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FLUID SCIENCE REQUIREMENTS FOR COLUMBUS

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Abstract—Peculiarities of fluid science experimentation in microgravity are discussed, aiming at a synthesis of general needs and requirements from the investigators for a space laboratory. Particular emphasis is put on the characterisation of fluid science experiments in microgravity.

INTRODUCTION

The subject of fluid science (FS) has the main task of analysing the flow field (velocities), pressure field, temperature field and concentration field of a fluid governed by some initial and boundary conditions. A fluid is a macroscopic ensemble of microscopic entities that can be described as a continuous medium and that can flow, i.e. deform indefinitely when subjected to shear forces. A keyword in this description is that of a fluid particle, which is a small representative portion of the continuous that can be considered in thermodynamic equilibrium at every instant (because of its very small relaxation time).

Except when the emphasis centres in the thermodynamic study of the system (i.e. phase transition and critical point phenomena) the fluid is not in a state of global equilibrium but only in local equilibrium as mentioned before, and the interest is on studying the evolution of the fluid system (mass, momentum and energy diffusion, convection, waves) when certain internal restrictions are set free (a typical initial value problem), or when certain external forces are applied and the stationary state is sought (typical boundary value problem).

The equations that describe the evolvement of the fluid are well-known (generally known as Navier–Stokes equations), but their mathematics are rather involved and with such a wealth of discontinuities, fluctuations and variety of different space and time scales that full solutions can hardly be achieved even with the best numerical simulation facilities. Moreover, although the balance equations are the same for every problem, each of them has its own peculiar initial and boundary conditions that precludes the detailed solution of every problem of interest, and dictates that analytical models of key problems should be pursued at high priority.

But theories need to be contrasted with experiments, and the latter require experimental facilities that in the case of a space laboratory have to be designed and built (at least in its major parts) well in advance of their utilisation, forcing the investigator to wait after his experiment proposal has been accepted and a suitable facility is developed, or forcing the administrators to develop general-purpose equipment hoping to suit the future investigator needs.

This paper tries to shed some light to guide on the last scenario, contributing in this initial phase of defining what a fluid science laboratory in space (to be operated in nearly 10-years' time) should offer to fluid science investigators.

To this aim, first some general FS problems are presented, being classified in increasing order of complexity (at least at first sight), and the relevance of the microgravity environment that characterises the experimentation in space is analysed, pointing out that the advantage of decreasing the ever-present constant gravity on ground, comes together with the disadvantage that the now very small gravity field (residual accelerations) is uncontrolled and, up to now, unknown (it has resisted a precise quantification).

The characteristics of FS experiments are then considered in detail, and in particular the geometry of the configuration (that best identifies an experiment) is categorised. The different states of the fluid sample impose additional constraints, that are revised, and illustrated with some past experience of the author. This analysis gives way to a more general discussion on the purpose of experimentation, even at a risk of mixing physics with metaphysics.

Finally, a summary of general requirements that FS research is expected to put on a FSL for Columbus is presented.

FLUID SCIENCE AND MICROGRAVITY

A scientific categorisation (purpose) of foreseeable FS experiments under microgravity is of secondary importance for the definition of user needs and requirements, being more important what configuration, procedures and resources the investigator intends or desires to use. Besides, characterisation by scientific discipline is appropriate only for basic research; applied research very often draws upon the knowledge of several disciplines. But if one still insists on having some general ideas of research topics expected, a grouped list (perhaps with some order of relevance) may be as follows:

- Structure of matter: equilibrium and transport constitutive equations in single phases, interfaces and critical points. Common and exotic fluids (liquid crystals, ferrofluids, polymer fluids, superfluids). Wetting and spreading.
- Fluid mechanics: equilibrium and stability of interfaces, bulk and interface driven free convection, multiphase flow, dynamics and interaction of drops, bubbles or particles in a medium, pattern formation (dissipative structures), oscillatory flows, turbulence (onset, development, decay, control).
- Electro- and magneto-hydrodynamics: particle migration, flocculation and dispersion, effects on the turbulence level, interface effects, etc. on polar, polarizable and nematic fluids, electrocapillary and electrokinetic coefficients.
- FS applications to materials science (with model substances): crystal growth, directional solidification (effect of the speed and undercooling), growth from the melt, growth from solution, growth from the vapour. Metals and alloys, segregation, immiscible alloys, miscibility gap, nucleation, coalescence, etc. Glasses and ceramics, containerless management of molten material, glass formation in model substances.
- FS applications to engineering science: combustion, heat transfer (with and without phase change), combined heat and mass transfer, etc.
- FS applications to life science: biotechnology, protein crystal growth, cell separation, cell growth, etc.

