Fluid statics and dynamics in microgravity

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Fluid statics and dynamics in microgravity

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Abstract. Research into fluid physics under reduced gravity conditions has been stimulated by basic research and numerous applications. For example, research includes the shape and stability of liquid surfaces; the bifurcation of convective flows; the stability of Marangoni flows; and with respect to applications, surface tension tanks; spacecraft dynamics; crystal growth; the production of composite materials and the extremely large field of life sciences. The stability criteria of liquid bridges between coaxial circular discs are discussed. The stability of liquid volumes at edges is considered. Respective experiments performed in parabolic flights of a KC-135 aircraft, in sounding rockets and in the Spacelab are reported. Special attention is paid to the various effects of Marangoni convection on crystal growth and on the separation of binary liquid mixtures exhibiting a miscibility gap.

1. Introduction

Fluid physics holds a key position among the areas of microgravity research. Each experiment or procedure on material sciences or in life sciences, which may gain from performance under microgravity conditions, involves at least one fluid. In addition, fluid physics dominates many questions of fluid handling and of spacecraft stability. The term fluid in this context includes liquids and gases, for example water or a metallic melt used for production of composite materials, a drop created for studying its vibrations or an unwanted gas bubble hampering the growth of a single crystal.

It is always in the fluid phase where reducing gravity causes many changes. The most obvious effects are the constancy of fluidstatic pressure, the absence of free convection and the absence of sedimentation. The constancy of fluidstatic pressure allows the establishment of large fluid surfaces. The absence of free convection affects heat and mass transport and enables accurate investigations into diffusion to be made. The absence of sedimentation influences the separation of monotectic alloys. All the effects mentioned clearly affect crystal growth and investigations into critical phenomena.

Under microgravity conditions the shape of the liquid surface is no longer determined by gravity 'pressing' the liquid to the container bottom, but rather by the shape of the container and the contact angle of the liquid with the container material. This has important consequences for the design of fuel tanks for spacecrafts which have to guarantee fuel outflow on demand. By using large fluid volumes and surfaces it is possible to study volume and surface oscillations, surface stability, non-linear oscillatory effects, wetting dynamics, convective stability, and thermocapillary and solutocapillary convection (Marangoni convection).

2. Liquid bridge stability

Since the beginning of research into materials under microgravity conditions, particular attention has been given to liquid bridges or columns between coaxial circular discs. This has been stimulated by axisymmetry considerably reducing the theoretical effort, by the fact that the supporting discs allow application of precise stimuli and diagnostics and, in particular, by the applications of this geometry to crystal growth from floating zones.

It has already been shown by Rayleigh (1879) in the last century that a cylindrical liquid jet breaks if its length L exceeds its circumference $2\pi R$. This stability criterion also applies to cylindrical liquid bridges between coaxial circular discs. When lengthened to $L \geqslant 2\pi R$, one half of the bridge widens whereas the other half shrinks accordingly. The surface enlargement in the region of widening is smaller than the surface reduction in the region of shrinking. Figure 1(*a*) shows the breakage of a liquid bridge of silicon oil during the Spacelab D1 experiment by Da Riva and Martinez (1986). The picture shows two successive video frames: in the first one the bridge still exists; it has broken into two liquid volumes at the supporting discs in the second one. These volumes have not yet assumed their final shape, which are clearly spherical caps. The diameter of the supporting discs was 35 mm, the height of the liquid bridge was roughly 100 mm (Martinez 1987).

In view of the numerous applications of materials under microgravity conditions, extensive stability diagrams of liquid bridges dependent on gravity and on the frequency of rotation have been calculated (Martinez 1984, Langbein 1990c). The relevant dimensionless numbers are the Bond number

$$B = \Delta\rho g R^2/\sigma \tag{1}$$

and the Weber number

$$W = \Delta\rho\omega^2 R^3/\sigma \tag{2}$$

where $\Delta\rho$ is the density difference between the liquid and the outside fluid, g the acceleration due to gravity, ω the circular frequency of rotation, R the radius of the supporting solid discs and σ the surface tension.

