FLUID PHYSICS UNDER REDUCED GRAVITY – AN OVERVIEW

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ABSTRACT

Problems related to several fluid physics experiments to be performed under reduced gravity, onboard Spacelab (1st Mission), are discussed. Special attention is placed on parallel and preparatory work on Earth, which could throw some light on the opportunity, present interest and limitations of these experiments.

The need for strong supporting fundamental research and, in particular, a more precise determination of the parameters involved, is stressed.

Keywords: Microgravity, Spacelab, Spreading of liquids, Surface tension, Contact angle, Liquid bridges, Drops, Marangoni convection.

1. INTRODUCTION

Research in low-gravity fluid physics started in Europe in the middle sixties with the aim of solving problems posed by fluid management in spacecraft. Typical problems were, sloshing, thermal control, capillary liquid retention, gauging of partially filled tanks, etc. Refs. 1 to 5.

On the other hand, industrial processes based on the *freezing during free-fall of drops (manufacture of* hunting small shots, glass fibers,...) use other than normal gravity conditions at least for short times.

Finally, studies on capillary-dominated fluid configurations, which are relevant to microgravity, were undertaken in the 19th century by scientists quite unaware of the feasibility of orbital laboratories. The names of such distinguished men as Young, Laplace, Gauss, Plateau, Rayleigh should be mentioned in this regard.

Nevertheless, our history begins in 1974 when ESRO (the forerunner of ESA) issued an "invitation to submit ideas for the definition of the experimental objectives for the First Spacelab Mission".

From the nearly 80 ideas received, 13 dealt with pure fluid physics, although several more were in the never clearly defined fringe between fluid physics and material sciences.

Most of the ideas concerning fluid physics were accepted, and those rejected were on the basis of foreseable technical difficulties. This was, for example, the case of two experiments requiring liquid helium temperatures.

The accepted ideas were accomodated in the Fluid Physics Module, and the incorporation of so many *conflicting requirements into a single apparatus* was not a mean task for which FIAT CR, the developer, should be praised.

2. THE PLATFORMS

Figure 1 shows the microgravity capabilities of three types of platforms which are being used or will be used in the near future to perform experiments under reduced gravity conditions.

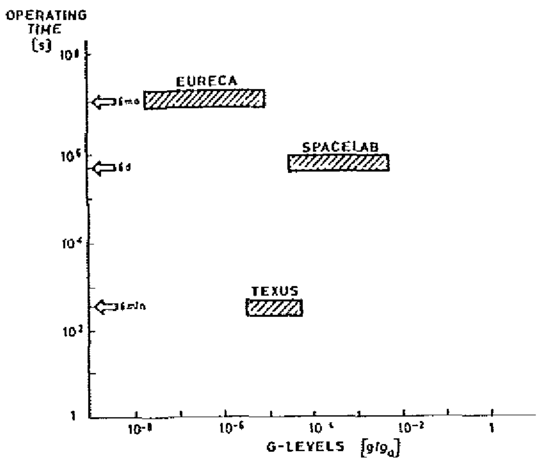

Figure 1. Operating time vs. gravitational levels with three microgravity platforms.

TEXUS Sounding Rocket Programme was initiated in 1976. It is sponsored and financed by the German Ministry of Research and Technology and administered by the DFVLR.

The carrier is the Skylark VII which provides for approximately 6 min of free-fall conditions, with residual accelerations below 10^{-4} g, for a payload

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in the range 330 to 350 kg.

The rockets are launched from ESRANGE, near Kiruna, Sweeden, in cooperation with the Swedish Space Corporation.

Up to the moment six TEXUS Missions have been accomplished. TEXUS VII and VIII are scheduled for April/May 1983.

An overview of experiments conducted so far under TEXUS programme is presented in Ref. 6.

SPACELAB is a modular facility carried a board the Space Shuttle Orbiter. It consists of an enclosed, pressurized laboratory instrumented for the conduct of experiments, and outside platforms where telescopes, antennae and sensors are mounted for direct exposure to space.

SPACELAB is a cooperative venture of ESA and NASA. ESA is responsible for funding, developing and building SPACELAB. NASA is responsible for the launch and operational use.