Fluid science studies with materials of practical interest as semiconductors, glasses and living cells should be left to a final stage, once the basic principles have been learnt with model fluids, but should not be discarded for a FS laboratory in Columbus, the advantage being that this type of laboratory is best suited to nonintrusive realtime diagnosis than the materials-dedicated facilities (floating zone furnaces, containerless processing facility, biolab, etc.).

From another point of view, focusing more on the complexity of the configuration than on the scientific discipline, one may classify the different areas of interest in the behaviour of fluids, in a more or less gradation of increasing complexity, as follows:

- statics (position and stability of interfaces);
- dynamics (without thermal effects);
- convection (induced by temperature gradients);
- diffusion (of species, usually combined with convection);
- phase change processes (static and dynamic);
- electric and magnetic effects;
- reactive processes (including combustion).

This is a rather arbitrary categorisation, and it may be difficult for instance to argue about the differences between dynamic effects and convective effects. Trying to be more explicit and illustrative, an example is going to get along with all the discussion: the fluid science of the floating zone as used in the floating-zone-technique of crystal growth [1]. For this example, the above categorisation is useful to group the following problems:

Statics: equilibrium shapes and stability of the liquid bridge that comprises the floating melt [2]. It helps to know the maximum height achievable for a given diameter, the quasi-static variation in shape due to a material receding angle of growth, and so on, but experiments are needed to verify that the assumptions (i.e. of free-surface attachment at the solids) are tenable.

Dynamics: free surface deformation and internal motion when the liquid bridge is vibrated [3] or rotated [4]. Up to now most of the studies have centred on predicting the behaviour of the fluid when unwanted forces were acting (the uncontrolled vibrations in any real set-up, and the effect of the forced rotation imposed to uniformize the temperature due to a lobular heating), but it has been pointed out that mastering the response to this easily applied forces may be used at an advantage to control the shape or the internal motion in situations of practical interest.

Convection: thermocapillary motion and interface deformation [5] induced by a gradient of surface tension. One of the findings of previous microgravity experiments has been that, contrary to what was believed just a decade ago, dopant striations in grown crystals are due to this surface-driven convection, both on ground and in space [6].

Diffusion: when solutes are involved, and this is the most important case from the technological point-of-view, because the floating zone technique (and its predecessor, the molten zone technique) are used to take advantage of the segregation at a phase change to purify the material. Sometimes, diffusion of an internal dopant is used to diagnose the extent of convective motions [7]. Evaporation of a liquid bridge in a gaseous atmosphere and interdiffusion if surrounded by an immiscible liquid (in a Plateau tank or in a miscibility gap) are also typical problems in this group.

Phase change: the advancing fusion front and solidification front in the floating zone, when dealing with melts, or the dissolution and solidification of solutions are good examples of interesting problems in this group. Floating zones and liquid bridges are good configurations to analyse phase change problems because of the highly controllable geometry [8].

Electric and magnetic effect: that may be static or dynamic, and that are imposed to levitate the molten zone on ground, to stir the sample, to prevent the development of the thermocapillary convection [9], to extend the stability range [10], and so on.

Chemical reactions: that can take place in the free surface (as some oxidation processes already used to create a semirigid membrane surrounding the melt to prevent surface-driven motion) or in the bulk (not yet tried).

Microgravity relevance

The reason for performing FS experiments in space is that microgravity offers a new working environment, that can be put to the advantage to simplify some FS problems where gravity forces are overriding. Most of the FS phenomenology related to gravity forces on ground can be understood by just looking at the hydrostatic equilibrium equation

$$\Delta p = -\Delta\rho g \Delta h \qquad (1)$$

where Δp is the pressure difference inside the fluid through a vertical height Δh, g is the constant-gravity acceleration on ground (vertical component), and $\Delta\rho$ is the density difference between the fluid of interest and the surrounding fluid (the atmosphere, an immiscible liquid, a differently heated fluid column, etc.).

The first and more obvious microgravity effect on fluids is the reduction of its weight, that for gases is not so drastic (they continue to occupy the whole available volume), but for liquids is remarkable: free liquid surfaces are no longer restrained to be flattened, and the small capillary and wetting forces (that normally can only curve up millimetric regions of the free surface) become dominant. Looking at equation (1), if $g \to 0$ then the pressure field is uniform (at least by regions).