In addition to the amphora-mode instability shown in figure 1 there exists a symmetric instability of liquid columns. The column may widen close to both supporting discs and shrink in the middle. This symmetric breakage has a higher increment, i.e. it is faster than that according to the amphora-mode instability. On the other hand, in the case of cylindrical columns it requires a larger height and therefore can hardly be observed.

During the Skylab mission Carruthers *et al* (1975) observed still another instability of rotating liquid bridges: they may rotate around their axis like a skipping rope. With liquid bridges exhibiting small neck radii the symmetric instability is most likely. For nearly cylindrical bridges and Weber numbers $W < \frac{1}{3}$ the amphora-mode instability is favoured, whereas for $W > \frac{1}{3}$ the skipping rope instability will arise. One should keep in

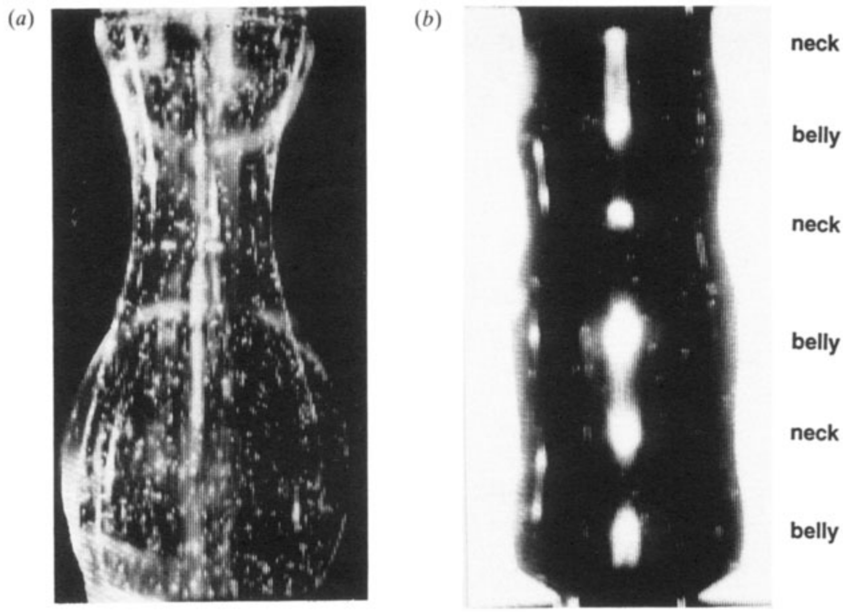

Figure 1. (*a*) Breakage of a liquid column of silicon oil with 35 mm diameter and 100 mm height and (*b*) a resonance mode exhibiting three necks and bellies.

mind however that breakage due to the two former instabilities becomes more likely once the skipping rope mode has been assumed.

3. Liquid bridge oscillations

Liquid bridges in addition are well suited for studying dynamical effects. A liquid bridge may be accurately excited by vibrations of the supporting discs. Additional sensors may be integrated into the discs. Figure 1(*b*) shows a resonance mode of a liquid bridge exhibiting three necks and bellies. It is the same bridge of silicon oil as shown in figure 1(*a*).

Figure 2 depicts the resonance frequencies of infinitely long liquid columns. The abscissa gives the reduced wavelength $\lambda/2\pi R$, the ordinate gives the Ohnesorge number

$$Oh = \rho\nu^2/\sigma R \tag{3}$$

which is the ratio of viscous damping over the restoring force of the surface tension σ. If damping is strong there is no actual oscillation of the column. Any perturbation of the shape fades away aperiodically (Bauer 1984, 1986). The full curves shown correspond to constant values of the reduced frequency $\omega' R^2/\nu$. An increase in frequency obviously requires a decrease in the Ohnesorge number. The broken curves correspond to constant values of the imaginary part $\omega'' R^2/\nu$ of the frequency, i.e. the strength of damping.

