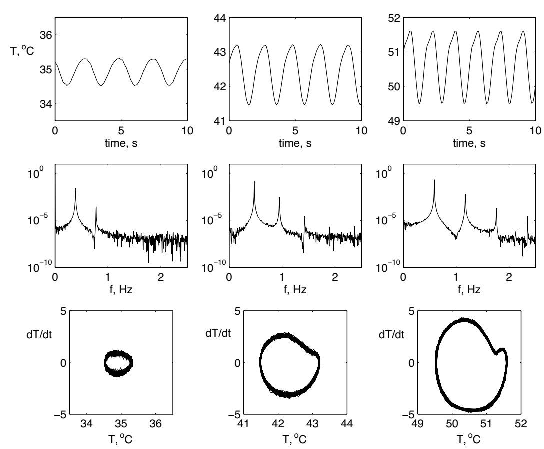

Fig. 3: Temperature records, Fourier spectra and phase planes for slender LB V/V_0>=0.75 at different ΔT=16.0 K, 25.2 K and 35.3 K (non-shielded liquid bridge)

3. Results

The switching of the experimental conditions from shielded to non-shielded LB is one of the ways to change the ambient conditions. Kawamura has identified [3] that the structure and the intensity of gas motion around LB significantly vary in experiments in open air and in experiments with some type of shielding: solid horizontal plates were placed near the hot and cold interfaces. It was found earlier [1, 3] that onset of instability as well as stability of the established non-linear oscillatory flows strongly depends on volume for liquid bridges with non-flat interfaces (disturbed by gravity). Moreover, the influence of surrounding thermal conditions is very different in the case of slender and fat LB. Therefore the study of the effect of the surrounding conditions on the LB stability was carried out for different volumes of LB. Most comprehensive analysis of LB stability was done for two extreme volumes of 0.75 and 1.20.

3.1 Convection in under-filled (slender) liquid bridge

The convective flow in slender LB is found to be quite stable to external disturbances. The analysis of temperature readings on thermocouples for the $V/V_0 = 0.75$ has indicated that instability begins as hydrothermal wave with azimuthal wave number $m = 1$. This type of flow organization is in agreement with previous results, obtained for silicone oil 10 cSt with large Prandtl number, see [4]. We have found that the threshold of instability is *not* sensitive to variations in the thermal conditions of the ambient gas. For instance, for $V/V_0 = 0.75$, $\Delta T_{cr} = 15.0$ K±3% is very stable and well repeatable. This variation of 3% covers all shielded and non-shielded experiments with different room temperatures.

The fundamental frequency f_{cr}, determined by the Fourier analysis, is also quite stable and is about *0.38 Hz* for non-shielded LB, slightly reducing to $f_{cr} = 0.36$ *Hz* in experiments with shielding.

In addition, the sustained oscillations are as well stable with respect to external perturbations. The role of ambient conditions for slender LB is noticeable in smaller effects. For example, let us compare evolution of fundamental frequency and the first harmonics with increasing ΔT. Results in Fig. 2 for experiments in the open air demonstrate strong presence of first and second harmonics from the beginning of oscillatory instability. However in the case of shielded liquid bridge, the spectrum is rather clean (no strong harmonics) even far above the threshold of instability. The temperature records, Fourier spectra and phase planes for slender LB for different ΔT are shown in Fig. 3 (non-shielded liquid bridge). They correspond to the different