The other microgravity effect is the reduction of buoyancy of differently weighting parts in a fluid, either because of thermal or solutal density variations or because of different materials (bubbles, drops or solid particles in a fluid).

The above microgravity effects on fluids can be used at an advantage to better analyse complex FS problems, but may also be a nuisance (i.e. natural and artificial thermal control on ground heavily depends on natural convection, and this is so much reduced under microgravity that forced convection must be applied to cool electronic equipment and to ventilate habitable sites).

On the other hand, the loss of the perfectly defined constant gravity field on ground has its own disadvantages: the constancy is also lost, and the residual microgravity field is unknown and uncontrolled, what is a severe handicap for any kind of experiment, as discussed later on.

The effects of microgravity on fluid science can thus be summarised as follows:

- reduced weight;
- reduced buoyancy;
- reduced sedimentation;
- uncontrolled 3-D g-jitter.

Going back to the former example of the floating zone, large liquid bridges can only be established under microgravity; on ground, quiescent fluid interfaces are always flat except at the corners and other small scale regions (a few millimetres). The shortest time to create a large liquid column (35 mm in diameter and 100 mm long) is nearly one minute, what precludes experimentation in short-time microgravity platforms as drop towers and parabolic flights with airplanes. The 6 min of microgravity time provided by the TEXUS sounding rocket has already been proved adequate for experiments in the mechanical behaviour of the liquid, but maybe too short for thermal or diffusion problems. In any case, selecting the most appropriate microgravity platform (drop tower, parabolic aircraft, sounding rocket, orbiting laboratory) just based on the experiment characteristic time may be misleading if other logistic time-scales are not considered.

Going to space for better experimental conditions also poses new experimental problems, as the following experience illustrates [11]. Fluid management with free boundaries under microgravity is not a mean task. For instance, the sophisticated liquid-injection system developed for the Fluid Physics Module (FPM) in 1977, was of little use in the first Spacelab flight in 1983, due to infancy operating problems during real microgravity conditions: it was cumbersome to operate and, after a few trials, air bubbles were ingested while trying to recover liquid from spillages, and the liquid supply became useless. For the second FPM flight (1985) an add-on manually-driven liquid injection system was provided, but then it proved unrealistic to expect that an astronaut stressed to the limit (working in a multitask, multi-surveyed, round-the-clock, heavy demanding environment) would waste precious time of pioneering experiments just reading a counter and writing sets of numbers on a piece of paper.

FS EXPERIMENT CHARACTERISTICS

In order to foresee future laboratory requirements of the FS community, one may follow two approaches: first, look at actual FS laboratories, and second, make a sound guess. In view of the peculiarities and lack of experience on space laboratories, and the prolonged time-frame to be considered, the last one seems to be the better approach.

Even restricting fluid science experiments to water-like substances, one may be tempted to say that all microgravity experiments pertain to fluid science, from cardiovascular and vestibular research in life science to crystal growth by melt, solution or vapour deposition, in materials science, and it is clearly impossible to make a guess on such an ample frontier of knowledge.

But one must be respectful of traditions and think of common fluid science laboratories on ground and the scarce microgravity experience existing. Fluid science experiments are characterised by the use of a model working fluid that is transparent to allow

3-D optical diagnosis. Other research areas dealing with fluids are related to peculiar fluids of interest (i.e. blood in life science experiments or molten silicon in materials science experiments). More precisely, fluid science research is characterised by a set of nondimensional parameters (*Pr*, *Re*, *Bo*, *Ma*, *Ra*, *Wb*, *Sc*, . . .) to be related amongst them or the critical limits of which are to be found in a particular configuration.

Experiments with peculiar fluids would demand so many parameters to be adequately characterised (some of them may be still unknown) that the only practical model-fluid is the real fluid itself. Another important characteristic of fluid science experiments is that the diagnosis is done during experiment execution, and thus the fluid sample can be discarded afterwards, whereas in life science and materials science research the recovery of the sample for after-experiment analysis is a requisite (most of the diagnosis is made afterwards). This advantage of real-time diagnosis in fluid science is at the expense of the need to have sophisticated diagnosis equipment embarked, which is a drawback if mass and volume is at a premium and equipment quickly becomes obsolete.