First SPACELAB Mission is scheduled for September 1983. Second (D1) will follow in 1985.

SPACELAB 1 carries the so called Material Sciences Double Rack (MSDR) where most of the Material Sciences experiments will be performed. Fluid Physics experiments will use the Fluid Physics Module (FPM) which is a part of the MSDR package.

The FPM has been developed by Centro Ricerche Fiat under the sponsorship of the Italian CNR. For recent descriptions of this facility see Refs. 7 and 8.

EURECA is a retrievable space platform the development of which has been recently approved by ESA Member States.

The spacecraft will be launched from and retrieved by the Space Shuttle. Operational lifetime will be 6 months.

The payload, of approximately 1100 kg, will consist of up to six multiuser facilities for processing metallurgical samples and performing botanical investigations. In addition, suit-case type experiments, up to 200 kg in total, can be accommodated.

First EURECA mission is planned for 1987.

3. FIRST SPACELAB MISSION EXPERIMENTS

The experiments, related to low-gravity fluid physics, planned for the first Spacelab mission are sketched in Figure 2.

3.1 Oscillations of a partially free drop

The oscillations of a drop supported on -and disturbed from- an axisymmetric disc are being considered in experiment 1 ES 326. Experimental results by use of the Plateau simulation technique have been reported (Refs. 9-11).

At present there is not analytical tool, even simplified, to evaluate these results. The application of Lamb's linear potential theory for a nearly-spherical liquid drop freely oscillating in an infinite mass of another liquid (Ref. 12) hardly can be justified, since the boundary conditions at the supporting disc couple modes of deformation which in Lamb's solution remain uncoupled. The situation resembles the analogy between a jet and a liquid bridge to be discussed in §3.4.

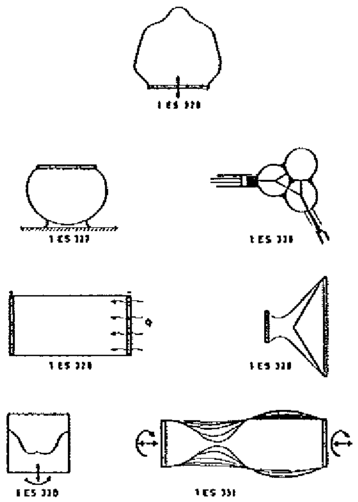

Figure 2. First Spacelab mission experiments on fluid physics.

1 ES 326 Oscillation damping of a liquid in natural levitation.
1 ES 327 Kinetics of spreading of liquids on solids.
1 ES 328 Free convection in low gravity.
1 ES 329 Capillary surfaces in low gravity.
1 ES 330 Coupled motion of liquid-solid systems in near zero gravity.
1 ES 331 Floating zone stability in low gravity.
1 ES 339 Interfacial instability and capillary hysteresis.

The two more relevant results from the above mentioned experiments are:

1. The fundamental frequency varies with the drop diameter, D, as D^{-2}. Inviscid linear analysis predicts $D^{-1.5}$.
2. Extrapolation of experimental data to vanishing supporting-disc radii suggest that an equatorial nodal circle appears for the lowest mode. Lamb's analysis predicts two nodal circles in the North and South hemispheres, respectively.

The difference is due to the very concentrated disturbance resulting in the limit of zero disc radius.

These experiments were performed with kinematic viscosities in the range 5 Cst - 100 Cst.

Neglecting viscosity effects, on the other hand, is certainly justified. Trinh, Zwern & Wang (Ref. 13) measured, by use of the acoustic supporting (and disturbing) technique, the lowest resonance frequencies, as well as the first mode damping constant for a liquid drop oscillating in another liquid of the same density. Viscosities where in the range 1.22 Cst to 124 Cst. For small amplitudes, $\Delta D/D < .1$, the first mode frequency varied as $D^{-1.51}$, close to Lamb's prediction. The damping constant, on the other hand, agreed with results of available viscous linearized theories. The comparison is not so good for higher modes.

Large amplitude oscillations, $\Delta D/D > .1$, have been also explored (Ref. 14). Nonlinear effects on the fundamental resonant frequency are not large, but internal flow patterns not directly predictable by linear theories have been detected.