When finite bridges between vibrating supporting discs are considered, the boundary conditions of the discs require that the axial flow velocity equals the disc velocity and the radial flow velocity vanishes. The resulting surface oscillations are no longer axially periodic, but rather are damped. At large distances from the discs no surface oscillation

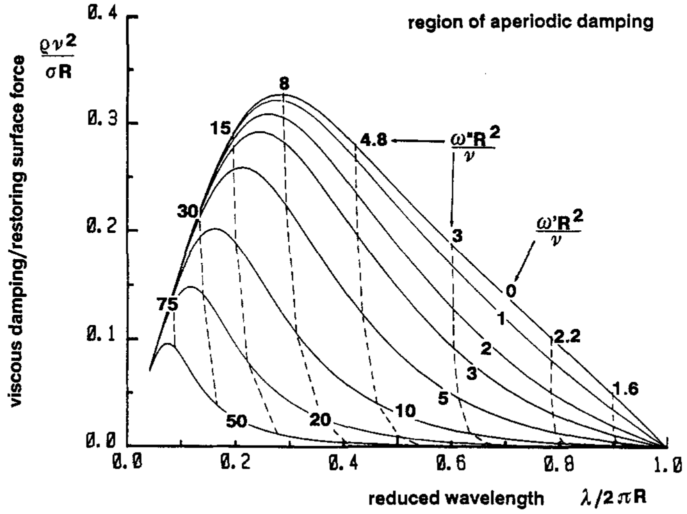

Figure 2. The resonance frequencies of infinite cylindrical columns against wavelength and Ohnesorge number. The full curves show the reduced frequency $\omega' R^2/\nu$, the broken curves exhibit the strength of damping $\omega'' R^2/\nu$.

remains. This problem may be solved by superposition of the solutions of the dispersion relation for real frequency and complex wavenumber. Quantitative experiments on the resonance frequencies of finite liquid columns are foreseen for the German Spacelab Mission D2 in 1992.

4. Liquid volumes at edges and corners

Let us now turn to liquid volumes in edges and corners. By a solid edge we understand a wedge with dihedral angle $2\alpha < \pi$ and edges in their more common sense with dihedral angle $2\alpha > \pi$. A complete knowledge of the behaviour of fluids at edges and corners is very important for technical aspects such as the design of fuel tanks (surface tension tank) and for all aspects of materials processing in a microgravity environment. Figure 3(a) shows a sample of the monotectic metallic pair aluminium/indium, which has been cooled and solidified during the six minutes of microgravity provided during the free flight of a sounding rocket (Ahlborn and Löhberg 1976). The sample shown belongs to a series of attempts at producing finely dispersed mixtures of alloys under microgravity conditions. Since the heavier of the two components no longer sediments, better chances for obtaining such mixtures than on the ground have been conjectured. However, capillary effects and Marangoni migration of the precipitates hitherto annulled these expectations (Ahlborn and Löhberg 1984, Langbein 1990a).

Figure 3(b) shows the spreading of methanol around cyclohexane during a parabolic flight of a KC-135 aircraft (Langbein and Heide 1986). The microgravity time available during parabolic flights is up to 30 s. During good weather conditions an experienced pilot may achieve about $10^{-2}\,g$. The liquid container of dimensions $40 \times 20 \times 10$ mm has been used earlier for studying phase separation in two sounding rocket flights.

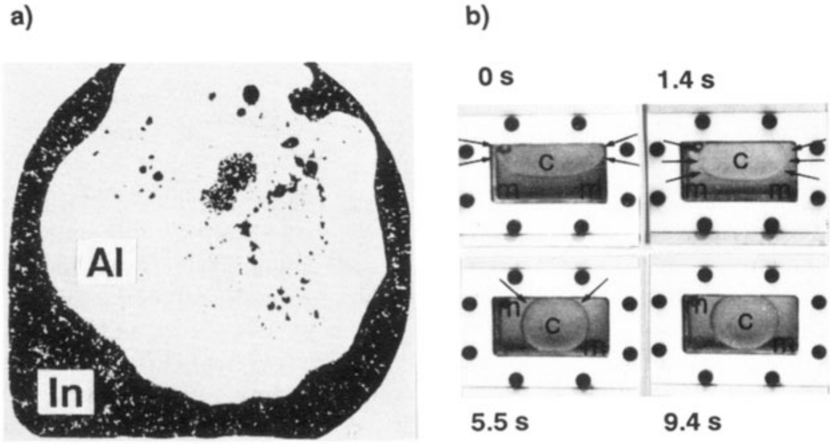

Figure 3. (*a*) Cross section of a cylindrical sample of the monotectic alloy aluminium/indium, which has been solidified in the SPAR-II mission (Ahlborn and Löhberg 1976). (*b*) Spreading of methanol (m) around cyclohexane (c) during a parabolic flight of the KC-135 aircraft. The inserted times mark the beginning of reduced gravity.