The following list tries to summarise the basic points:

- model fluids (defined by *Pr*, *Re*, *Bo*, . . .);
- repeatable (no "supernova" events);
- consumable samples (fluids are discarded after trial);
- visualisation (transparent fluids, image processing, tracers);
- multi-dimensional configuration;
- multi-dimensional diagnosis (v,p,T,x_i);
- quick analysis (almost real time during execution);
- easy qualitative evaluation, but sophisticated quantitative diagnosis;
- whole field monitoring and narrow field measuring (zoom and pan views);
- tunable sensitivity and resolution.

Most FS experiments use model fluids defined by the nondimensional parameters that enter into the balance equations or the initial and boundary conditions, without regard to their specific properties (i.e. a low viscosity liquid is specified for a given experimental configuration if one looks for large-Reynolds-number flows, and water is the first choice, irrespective of the practical problem in mind, that can be the fluid-dynamics modelling of a silicon floating zone). The Prandtl number *Pr* (characterising the ratio of viscous to thermal diffusivity) and the Reynolds number *Re* (characterising the ratio of inertia to viscous forces), are the most usual ones, both on ground and under microgravity. The Bond number *Bo* is perhaps the most genuine nondimensional microgravity parameter in FS, being the ratio of hydrostatic pressure to capillary pressure, although other well-known parameters where gravity enters explicitly (as the Rayleigh number *Ra*), or which are of special interest in microgravity research (as the Marangoni number *Ma*) are also commonly used.

To further sustain this concept of model fluid, it may be pointed out that this author proposed water as the working liquid for his research on liquid bridges, but agreed to share silicone oil as working fluid for several investigators in the FPM (although it is more difficult to clean than water and was painfully realised during the infancy spillages in the first flight).

It must however be always kept in mind that model fluids can never meet all the characteristics of a certain real fluid, so that first of all the main characteristics to be simulated must be analysed, and thus, although water has the same peculiarity as silicon regarding the volume increase upon solidification, it may be unsuitable regarding vapour pressure or other properties.

Once a model fluid is to be considered, an important point is to choose a transparent one to better look inside with unintrusive means, and thus, visualisation and image analysis become the major diagnostic means, supplemented by local measurements at the boundaries or in selected points in the interior.

The ease of fluids to flow makes the flow field multidimensional, mostly three-dimensional (although under very especial conditions it can be reduced to an axially-symmetric or even bidimensional configuration), which renders in general the diagnosis rather involved. Besides, there are several 3-D fields of interest to be diagnosed: three velocity components, pressure, temperature and concentration of chemical species if composition changes due to redistribution or reaction.

Because model fluids are used, they are selected amongst the cheapest ones and they are usually discarded after the experiment, because it would be difficult anyway to regenerate them to their initial conditions. This is of particular importance to a FS laboratory for Columbus, because the generation of fluid waste may impose one of the major design constraints.

A particularly welcomed characteristic of FS experiments is that they can be analysed (at least qualitatively) in real time, without having to wait many hours or days for characterisation of results, as happens with most material and life science experiments. This quick-analysis capability may be used advantageously to accelerate the iterative process of trial and error (not to be confused with poorly thought experiments), of basic character in research work.

The last point to emphasise in the characterisation of FS experiments is the widely different spatial and time resolution involved, and the associated sensitivities demanded on the diagnostic equipment. Not only the diagnosis, but the conditioning and stimuli in FS experiments heavily depends on the geometry of the fluid configuration, which can be categorised as follows:

- large single free interface (drop);
- large single anchored interface (liquid bridge);
- large double interface (liquid sheet);
- large multiple interface (drops and bubbles);
- dispersions (bubbles, drops and particles);
- homogeneous phase.

The above discussion applies to the spatial configuration. Concerning the time variable, the instantaneous estates can be classified in the three following types, best illustrated by reference to the ever-present example of the liquid bridge.

(1) Equilibrium states (static problems)

This simplest case corresponds to a system that can be assumed to be isolated from the surroundings and already relaxed from possible initial non-equilibrium conditions. As every model, this is just an idealisation because it is impossible to guarantee perfect isolation, but nevertheless it can be successfully applied in many practical circumstances.

For instance, if only conservative forces are acting on a liquid bridge, the fluid may come to an equilibrium configuration where its possible shapes can be easily computed with a simple theory, the Young–Laplace equation [12]. An experiment to analyse equilibrium shapes may consist of procuring well-defined stimuli, here defined by the non-dimensional parameter set (H, Λ, V, Bo, We), where H measures the size ratio of the liquid bridge supports, Λ the liquid bridge slenderness, V the liquid volume made dimensionless with that of a cylindrical bridge, and Bo and We the Bond and Weber numbers [13]. The aim of the experiment may be to record the actual shapes, extracting from them the corresponding theoretical values of the parameter set (H, Λ, V, Bo, We), comparing both sets of parameters, and, after the uncertainties due to experimental error been accounted for, trying to explain the differences found, if any.