The influence of surface tension on the above results can not be easily assessed when the Plateau technique is used, because surface tension strongly depends on the density ratio when $\Delta\rho/\rho$ tends to zero.

3.2 Spreading of liquids on solids

Experiment 1 ES 327 deals with the spreading of a liquid drop on a plane surface. This is a highly controversial topic. See the review by Dussan (Ref. 15) and additional comments in Ref. 16.

Hocking & Rivers (Ref. 17) took up again very recently the problem of the fluid motion near an advancing contact line. To this aim they considered a geometry which is very similar to that of the above mentioned experiment.

It is well known that the classical solution of the Navier-Stokes equations with zero slip at the wall results in a force singularity at the contact line. The most simple way of circumventing this difficulty consists in assuming that not too far from the contact line there is a fluid slip at the wall which is proportional to the normal gradient of the velocity component parallel to the wall ($u=\lambda u_z$ on $z=0$), thus introducing a characteristic length, the constant of proportionality λ, which could be related to the wall roughness (Refs. 18,19).

Hocking & Rivers tackle the problem through the method of matched asymptotic expansions showing that there is an outer region, far from the contact line, whose characteristic length is the radius of the drop. There is an inner region, length order λ, enclosing the contact line, where the contact angle is the "static" contact angle, and an intermediate region which appears because terms in $\log\lambda$ from both inner and outer regions do not match.

The "dynamic" contact angle is calculated by extrapolation to the wall of the interface corresponding to the outer region, overlooking the very sharp changes of the interface slope in the inner region.

Incidentally, the outer solution results to be fairly insensitive to the value of the ill-defined λ, Figure 3, a characteristic which this model shares with similar approaches (Ref. 20).

Ngan & Dussan (Ref. 21) showed that and additional characteristic length is required to analyze the experimental results within the framework of continuum theories. They measured the apparent contact angle by use of a "two-dimensional capillary tube": two parallel slice-plates separated by spacers of different thicknesses, thus avoiding the usual criticism to results obtained with capillaries of different bore diameters, *which, being manufactured under different* conditions, exhibit different surface properties.

The results of Ref. 21 indicate that the ratio h/a, from which the apparent contact angle is deduced, depends on a (Figure 4). Dimensional analysis tells us that some length must be implicit in the problem in order to form with a another dimensionless group. It can be seen that, provided that Reynolds and Bond *numbers effects are negligible, no length appears* other than h and a, unless λ is introduced.

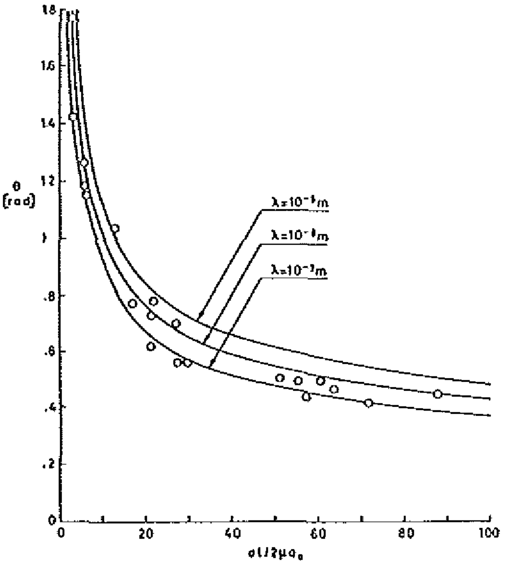

Figure 3. Dynamic contact angle, θ, vs. time, t, for drops of initial radius a_0 spreading on a plane surface. Curves have been calculated with the shown values of the slip length, λ. Experimental points are for drops of molten glasses having slightly different composition and at different ambient temperatures. From Ref. 17.