Figure 3(*b*) demonstrates that spreading of the wetting liquid methanol around the non-wetting liquid cyclohexane takes only about 5 s.

5. Wetting of edges

It has been proved by Concus and Finn (1974) that a fluid must penetrate into a solid edge if the sum of half the dihedral angle α of the edge and the contact angle γ of the fluid is smaller than a right angle

$$\alpha = \gamma < \pi/2. \qquad (4)$$

In such an edge the fluid surface assumes a negative curvature. It gives rise to a capillary underpressure which sucks the fluid into the edge. If edges with differing dihedral angles 2α all satisfying equation (4) are interconnected, the same capillary underpressure, i.e. the same curvature of the fluid surface, is assumed.

In the opposite case, if the sum of half the dihedral angle α and the contact angle γ of the fluid exceeds a right angle, the capillary equation implies cylindrical fluid surfaces exhibiting positive curvature. However, if such a cylindrical surface is preformed in an infinite edge, it must break into drops in the manner of the cylindrical jet. The respective stability criterion has been derived by Langbein (1990b).

The wetting of edges by liquids and the breakage of preformed surfaces has been investigated during several campaigns of parabolic flights (Langbein *et al* 1990). It also provides a convenient method of measuring contact angles between non-transparent liquids (e.g. metallic melts) and containers. Let us take a set of containers with differing dihedral angles 2α of the edges. Fill them with binary metallic mixtures; heat them and quench them under microgravity conditions. By later inspection on the ground it will still be possible to decide whether an edge has or has not been wetted, i.e. whether

$\alpha + \gamma < \pi/2$ or $\alpha + \gamma > \pi/2$. The accuracy of this method depends on the time and quality of reduced gravity.

6. Marangoni convection in liquid bridges

A large number of microgravity experiments has been devoted to Marangoni convection. The absence of buoyancy driven convection makes it the main source of natural convection in a microgravity environment. Marangoni convection can be studied unperturbed by other convective effects on the one hand, and on the other hand, has to be carefully controlled in all investigations in materials science and life sciences.

Let us start with thermocapillary convection in liquid bridges. When the discs supporting a liquid bridge are heated to different temperatures, Marangoni convection is directed from the hot disc to the cold disc along the surface. If the temperature difference is small, the convection rolls are axisymmetric. However, with increasing temperature difference oscillatory flows arise which are non-axisymmetric and appear to rotate around the axis. Investigations on liquid bridges have been promoted by Chun and Wüst (1982), Chun (1983, 1984), Monti *et al* (1984) and Napolitano *et al* (1986, 1987) and by Schwabe *et al* (1982), Preisser *et al* (1983) and Schwabe and Scharmann (1984). Earth-bound experiments on small liquid bridges, experiments in sounding rockets, experiments in autonomous containers and Spacelab experiments have been performed. The onset of oscillatory convection still is a main topic of interest.

In theory the momentum equation, the energy equation and the capillary equation have to be solved simultaneously. The researchers therefore tried to predetermine the onset of oscillatory flows by plotting the Marangoni number at the onset against the aspect ratio of length to diameter of the bridges. The Marangoni number

$$Ma = \Delta\sigma L/\eta\kappa \tag{5}$$

is the ratio of the driving difference $\Delta\sigma$ in surface tension over the parameters reducing the flow and the temperature field, i.e. the dynamic viscosity η and the thermal diffusivity κ, respectively. The diagrams of the onset of oscillatory flows obtained from investigations on small liquid bridges on the ground, however, do not fit with the results from microgravity experiments in sounding rockets and in the Spacelab. This still leaves a strong challenge to theory and experiment.