(2) Steady and periodic states (stationary problems)

Here, the time variable can be taken out of the problem because it does not appear (steady states) or because it enters as a separate harmonic term (periodic states) that modulates in a simple manner the spatial response (the period is well defined), but the system is not in equilibrium and in a real system there would be a continuous entropy generation. Typical problems in this case are the periodic oscillations of the column when one (or both) of the end supports is forced to oscillate axially, and the steady state reached when one of the discs is forced to rotate at a constant rate (or both, at equal or different speeds). Besides the forcing parameter, other degrees of freedom appear on these problems (as the transport coefficients: viscosities of working liquid and outer fluid). In these cases, besides the outer shape of the bridge, the relative motion inside the fluids is also of great interest. Steady state theories are less developed, and a lot remains to be done (i.e. how is the flow structure in a counter-rotating liquid column?). Nonwithstanding the fact that the dimension of the problem has grown (still confining oneself to axisymmetric motions), a major experimental handicap appears also: the diagnosis of the motion inside the liquid column is very difficult because its curved interface (particularly if it is not nearly-cylindrical) renders the optical diagnosis cumbersome. Small tracer particles added to the liquid are normally used for qualitative visualisation (as was done in these experiments) making them visible with a meridian light sheet, but quantitative analysis has always somehow resisted.

(3) Transient states (moving problems)

In this case, time is the most important variable. Besides all the transient problems encountered during the formation of a long liquid column (emerging capillary flows, detachment, spreading, anchoring, filling liquid, separating the discs, removing liquid, etc.), some transient problems with already established cylindrical liquid columns are of interest. Particular attention has been paid to the evolution during the breakage of the column beyond the stability limit [14], to the onset of convection by spinning one or both discs, and to the cylindrical liquid injection (injection and separation to keep a cylindrical volume). Transient problems require such a strict control of the initial conditions, and demand such a comprehensive diagnosis (with variables changing their ranges and relative importance through the evolution) that no attempt to have detailed quantitative measurements has yet been exercised in a microgravity platform; a coarse experiment in this context was performed in 1985 on TEXUS-12 to know the maximum allowable injection rate to establish a long cylindrical column [15]. Although the aim of SL-D1 experiments was focused on equilibrium shapes, stability limits, and steady-state axial oscillations, a sudden stop of the separating disc at the end of the formation of a 100 mm long column did provide (without being intended) another example of a transient response (they might be used e.g. to evaluate liquid transport properties *in situ*).

Film frames can be digitised with a microdensitometer and video frames electronically scanned to found the edges of the liquid column. There are commercially available procedures to automatically digitise film frames and video frames, to enhance the image contrast, extract edges, compute areas, and so on, but they are of little use if the raw image is not adequate. Here, the poor visualisation in the FPM yielded images where key points as the edge of the discs (where the fluid interface starts) were very difficult to locate accurately [13]. Besides, the simultaneous use of a transversal light-sheet to make the internal tracers visible (in concurrence with the background light for shape visualisation), is the cause of reflections and lack of definition at precisely the two outer extremes of the outline. All these facts forced to implement a manual process of image digitisation (drawing contours at free-hand from an A4-size optical enlargement of the film frames, and inputting them to a computer with a manual digitising tablet), in spite of the high-tech commodities at hand. A good lesson to be drawn from that is that some effort must be devoted already during experiment conception to prepare for final data analysis, even at a risk of being of no use if the experiment fails.

EXPERIMENT PURPOSE

Although this is an epistemological question, it may help to define a future FS laboratory, and thus is of relevance here.

The scientific method requires the confrontation of theories with experiments from time to time, and specifically at a research stage. An experiment is an event purposely excited to pinpoint a particular variable, which value is measured and compared with the expectation. Sometimes the measure is purely qualitative (i.e. should a liquid bridge break when rotating its solid supports?, should an internal motion appear when differently heating the end supports?), but the majority of measurements are quantitative.

Experiment preparation is as important or more than experiment evaluation, because poorly conceived experiments generate more confusion than shedding light on the problem. As in theoretical analysis, experimental work must be designed so that only the most relevant variables appear, and every step must be followed to ensure that side effects have negligible influence. Amongst the precautions to be adopted in this direction one may consider the following precautions. First, the simplest state of the system should be analysed, promoting static and stationary states over the more complex transient ones. Second, simple direct measures should be preferred to indirect ones, although the ease and convenience of modern microelectronic data acquisition and control equipment may dictate otherwise and make preferable to measure e.g. disc separation in a liquid bridge by counting rotation steps with an optical encoder in the driving mechanism, that by just adding a linear displacement potentiometer.

