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Hydrodynamic instabilities under microgravity in a differentially heated long liquid bridge with aspect ratio near the Rayleigh-limit: Experimental results

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Abstract

A liquid bridge of 15.0 mm length L and 3.0 mm radius r (aspect ratio $A = L/r = 5$) from 2 cSt silicone oil ($Pr = 28$) was established under microgravity during the flight of the sounding rocket MAXUS-4. Four different temperature differences $\Delta T = 7, 9, 10, 12$ K have been applied between the ends for sufficient time to reach steady state thermocapillary flow conditions. The aim of the experiment – to observe the onset of hydrothermal waves and to measure their features, like the waves phase speed and the angle between the wave vector and the applied temperature gradient – was reached. Moreover, we can report about the occurrence of a further hydrodynamic structure or instability occurring at the same time in this experiment, namely convection cells of the type of the Bénard–Marangoni instability, drifting in the surface flow from the hot towards the cold side. The latter instability has not been observed in the liquid bridges with $A = 1$ investigated normally, because of geometric restrictions. The Bénard–Marangoni instability is due to the cooling of the free liquid surface in our experiment.

Keywords: Thermocapillary flow; Bénard cells; Marangoni instability; Hydrodynamic instability; Liquid bridge; Hydrothermal wave; Microgravity experiment

1. Introduction

Surface tension gradients due to temperature gradients along the free liquid surface drive thermocapillary flow (from "hot" to "cold" along the free surface, called "surface flow", and reverse in confined geometries, called "return flow"). Thermocapillary flow can undergo various instabilities like oscillatory thermocapillary flow in short liquid bridges (Preisser et al., 1983; Schwabe et al., 1982; Schwabe and Frank, 1999; Leypholdt et al., 2000) or hydrothermal waves in extended liquid layers (Smith and Davis, 1983). A recent review paper is by Schatz and Neitzel (2001).

The original aim of the present microgravity experiment was the verification of the existence of hydrothermal waves in long floating zones as predicted theoretically (Xu and Davis, 1984). This is only possible under microgravity where liquid bridges with a length $L \leqslant 2\pi r$ can be established ($L = 2\pi r$ is the Rayleigh limit) whereas L is restricted in experiments at normal gravity to approximately 3 mm for liquid bridges from silicone oil. In the short bridges with $A = 1$ investigated normally under Earth gravity (1-g), oscillatory thermocapillary flow arises in the form of azimuthally travelling waves (Preisser et al., 1983; Leypholdt et al., 2000) whereas the hydrothermal waves in extended liquid layers or extended liquid bridges should exhibit another angle of the wave vector with the applied temperature gradient, resulting in an axial component of

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the wave motion. The aim of the present experiment was the study of the hydrothermal wave in a suitably long liquid bridge. We have chosen $A = L/r = 5$ which is near the stability limit of $A = 6.28$, but seemed to allow safe experimentation without rupturing of the zone by small disturbances. Some selected result regarding hydrothermal waves are reported here and the full paper is under preparation (Schwabe, under preparation, 2005).

The focus of the present paper is on the unexpected results of this experiment; besides the travelling hydrothermal wave we observed a cellular pattern, drifting with the surface flow from the hot towards the cold side. This "drifting cellular pattern" was assigned to the Bénard–Marangoni cells observable in thin liquid layers heated from below and cooled from above (Bénard, 1900; Schwabe, 1999), first analyzed by Pearson (1958). Such drifting cellular patterns are often observed on melts in Czochralski crystal growth systems which are heated from the side strongly cooled from above by radiative emission (Schwabe, 1981). We analyze our experiment to find out whether the critical Marangoni number $Ma = (-\partial\sigma \cdot \partial \mathrm{T}) \cdot (\Delta T^{\mathrm{c}} \cdot d) \cdot \eta^{-1} \cdot \chi^{-1}$ was exceeded for the Bénard-Marangoni instability to occur. Here, $\partial\sigma/\partial T$ is the temperature dependence of the surface tension σ, ΔT^{c} is the critical temperature difference between the liquid interior (e.g., at the axis of the liquid bridge) and the free surface, d is the thickness of the liquid "layer" under consideration (e.g., the radius r of this liquid bridge), η is the dynamic viscosity and χ is the thermal diffusivity of the liquid. Because a liquid bridge is geometrically quite different from the liquid layers studied normally in connection with the Bénard–Marangoni instability, and the basic flow state of a thermocapillary liquid bridge is dynamic in contrast to a quiescent liquid layer heated from below, our analysis can only estimate a Ma^{c} for the Bénard–Marangoni instability in the liquid bridge geometry. But after the theoretical analysis of Pearson (1958) and the experiments under microgravity of the author (Schwabe et al., 1990; Schwabe, 1999) there is no doubt about the occurrence of the Bénard–Marangoni instability in suitable hydrodynamic systems under microgravity, liquid bridges included. The thermocapillary liquid bridge is an even more complicated case because of the hydrodynamic instabilities occurring at the same time. This needs a dedicated numerical simulation.