The microgravity experiments on crystal growth from floating zones performed hitherto together with the basic fluid dynamic investigations have led to a reorientation of the growth experiments. Marangoni convection gives rise to oscillatory flows, which cause striations of the growing crystal in a like manner to buoyancy driven convection on the ground. Magneto-fluid-dynamic damping is now being considered as a counter measure.

7. Marangoni migration of drops and bubbles

A second line of research is Marangoni convection of drops and bubbles. This topic has been strongly stimulated by the metallurgical investigations on the separation of monotectic alloys. The final component distribution in the aluminium/indium sample shown in figure 3(*a*) is no doubt determined by capillarity. Indium wets the container material alumina better than aluminium. Its contact angle satisfies equation (4). In

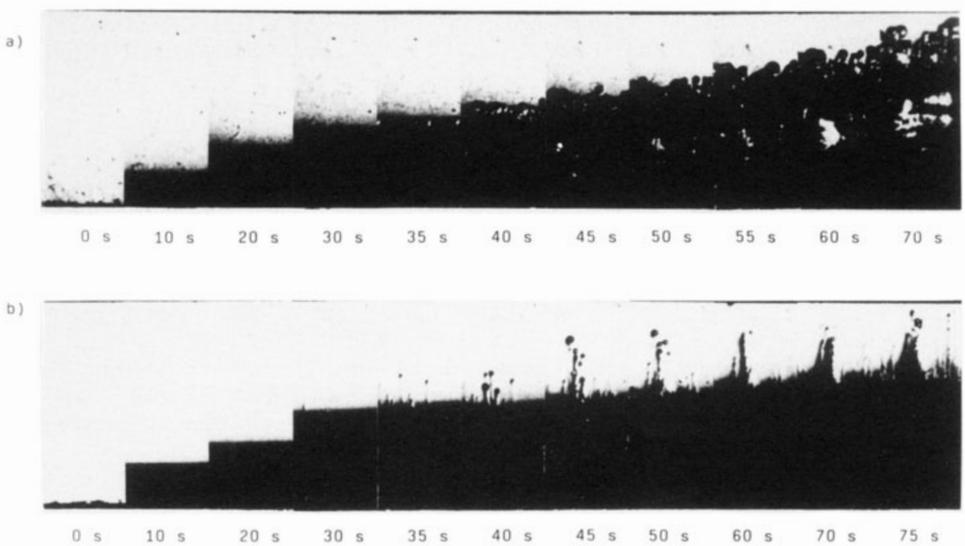

Figure 4. (*a*) Progression of a fog front followed by Marangoni migration of cyclohexane droplets during cooling a $\text{cyclohexane}_{0.35}/\text{methanol}_{0.65}$ mixture into the miscibility gap. (*b*) Progression of a fog front followed by Marangoni migration of methanol droplets during cooling a $\text{cyclohexane}_{0.95}/\text{methanol}_{0.05}$ mixture into the miscibility gap.

addition, nucleation of the component exhibiting the smaller contact angle is favoured in edges and corners.

The kinetics of separation, however, is mainly determined by Marangoni migration. Cooling a metallic melt is possible from the outside only, such that a temperature gradient from the wall to the centre of the sample arises. Drops of the minority component formed inside the sample may thus lose surface energy by migrating towards the centre. The velocity of this migration is mainly given by the change in surface tension $2R\nabla\sigma$ along the particle's surface over the dynamic viscosity η.

Microgravity experiments on the Marangoni migration of drops have been performed on the sounding rocket missions TEXUS-7 and TEXUS-9 (Langbein and Heide 1984, 1986). The liquid pair used was cylohexane/methanol, which exhibits a miscibility gap with a consolutal temperature of 46 °C. The liquid mixtures were heated to 50 °C before launch and unidirectionally cooled into the miscibility gap after beginning of microgravity. After about 30 s, when the drops of the minority component (i.e. cyclohexane in mission TEXUS-7, methanol in mission TEXUS-9) had reached sizes of 100–200 μm, very strong collective Marangoni convection to the hot side was observed (see figure 4).

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