Moreover, one should try to physically decrease the influence of an unwanted parameter, i.e. going to space to reduce gravity, or procuring adiabatic walls; but another method may be able to modulate one of the variables (that of interest or unwanted) with a known time-frequency, filtering them apart subsequently. In any case, and particularly for highly costing experiments as those in a space laboratory, it is important to add suitable sensors to measure (if not to control) the level of variables presumably negligible, or at least to make redundant measures of the variable of interest by different procedures.

After every precaution to design a good experiment has been taken by the investigator, there still remain several approaches that can be followed in the preparation and evaluation of the experiment, and that normally have a sequential order in the research programme. As before, the discussion will be illustrated with the author's experience in liquid bridge research under microgravity. The experimental purposes can be summarised as follows.

(1) To check that the response of the system to the applied stimuli is as predicted by theory

To this purpose, clear-cut check points (i.e. minimum volume of liquid for a bridge), with well controlled applied stimuli (precision control of disc separation, rotation and vibration) and little sensitivity to uncontrolled forces (i.e. working temperature), are proposed for measurement. Perhaps the obvious example may be to check the Plateau limit: it is known since the last century that the maximum stable length of a capillary cylinder in absence of applied forces is π times its diameter, $\Lambda \equiv L/D = \pi$ (Plateau or Rayleigh limit), because beyond that, any local deformation narrowing the radius would increase the pressure in that region and force the liquid out, narrowing the neck further and further until breakage. This well-defined characteristic was experimentally checked on ground by Plateau more than a century ago, balancing the gravity effect by immersion of the liquid column in an immiscible bath of precisely the same density (Plateau tank); and many others after him repeated the experiment. Why then go to space to check it again? There seems to be no reason why a 100 mm long liquid column should behave differently (in this respect) when free-floating in space, surrounded by air, or when on the Plateau tank on ground, surrounded by another liquid of the same density. But scientists want to know more; and most of the time they get a reward (they gain some new knowledge): if a cylindrical column is stretched cylindrically (feeding while separating the discs) aboard Spacelab, it will break well in advance of the Plateau limit (say when its reduced slenderness, Λ/π is 0.93 instead of 1 [13]). What is wrong?

(2) To check the assumed hypothesis

When the response of the system is not as expected, the consistency of the theoretical development must be reviewed, and thence the applicability of the hypothesis introduced to simplify the analysis or model the system. From that, and the uncertainty analysis of the experimental procedure, it was deduced that, in the case above, the effect of the residual accelerations in the SL-D1 experiments must be accounted for (electrical effects were deemed to be absent). But the value of the residual acceleration was not known (the accelerometers in SL-D1 only measured vibrations and had large zero-frequency uncertainty).

(3) To see if new phenomena appear, and to quantify them

For instance, if a theory to account for the effect of the residual acceleration is available, and in this case it is, the experiment allows to estimate the actual value: for the experiment in SL-D1 a value of about 70 μg_0, that is $7 \cdot 10^{-5}$ m s^{-2}, was obtained [13]). In the words of the astronaut that actually performed those experiments, "the best accelerometer ever thought" was invented, so to say, as a spin-off of this research in the stability of liquid columns. And this is but one example. During the same trials, it was realised how difficult it was to merge the two drops left in the solid supports after breaking the bridge (this effect was well known in Plateau tank work on ground, but we thought it would not show up in the absence of the liquid bath, in space). More painful was to realise how different the dynamical effects can be when changing from the Plateau tank to space: in the first series of trials with the FPM in space, aboard Spacelab-1 in 1983, the injection speed set to fill the liquid and establish the bridge between the discs, similar to those used on ground, was too high there, and that, combined with a compromised sharp edge in the solid supports (to save space and complexity, the discs were just protruding half of a millimetre from the chamber wall) spoiled most of the trials in that occasion (only by manual refitting of the set-up by an expert payload specialist could part of the experiments be saved) [16].