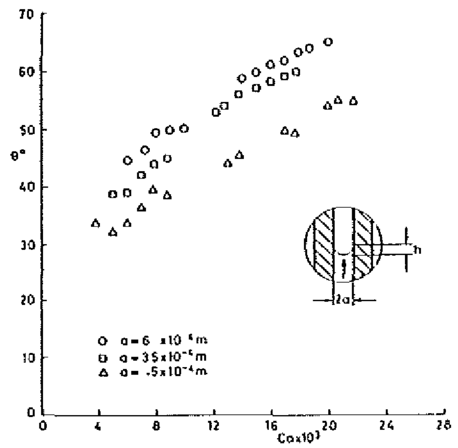

Figure 4. Dynamic contact angle, θ, vs. capillary number, $Ca=\mu V/\sigma$, for the displacement of air by silicone oil between plane parallel glass surfaces of nominal separation 2a. ○ $a=6\times10^{-4}$ m, □ $a=3.5\times10^{-4}$ m, △ $a=.5\times10^{-4}$ m. From Ref. 21.

Microgravity increases the outer characteristic length by a factor of 10 or more. We do not think that λ will increase in the same proportion because from out limited knowledge on λ we infer that it will depend on the surface texture. Nevertheless, with larger values of the drop diameter, the characteristic time will be larger, the spreading rates smaller and the capillary number quite negligible. Thus, the shape of the free surface will not depend on the velocity field, dynamical effects will be minimized and the experimental conditions more easily controlled.

Wetting phenomena in porous media present an intrinsic scientific value and technological importance. It is not surprising that experiments simulating these phenomena under reduced gravity conditions were proposed, and some of them already accomplished.

In Spacelab experiment 1 ES 339 (Fig. 2) the porous medium is simulated by three mutually contacting spheres through which exactly metered volumes of liquid are injected or sucked in order to produce advancing or receding contact lines and, if detectable, contact angle hysteresis.

In Texus III experiment the model of porous medium is a tube with axial corrugations (Ref. 22).

3.3. Marangoni convection

The relevance of reduced gravity levels becomes paramount when interfaces are present and imposed pressure gradients and velocities are absent. This is due to the increased importance of surface forces and greater extensions of interfaces in the direction of the residual gravity vector.

Even when buoyancy forces are negligible, free convection may be caused by the shear stresses acting on the interface to balance surface gradients of interface tension. The resulting flow field in the bulk of the interfacing fluids is strongly coupled via the transport (convective or diffusive) of mass, momentum and energy in both volume and surface phases.

Whereas coupling due to buoyancy forces is distributed throughout the volume and fades out with diminishing gravity levels, coupling due to surface forces is concentrated on the interface, depends strongly on its dynamics and thermodynamics (Ref. 23), and increases at low g levels because larger interfaces can be stabilized under these conditions.

Marangoni convection is induced by surface tension gradients at the interface. These gradients can be due to gradients of temperature (thermal convection), of concentration (solutal convection), or of electric potential. Here we are mainly concerned with thermal convection.

The imposed temperature gradients could have a component parallel to and/or a component normal to the undisturbed interface.

The parallel component produces the surface tractions which induce the motion in the bulk through the viscous forces. The motion immediately results whenever a temperature gradient exists, no matter how small.

The normal component of the temperature gradient transfers thermal energy to or from the surface, this would imply a work of surface tension forces and, thence, motion. But the fluid remains in a state of unstable equilibrium until a critical temperature gradient is exceeded. This threshold value decreases to zero when the surface becomes wrinkled (Ref. 24) thus indicating that both convection driven mechanisms are coupled.

As pointed out, velocity, temperature and concentration fields are influenced by convective and diffusive fluxes of mass, momentum and energy. In order to determine a priori whether the effect of the different convective and diffusive processes are dominant one must resort to appropriate dimensionless numbers. These are, for the thermal Marangoni convection in Newtonian fluids:

$$\text{Reynolds number, } Re = \frac{V_r L}{\nu}$$

$$\text{Peclet number, } Pe = RePe = \frac{V_r L}{\alpha} ,$$

where V_r is a reference velocity and L the length of the interface parallel to the imposed temperature gradient. ν and α are the viscous and thermal diffusivities respectively.

Diffusive fluxes in the direction normal to the main flow may be larger than those in the direction of motion and thence and additional scale factor, ℓ, is required.

When there is not imposed velocity field, the choice of the reference velocity poses some problems. An order of magnitude analysis of the equations and boundary conditions of each specific problem leads to expressing V_r as the product of a known characteristic speed, V_m, and a power, p, of the scale factor, ℓ. For thermal Marangoni flows in liquid-gas systems the characteristic velocity is the Marangoni speed of the more viscous liquid, $V_m = |\Delta\sigma|/\mu$ and $p = 1$ (Ref. 25).