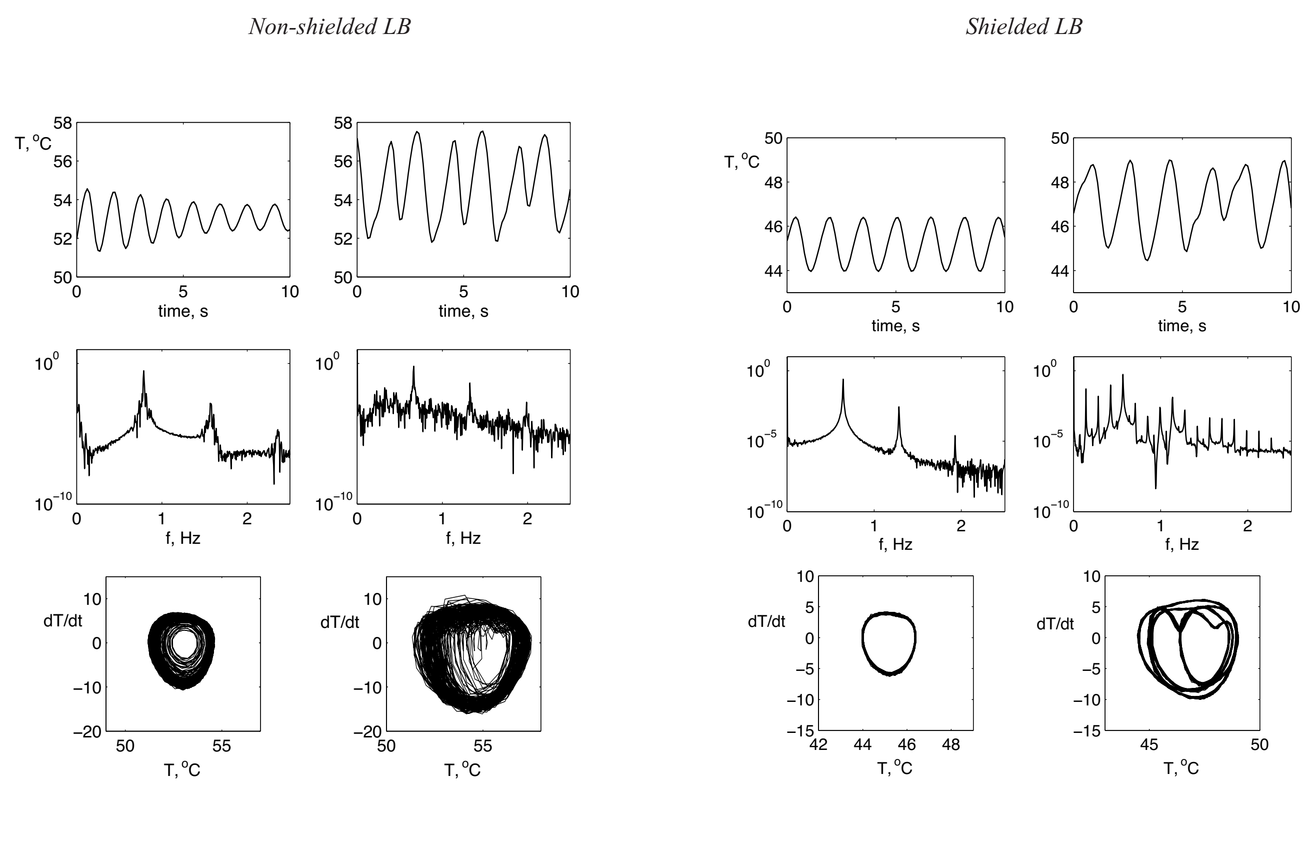

Fig. 4: Temperature records, Fourier spectra and phase planes for fat LB of $V/V_0 = 1.2$; non-shielded at $\Delta T = 40.2$ K and 45.4 K (left side) and shielded at $\Delta T = 30.5$ K and 34.5 K (right side) around point of frequency skip.

distance from the critical point ΔT_{cr} = 15 K. The first signs on the non-linear transitions are appeared when ΔT approaches $\Delta T \approx 2.0\ \Delta T_{cr}$. These supercritical transitions are accompanied by the transformations of originally sinusoidal shape of temperature signal $T(t)$ and the limit cycles. The small non-uniformity from right on the shape of the limit cycles becomes more pronounced with increasing of ΔT.

3.2 Convection in overfull (fat) liquid bridge

On the contrary, the threshold of oscillatory instability in fat LB is extremely sensitive to surrounding conditions. The application of a shielding, kept at room temperature, already changes ΔT_{cr} drastically. Compare ΔT_{cr} = 22.5 K for shielded LB versus ΔT_{cr} = 30 K for non-shielded LB when V/V_0 = 1.2. So, the use of shielding for the fat LB destabilizes the flow. It was found that the threshold of oscillatory instability for the fat LB is extremely sensitive not only to the LB shielding, but also to the ambient temperature level. Variation in the temperature of the ambient gas by 4 K results in changing ΔT_{cr} by almost 40%.

Comprehensive examination of all thermocouples records allows to determine that in the fat LB the instability begins as a standing wave with azimuthal wave number m = 2 and the frequency at the threshold noticeably higher than in slender LB. The temperature records, Fourier spectra and phase planes for the fat LB are shown in Fig. 4 for the LB with shielding and without. In the case of shielded LB an interesting nonlinear transition is observed when $\Delta T = 1.51\ \Delta T_{cr}$, see the right plot in Fig. 4, which corresponds to the ΔT = 34.5 K. At this ΔT the phase plane exhibits quasi-periodic regime. Note, that at the same distance from threshold of instability, i.e. $\Delta T = 1.51\ \Delta T_{cr}$, the non-shielded LB exhibits transition to the non-periodic (chaotic) regime (see left part in Fig. 4 when ΔT = 45.4 K).

In non-shielded LB the temperature oscillations are highly noise polluted. It is clearly seen even for ΔT = 40.2 K when the oscillations are periodic (left side in Fig. 4). Unlike to the shielded LB, the shape of the phase plane is close to be a perfect circle, but trajectories don't repeat exactly the same path. So the limit cycle is rather thick. Also Fourier spectrum displays much wider peaks in comparison with shielded LB for the same mode. In addition, the oscillatory states in the fat liquid bridge are quite unstable with respect to the external disturbances.

4. Conclusions

The influence of the ambient condition on the development of thermoconvective oscillatory flows in non-cylindrical LB is investigated experimentally. Experiments were conducted with high Prandtl number fluid, Pr = 68.4. The described experiments demonstrated the strong influence of interfacial heat transfer on stability of convective flows in LB. The critical temperature difference for slender LB weakly depends on the environmental conditions. However the velocity and temperature fields in the fat liquid bridge strongly react at any small perturbation.

5. Outlook

The development of instability in microgravity experiments is shown to be similar to those observed in tiny LB in normal gravity conditions. Thus the Marangoni force plays the crucial role as the mechanism of instability. It was shown in terrestrial experiments that the ambient conditions around the LB are also important. The recent experiments by Kawamura [4] revealed the existence of relatively strong gas flow in the ambient air that consists of two vortexes. This gas flow near the interface is driven by shear and modified by buoyant convection. However authors of Refs. [1] and [2] have different points of view on the contributions of shear stress and buoyant convection to the strength of the gas circulation. The buoyancy force can be removed in μg-conditions and thus the ambient gas would be driven only by interfacial shear. This is one of the topics suggested for an International Space experiment jointly by ESA (Belgium, Germany, Italy) and JAXA (Tokyo University of Sci., Yokohama National University). We believe that the experiment will provide definitive understanding of the mechanisms driving the ambient gas flow.

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