What can be learned from an experiment is only limited by the investigator's curiosity and knowledge (and time): why a half-millimetre step down on a solid, with a sharply cut edge, is not good enough to prevent a liquid mass from jumping over it, and a several millimetre step is good enough, and even better a cut-back edge? Can the liquid border feel the depth of the step? The answer may come from the theory of the spreading of liquids (i.e. the existence of a precursor film), but meanwhile the investigator must set adequate margins against this and other similar uncontrolled phenomena (i.e. study stability limits of liquid columns anchored to the edge of the supports, and not the stability of bridges whose attachment at the ends are free to move, in spite of the fact that the theory appears simpler in the latter case).

Similarly, when does an emerging capillary flow detach and becomes a jet?, or when does it remain attached at the orifice and later spread laterally along the wall? What is the influence of the electrostatic charging of the liquid when forced through the duct? Electrical effects are not contemplated in this paper, but they may be of great interest in this context also: i.e. it has been demonstrated experimentally that the Plateau limit can be overpassed if a strong enough electric field is applied through the liquid column [10].

On the other hand, it should be always kept in mind that every experimental programme has different needs at different stages in the development of the research. For example:

First, an investigator needs not-too-demanding feasibility trials that cannot always be carried out before on ground or in other microgravity platforms. He is willing to use either existing facilities configured for other purposes or a simple special set-up with available modular elements. For instance, before any meaningful experiment on bubble migration in a differentially heated liquid matrix, one must master the initial conditions (how to create a bubble, how to detach and position it, how to measure its size, etc.). Of course, a lot of preliminary work must be done on the ground, and later in sounding rockets, but there will always be the need for feasibility trials in the Columbus lab itself.

Second, an investigator needs prototyping and tuning trials. To perform them, he already puts some special requisites that force non-marginal modifications of existing preconfigured facilities, or require an elaborated configuration to be set up with available modular elements, perhaps slightly refitted. For instance, to look at the kinematics of a drop spreading on a solid, the FPM could be modified to have a suitable drop formation and release mechanism, a special end-plate, a proper view of the advancing edge, etc. or the same special hardware mounted on a test-rig and standard lighting, viewing and recording elements disposed all around. At this stage, the information gathered is already of a quantitative nature but not of high accuracy.

Finally, an investigator wants to perform detailed and conclusive experiments that seem to terminate a research point (but that, most of the times, are just milestones in the endless path of an investigation). For these crucial trials, the experimenter wants to stress some parameter to the limit and consequently needs capabilities well beyond normal practice. The investigator on wetting and spreading of liquids asks for an ellipsometer to measure molecular thicknesses of a discovered precursor film, the investigator on bubble migration asks for a thermal-tomography interferometer to map the three-dimensional temperature field with high accuracy, the investigator on droplet burning asks for a laser-induced-fluorescence spectrometer for simultaneous temperature and concentration mapping, etc. For these experiments they need special purpose equipment not found in common fluid science laboratories, normally to be used for a short time, but without which no further progress in that direction can be attempted.

Once that one realises that no matter how perfect a FS laboratory may be, it will never satisfy all users at all stages of their research, the only reasonable policy left is a trade-off to a compromised solution that maximises the return on the investment, accepting the complaints of users not as failures of the design but as possible enhancements.

FS REQUIREMENTS

It is possible to set requirements without relation to existing or expected facilities, but the development of facilities need requirements, showing that availabilities and requirements are iteratively evolving in time.

The design of a FS laboratory for Columbus can only be successful if the potential users are involved in it, and this is why experienced scientists have been asked to assist from the very beginning. At the present conceptual phase they have been asked to foretell:

- what kind of fluid science experiments under microgravity may be expected;
- what kind of equipment can be expected to be needed in support of these experiments;
- how operations are envisaged to achieve those goals with these means.

Scientific forecasting is an art subjected to the will of chance, not as scientific predictions, which are bound to known laws. In any case, the foreteller must imagine a scenario where some boundary conditions are settled. The design of the laboratory is heavily dependent on the scenario assumed (think on the changes between an automated laboratory without maintenance capabilities and a laboratory operated and maintained by a specialist aboard); should it be like a set of push-button cabinets in a science museum?, or should it be free access to the elements with the possibility to modify hardware and software to better suit the user needs and with the associated risk of damage?

The several hours of past experience on Fluid Science research aboard Spacelab and other minor microgravity platforms have taught many lessons to both the investigators and the operations teams, and much more will be learnt in the future before a permanent FS laboratory is available in space, but several general guidelines can already be drawn.

