Marangoni Convection in Space Microgravity Environments

Abstract. *Thermally induced surface-driven convection (thermal Marangoni convection) was investigated in the Spacelab 1 microgravity environment. The configuration studied is related to the floating-zone technique used for crystal growth.*

Spacelab 1 experiment 1ES328 was conceived to investigate free convection in low gravity for configurations, such as liquid bridges (Fig. 1), modeling the floating-zone technique used for crystal growth. A preliminary analysis of the available data indicates that the experiment has demonstrated the existence of thermal Marangoni convection in a space microgravity environment; proved that it could be established in liquid bridges considerably higher than on the earth; confirmed the theoretical prediction that Marangoni boundary-layer regimes, rarely attainable on the earth, could be attained in space; and has shown that with the fluid used (silicone oil) and the geometry considered (liquid bridge) there is no detectable influence of imposed electric fields.

Not all the data are available yet and the analysis of the available data is still in progress. Hence no discussion can be presented of the full range of problems investigated: effects of variation of liquid bridge shapes; influence of rotations and of oscillations of the end disks; breakage and reformation of the liquid column; evolution or decay of Marangoni flows in the liquid volumes attached to the end disks. The investigation of some of these problems was made possible by the availability of additional crew time beyond that originally scheduled. A completely unforeseen event occurred during some of the unscheduled runs: the presence of gas bubbles in the liquid bridge. There are indications that the data available will be sufficient to obtain qualitative, and possibly quantitative, information on the dynamics of bubbles in Marangoni flows.

On the earth Marangoni convection is difficult to investigate experimentally, since the extension of the interface in the direction of the gravity vector is extremely limited and, in addition, Marangoni convection is masked by gravity-induced convection or convective instabilities. To reduce these masking effects and thus simulate Marangoni convection the extension of fluid regions in the direction of the gravity vector must be severely reduced. Adequate diagnostics then become even more difficult, and at any rate not all interesting flow regimes can be simulated since the relative importance of other forces (for instance, inertia and viscous forces) can be varied only in a limited range.

The Spacelab results have shown that these shortcomings are eliminated in a microgravity environment and that unique opportunities are thus offered for achieving significant progress in the understanding of Marangoni convection. This is needed since, as the same experiment indicates, Marangoni convection is present in many materials and life science experiments or processes.

Free convection is fluid motion in the absence of imposed pressure or velocity differences. When interfaces are present, free convection can be gravity-driven, surface-driven, or both, and is referred to, respectively, as natural, Marangoni, or combined free convection (*1*).

Marangoni convection is caused by gradients of surface tension σ (Marangoni forces) due to interface gradients of temperature, T, concentrations, or electric fields. The Marangoni force, $\nabla \sigma$, which drives the interface fluid particles in the direction of increasing surface tension, is balanced by the viscous shear stresses of the interfacing fluids, and they, in turn, induce motion in the bulk of the fluids (*2*). Whenever there is an imposed difference of a property affecting the density of the fluids and the surface tension, both buoyancy and Marangoni forces are, in principle, present, but they may be of different orders of magnitude. On the earth the main driving force is usually the buoyancy force, whereas in microgravity the main driving force is the Marangoni force. However, there may be situations, both on the earth and in reduced gravity environments, in which Marangoni and buoyancy forces are of the same order of magnitude (*3*).

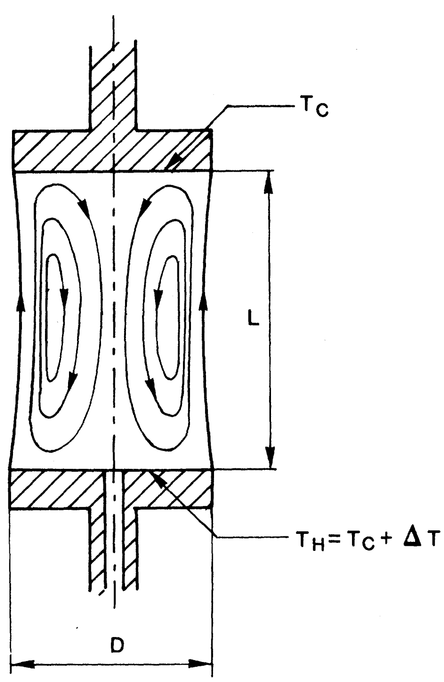

Fig. 1. Marangoni flow patterns in a liquid bridge.

Marangoni convection involves rather complex mechanisms which are not all well understood. Velocity, temperature, and concentration fields in the bulk of the interfacing fluids are strongly coupled through the transport (convective and diffusive) of mass, momentum, and energy in both volume and surface phases. Whereas coupling due to buoyancy forces is volume-distributed and fades out with diminishing gravity, coupling due to Marangoni forces is concentrated on the interface, depends strongly on its dynamics and thermodynamics (*2*), and increases at low g levels because larger stable interfaces are attained under these conditions. Bulk phases are often bound by both interfaces and solid surfaces, and this introduces the intricacies of dynamics and thermodynamics of contact lines and contact angles (*4*). The different runs of Spacelab experiment 1ES308 addressed some aspects of this complex phenomenology.

The apparatus used for the experiment was the fluid physics module, and the configuration chosen was typical of the floating-zone technique. It consisted of a liquid bridge established between two circular disks of equal diameter D (Fig. 1). The distance, L, between the disks could be varied. The temperature of one disk could be brought to 60°C, thus establishing a temperature difference that would induce the surface tension gradient driving the motion. The liquid used was a silicone oil (5 CS) whose surface tension decreases with temperature. Thus the direction of the surface motion is from the hot to the cold disk and, because of the continuity, the flow pattern schematically shown in Fig. 1 is established. Flow patterns were visualized by means of tracers (ecospheres of about 100 μm) and a number of thermocouples were located on the disks.