Marangoni boundary layers occur (Refs. 25-28) when the Reynolds or Peclet numbers based on V_m are much greater than one. For giving interfacing fluids Re_m and Pe_m increase with the length L. Hence, under microgravity conditions the flow pattern may be controlled by boundary layers, contrary to what will happen on earth.

Most of the work dealing with surface driven forces is based on the so-called "liquid bridge" configuration. That is, a liquid column held by surface tension forces between two parallel discs. The overall behavior of the configuration is reasonably well understood; it has large, controllable and geometrically simple interfaces and, finally, it simulates the floating zone crystal growth technique. However, from the analytical point of view this configuration presents the drawback of the very complicated flow pattern existing near the end discs.

Up to now, the vast majority of the theoretical models disregards end effects, either assuming infinitely long columns and Stokes approximation (Refs. 29-31), Poiseuille-type flows where the axial coordinate is missing (Refs. 32,33), or fully developed boundary layers (Refs. 25-28). Very useful qualitative results have been obtained this way.

End effects have been only taken into account in restricted cases, f.e. when the Stokes approximation is valid (vanishing Re and Pe numbers), for which case very efficient mathematical tools are presently available (Refs. 34,35). Nevertheless, substantial analytical work should be devoted to this problem which may be crucial to improve many crystal growth processes.

Experiments have shown (Refs. 36,37) that the steady Marangoni convection in a liquid bridge can become oscillatory when the Marangoni number exceeds some critical value. This could results in striations in monocrystals. Although the non-steady processes are at present not fully understood, experimental evidence has been reported (Refs. 38-40) indicating that oscillatory Marangoni convection can be suppressed rotating the bridge through one or both end plates or contaminating the interface (Ref. 41).

Given the geometry of the system, fluid characteristics and gravity level, Marangoni convection will depend on the imposed temperature gradient. Because of strict safety regulations, these temperature gradients will be small in Spacelab experiments. Thus visual observation and photographic recording of fluid motion is probably difficult.

Working with bridges as close as possible to the maximum stable length ($L=\pi D$) looks an obvious way of enhancing observable effects. But the only case in which this possibility has been analyzed (Ref. 34) indicates quite the contrary. In the Stokes limit the velocity becomes smaller the larger the ratio L/D. This conclusion seems to be strongly dependent on the low Reynolds number required to ensure the validity of the Stokes approximation.

Cylindrical bridges of annular cross-section have been suggested as a mean to enhance surface effects (Ref. 42) but, to the best of our knowledge, this idea has not been fully explored.

That Marangoni convection will increase the heat transfer between end discs is a third possibility. Nevertheless, since transparent liquids normally used in liquid bridge simulation are not much more thermally conductive than the surrounding air, a sufficiently accurate thermal balance must take into account the influence of the environment and this will require a simple and clearly defined geometry of the surroundings. It seems that no sufficient attention has been paid to this important point.

Recent European contribution to the study of surface tension driven thermal convection can be classified into three categories.

1. Experimental

   1a. Microgravity is simulated by the so-called short zone technique, where the length in the direction of gravity action is kept as small as possible (Refs. 36-41,43,44).

   1b. Sounding rocket experiments within TEXUS programme (Refs. 45-47).

Additional references will be found in these Proceedings.

2. Numerical simulation

Complete equations are solved by computer with appropriate boundary conditions in order to study the influence of the several relevant parameters. The fulfillment of the boundary conditions at the free surface, the position of which is unknown beforehand, poses serious problems (Refs. 48-50).

3. Analysis of simplified cases

   3a. Poiseuille-type flows (Refs. 32,33).

   3b. Creeping flows (Stokes approximation) (Refs. 29-31,34,35).

   3c. Fully developed boundary layer configurations (Refs. 23-28).

3.4 Mechanics of a liquid bridge

It has been said that interfaces are longer under reduced than under normal gravity conditions. This is one of the connections between the floating zone technique in crystal growth and microgravity.