On the other hand we will point out that experiments with floating zones (liquid bridges) under microgravity 1-g and under µ-g are likely to be strongly cooled from the surrounding air which could provoke the cellular pattern of the Bénard–Marangoni instability. But the phenomenon was not observed until now in thermocapillary liquid bridges because the length L of the bridges was only of the order of $\lambda/2$, with λ the wavelength of the Bénard–Marangoni instability.

2. Experimental

The experiment was conducted on the sounding rocket MAXUS 4 launched from ESRANGE in Kiruna, North-Sweden, on April 29, 2001. The launch and the experiment hardware was paid by the European Space Agency ESA, the hardware was realized by Astrium-Space, Bremen-Trauen (Modul TEM 06-27 M). We could establish a liquid bridge from 2 cSt silicone oil of $L = 15.0$ mm and $r = 3.0$ mm under µ-g. Four different temperature differences ΔT have been applied to the liquid bridge supported by a sapphire cylinder of $r = 3.0$ mm (cold side) and a copper cylinder of $r = 3.0$ mm (hot side). The mean temperature $\bar{T} = (T_{\mathrm{hot}} + T_{\mathrm{cold}})/2$ was kept constant at $\bar{T} = 35\,^{\circ}\mathrm{C}$. The temperature of the chamber was 30 °C at launch and increased linearly to 32 °C at the end of the µ-g time. The inner diameter of the cylindrical chamber was 10 cm, its height was 94 mm. The chamber was filled with air at a pressure of 1.05 atm.

Tracers in the liquid allowed to observe the flow with video cameras in a central vertical laser-light sheet and through the sapphire cylinder in a horizontal laser-light sheet. Parts of the observations have been downlinked and recorded.

Nine fine thermocouples made from unshielded 25 µm ∅ wire (type Cromel–Alumel) have been used to register temperature oscillations due to hydrothermal waves and phase shifts due to their different positions. Five thermocouples had the same radial and azimuthal but different axial position (Ax). Four thermocouples had the same radial and axial position as the middle-thermocouple (A × 3) but different azimuthal positions (Az). We could thus correlate five axial thermocouples

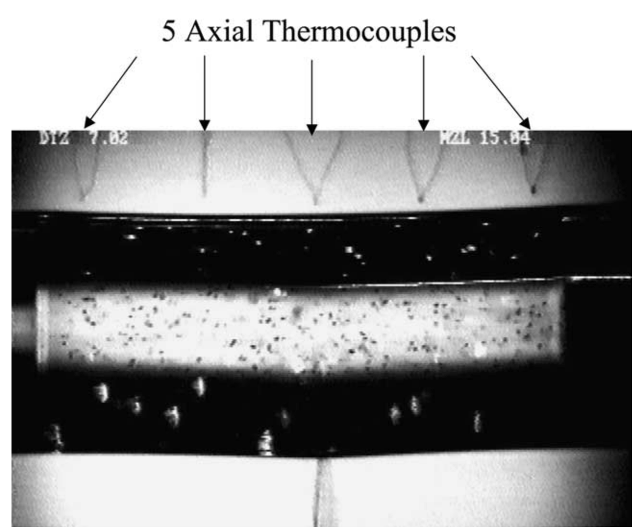

Fig. 1. Photograph of the liquid bridge with $A = 5$ under µ-g. Five thermocouples Ax are coming from the top and are near the free surface. Four thermocouples Az are introduced from below at $L/2$ which distorts the bridge slightly. The right side is heated.