The dimensions of the liquid bridge are essentially governed by the Bond characteristic length $L_b = \sqrt{\sigma/\rho g}$, where ρ is the density of the liquid and g is the intensity of the (residual) gravity vector. For most liquids of interest L_b, on the earth, is of the order of 10^{-1} cm ($L_b = 0.149$ cm for silicone oil) (*5*). If R denotes the smallest radius of curvature of the interface, hydrostatic equilibrium (*1*) and stability (*6*) analyses lead to the conclusion that both L (for g directed along the axis of the liquid bridge) and R can be at most of the order of L_b. Since L_b is scaled as the inverse square root of the gravity level, it follows that in the nominal Spacelab environment ($g/g_0 = 10^{-4}$) one can obtain liquid bridges two orders of magnitude higher than on the earth.

This has been confirmed by the Spacelab experiment. With a disk diameter of 6 cm, flow patterns of the type shown in Fig. 1 were observed in columns as high as 6.8 cm. Columns were formed by injecting liquid from a reservoir through a hole in the feeding disk and concomitantly increasing the distance between the two disks. After a column had been kept in isothermal conditions for a time, it was observed that it reached a truly quiescent state: all tracers were at rest. Power was then switched on and tracer movement was immediately triggered. Thus the flow was proved to be a Marangoni flow. This also shows that, at least during this experiment, the gravity level was less than 10^{-3}, otherwise the liquid column would have collapsed. By comparison, simulations on the ground could be performed only with liquid bridges having a radius of 3 mm and heights of the same order.

The momentum produced at the interface by the Marangoni force diffuses into the liquid. Let l be the nondimensional penetration depth for momentum diffusion, measured normal to the interface and referred to the column height, L. Flow regimes depend on the order of magnitude of l, which in turn depends on the order of magnitude of the conditional Reynolds number $R_m = V_m L/\nu$ (*4*, pp. 349–358), where ν is the kinematic viscosity of the liquid, $V_m = [\sigma(T_c) - \sigma(T_H)]/\mu$, the Marangoni speed, and μ is the dynamic viscosity.

For R_m less than or equal to one, the penetration depth is on the order of one and the flow regime is of the Stokes type (inertia forces negligible, $R_m \ll 1$) or the Navier-Stokes type [inertia and viscous forces of the same order of magnitude, $R_m = O(1)$]. For $R_m \gg 1$, l is much less than one and momentum diffusion from the interface into the liquid is confined to a thin layer, which we call the Marangoni boundary layer (*7*), whose nondimensional thickness δ (referred to L) is on the order of $R_m^{-1/3}$. Everything else being the same (fluids, geometry, and imposed temperature difference) in microgravity environments, the conditional Reynolds number R_m may be considerably larger than on the earth because of the much larger extension of the liquid bridge. Hence, Marangoni boundary layers are very likely to be established and features of the flow will be substantially different from those in ground simulations of Marangoni convection. This scale effect provides additional evidence of the need for experimentation in space.

Attainment of a Marangoni boundary-layer regime in the Spacelab experiment has been assessed by estimating the order of magnitude of the maximum flow velocity, V_r, from the available data. The order of magnitude of V_r in Marangoni convection depends on the flow regimes (*1, 3*). In the absence of Marangoni boundary layers, V_r is of the same order as the Marangoni characteristic speed, V_m. When boundary layers are present V_r is of the order of $V_m\delta$ and is thus substantially smaller. Estimates of V_r indicated that Marangoni boundary-layer regimes were attained in most of the runs.

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References and Notes

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Solidification and Ostwald Ripening of Near-Monotectic Zinc-Lead Alloys

Abstract. *Studies of melting and resolidification were carried out on Spacelab 1 on the zinc-lead binary, an alloy which exhibits a miscibility gap in the liquid state. The possibility of maintaining the state of homogeneous dispersion of lead in the zinc matrix in a microgravity environment was verified. The second objective of the experiment was to study Ostwald ripening of the lead droplets (manifested as slow coarsening of the droplets) within the region of immiscibility. An increase in droplet size was observed and may have been due to Ostwald ripening, although the effect on droplet size of precipitation during cooling must be analyzed before this can be determined conclusively.*

The Zn-Pb binary is representative of the large group of alloy systems that exhibit a miscibility gap in the liquid state. At high temperatures molten zinc dissolves lead completely, but below a critical temperature the liquid separates into two phases, forming a suspension of lead-rich droplets in a zinc-rich liquid matrix. Under terrestrial gravity, the lead droplets sink to the bottom, causing complete demixing of the system. Under zero gravity and in the absence of convection, such suspensions should be stable for extended times. This was demonstrated for the model system water-oil in a Skylab experiment (*1*). For immiscible metallic systems, however, coarse demixing has occurred in nearly all microgravity experiments so far, including one Apollo-Soyuz experiment on Zn-Pb (*2*). This was attributed to Marangoni convection, residual acceleration, or unspecified "special effects."

One objective of experiment 1ES313 on Spacelab 1 was to verify the possibility of maintaining the state of homogeneous dispersion in Zn-Pb alloys and of bringing the dispersion back to the solid state without disturbance by particles being pushed ahead of the solidification front. Terrestrial experimentation (*3*) had shown that, at the solidification rate envisaged for the Spacelab experiment, the lead particles would not be pushed ahead.

The second and main objective of our Spacelab 1 experiment was to study Ostwald ripening of the lead droplets within the region of immiscibility. This would manifest itself as a slow coarsening of the droplets, driven by the tendency toward minimum total interfacial energy