In order to analyze such a complex configuration as the floating zone the first is to consider independently its several aspects. Thus, the mechanics of the liquid bridge is studied by assuming that it consists of a pure liquid with uniform properties, in thermodynamic equilibrium with the surrounding atmosphere, and held by surface tension forces between parallel coaxial supports.

Many results concerning the static stability of liquid bridges are well known (Refs. 51-54). New developments appear in these Proceedings. These results hardly can be checked experimentally unless extreme care is paid in avoiding parasitic disturbances and in the control of the liquid properties.

Dynamical problems which have been considered up to the moment were of two main types.

1. Study of the internal structure of the bridge just following a sudden disturbance such as a spin-up from rest or a small spin-up or down induced from the end supports in an already rotating bridge.

The available body of work on rotating flows in enclosures is really impressive. The rotating liquid bridge presents the new feature of the free lateral surface. Unfortunately, the internal structure of spinning-up axisymmetric cylindrical bridges only differs from its rigid-walled counterpart in thin layers near the lateral boundaries (Ref. 55). We do not think that these fine details can be detected with the presently available FPM visualization system. Thus it is advisable concentrating on those phenomena most disturbing the shape of the free surface.

2. Dynamic stability of the bridge. The time evolution of an initially cylindrical interface after a disturbance is imposed has been considered in Ref. 56. Although these studies are based on recent work with capillary jets and some results look alike, the main quantitative differences result from the fact that the supports do not exactly play the role of the nodal sections of the free jet. Thus, Figure 5, although the Rayleigh stability limit equally applies to liquid bridges and to jets the time evolution of both configurations is really different.

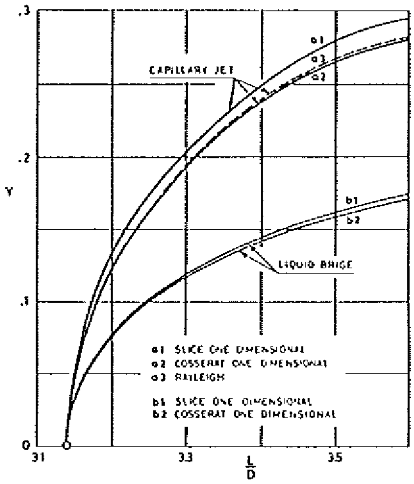

Figure 5. Unstable disturbances grow faster with jets than with liquid bridges. Figure shows the growth factor, γ, vs. dimensionless wave length (slenderness), L/D, for capillary jets (cylindrical liquid bridges) as predicted by several available methods. From Ref. 56.

Let us finish this paragraph with some comments on Plateau simulation. Plateau simulation is a simple way toward low Bond number operation. It consists in suspending a liquid inside another of precisely *the same density with which it is immiscible*, thus simulating zero gravity conditions for configurations at rest.

The static Bond number for a liquid column surrounded by another liquid can be written as

$$Bo = \frac{RL}{L_b^2}\frac{\delta\rho}{\rho_1} \qquad (1)$$

where R and L are the characteristic radius of curvature and the length in the direction of gravity action, respectively. $L_b = \sqrt{\sigma/\rho_1 g}$ is the so-called Bond length. ρ_1 is the density of the denser fluid and $\delta\rho$ the density difference.

A simple version of the FPM, the so-called Plateau Tank Facility (PTF) has been developed (Ref. 57). With this and similar facilities interesting results have been obtained (Refs. 9-11). Nevertheless, here are two words of caution on Plateau simulation.

1) When dynamical effects are present the static Bond number is no longer the only controlling parameter. Thus Plateau simulation of microgravity could be deceptive (Ref. 58).

2) For most couples of liquids of interest and normal gravity conditions, L_b in Eq. 1 is of the order of 10^{-3} m. In a Plateau facility where R and L are of the order of several centimeters, RL/L_b^2 could reach a value of the order of 10^3. Thus, the utmost precision is required in the control of the density of the balancing liquid. It is well known (Refs. 59, 60) that surprisingly small values of the density differences lead to results far different from those corresponding to neutral buoyancy.

4. ACHIEVING MICROGRAVITY

The body force due to earth's gravity, which in near-earth orbit is slightly less than at the earth's surface, is almost completely balanced by the force *due to centripetal acceleration*.

Although the achieved weightless condition is not so perfect as it could seem *at first glance*, the investigator must pay a large tribute in terms of experimental complexity to benefit of these low gravity levels.

Experiments performed onboard microgravity platforms are hindered with limitations regarding time, power, cooling, safety, etc. (Ref. 16).

Although the investigator should not overlook problems of this nature, the main concern here is the required vs. achieved gravity level.

The gravity environment onboard a spacecraft is not uniform. Many forces alter the nearly weightless condition (Refs. 61,62). In particular, transient disturbances (the so-called g-jitter) which can arise from spacecraft maneuvers, mechanical vibrations and crew motion, are a matter of concern. The available information indicates that in the Spacelab the oscillatory part of the g-jitter can be as great as 10^{-3} g.

Although this value can be reduced, at least while running sensitive experiments, the quoted figure is a bit disappointing for two main reasons:

1. Steps should be taken to accurately measure the acceleration vector at the correct places.
2. *Analysis of the effects of g-jitter on fluids is* at present in the beginnings and available information is scanty.

The stationary component which, according to most authors, is smaller is not so harmful, not to mention that, as will be discussed, our skill in accurately measuring, on earth, thermodynamic and transport properties seems to be incomparably less than that displayed in achieving microgravity levels.

Predictive analysis by the investigators is, of course, paramount. Usually this analysis follows three steps of increasing sophistication:

1. Zero-gravity step. Gravity is assumed to be literally zero. Second order effects, normally overshadowed by gravity, become apparent. The resulting configuration of the system is predicted on this basis. This step leads to overoptimistic expectancies on the usefulness of zero gravity.

2. Critical estimation step. An order of magnitude analysis, accounting for small (but not zero) gravity, and based on appropriate dimensionless parameters, provides information on the dependence of the flow regime on the data of the problem.

Such type of analysis displays the extreme richness of interdependent and previously unforeseen phenomena which could appear under microgravity conditions. For example, it can be shown (Ref. 63) that more than a dozen different configurations may appear with steady buoyancy induced, surface tension induced and coupled free convections in systems involving two interfacing fluids.

This approach also substantiates two points which were already mentioned in passing:

1. Limitations of partial simulation. Simulation of microgravity on earth would require, in principle, to exactly reproduce every non-dimensional parameter appearing in the real phenomena.

For example, to reduce the value of a parameter representing the ratio *of gravity to other force*, this force can be increased, but then a certain number of ratios of the other forces to the second one are also decreased and, thence, the real phenomena are not properly modelled.

2. Sometimes the requirement of a precisely fixed gravity level is unjustified (although the requirement of steadiness is not) in the face of the poor accuracy with which some physical fluid properties are known.

Let us consider an example. For thermal Marangoni convection in a liquid bridge, in a reduced gravity environment, and in the absence of dissipative layers, i.e., when viscous (and thermal) effects penetrate deeply into the fluids, a Reynolds number appears based on Marangoni speed and Bond length.

$$Re_m = \frac{\sigma_T \Delta T}{\mu\nu}\sqrt{\frac{\sigma}{\rho g}} \qquad (2)$$

Equation 2 indicates that the influence of a given relative error in σ_T (which is measured fairly in-accurately and is sensitive to contamination and aging) is twice that of the same relative error in g. The situation worsens when solutal Marangoni convection is considered or when fluid properties are strongly temperature dependent.

The third step in the predictive effort of the investigator consists in the search for analytical (and numerical) solutions for configurations under reduced gravity. In most cases gravity action is assumed to be constant and its direction such that the symmetry of the system is preserved. It is realized at this step that in many cases 10^{-4} g is not the same as zero and that effects whose observation was foreseen during the first step still remain hidden or strongly coupled to other effects.

5. CONCLUSIONS

An overview of microgravity fluid physics in Europe has been made, mainly in connection with Spacelab experiments. In the presentation of such a broad topic some choice has to be made. Thence, the authors touched upon points which are at present the subject of their interest and concern.

The need for a better fundamental understanding *should be strongly emphasized. This understanding* requires a very substantial work in the terrestrial laboratory which is absolutely necessary if future space experiments are to be carried out in a systematic and efficient basis.

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