First, and above all, the major handicap that FS investigators have suffered in the past (and will suffer until Columbus is operative), is the scarcity of microgravity time. Sporadic opportunities can only give as a return sporadic scientific achievements. The availability of microgravity time at a reduced cost is a requirement for the build-up of a mastery in FS in space. Although it is a charging policy issue and not a scientific one, it must be realised that microgravity experiments cannot be charged with the costs of space infrastructure and general operations, and only with direct additional costs as energy, crewtime, FS equipment, FS operations, and so on.

Assuming then that microgravity time will not be the first driver of experiment definition and that the investigator could concentrate on scientific issues, what are the requirements to carry out FS experiments under microgravity? The answer must come from the ingredients of typical FS experiments: fluids, fluid containers, fluid dispensers, conditioning of the test volume, stimuli, sensors, data acquisition, data logging, regulation and control, fluid waste, data interpretation, and result verification. Another ingredient genuine of microgravity must be added: the characterisation of g-jitter when it comes to play.

If the set of requirements were to be compiled by just gathering the wishes of present users or users-to-be, they would surely be contradicting and disperse, and a good example may be that different investigators using practically the same liquid bridge configuration in the FPM asked for widely different requirements: for some, a small field-of-view with micrometer resolution was essential, as well as clean-room purity of materials and procedures, whereas for others a large field-of-view was essential, a spatial resolution of 1% good enough but higher time resolution, and the purity of the liquid irrelevant. Yet some experimenters require that the liquid bridge be quite stable but others require to break it.

The individual requirements are going to be so different that the only workable answer is that modularization of hardware and software for the investigator to tailor the facilities to his needs. The two advantages of modularization are that common equipment can be used (i.e. a thermographic camera, or an image processing package for field velocimetry) and that uncommon equipment can be substituted (i.e. a special three-fluid dispenser).

Hardware is required in Fluid Science experiments for containing, conditioning, stimulating and diagnosing the fluid sample. A typical fluid sample volume is 1 litre, and most of the times it is *partially* in the liquid state. Usually, one wants to investigate solid/liquid, liquid/liquid or liquid/gas interactions.

Although there is not a clear distinction between conditioning, stimuli and diagnosis (i.e. the soft radiation beams projected over the sample to enhance the diagnosis may also be thought of as stimuli intentionally applied, as unwanted disturbance, or as conditioning of the sample), the following description may illustrate the essentials of the different aspects.

Conditioning includes the provision of initial values, boundary values and final values to the independent variables in the experiment, including sample fluid supply, positioning and disposal. The conditioning may impose the design driver for some facilities (i.e. drop levitator, channel flow, thermographic cavity).

Stimuli applied to the fluid sample are relatively simple: a pressure or shear force at the boundaries, a thermal field (normally isothermal or constant gradient), an electric or magnetic field, or some sort of trigger or catalyser, as an electrical spark, laser pulse, fluid injection, partition removal, etc. Apart from this well-controlled applied stimuli, one should always keep in mind that there are *uncontrolled stimuli* acting continuously on the fluid sample (mechanical, thermal, electromagnetic, chemical) imposed by the imperfect ambient conditioning; the best example is g-jitter. These uncontrolled perturbations have ruined a lot of experiments in the past, and measures should be taken to eliminate them (with passive dampers or active countermeasures) and, in any case, to record the level of them for ulterior analysis of possible influences.

Diagnostic equipment in fluid science is used to know the position of interfaces, and to measure the velocity, pressure, temperature and concentration fields (the latter mainly in physicochemical processes). This is a complex item because of the multidimensional and real-time character of the analysis, and the equipment tends to be sophisticated, expensive and bulky. Advance diagnosis is based on non-intrusive radiative coupling between the fluid sample and a detector, and most of the times an external radiation source. More traditional set-ups rely on classical optics, although the spectrum of the radiation emitted, absorbed or scattered as a function of wavelength carries a lot of information about the structure of the matter involved (what serves for the chemical analysis) and its state (what can be related to the thermodynamic state functions and transport coefficients). These methods are used extensively in chemical analysis, but their use for diagnostic of fluid science experiments is just emerging, handicapped by the sophistication and encumbrance of the equipment (i.e. ratios of volume of facility to volume of sample in the order of 10^4 to 10^6 are common).

No matter how advanced the fluid management and diagnostic equipment may be, it is felt that crew assistance in fluid handling and configuration set-up will be invaluable in many cases. The FS investigator in a manned space laboratory must be aware of the availability, although limited, of highly trained personnel aboard; for a man-tended space laboratory the research with fluids should be severely restrained and concentrated on fully contained fluid flow, where the probability of loosing control of the fluid be remote (it is not foreseeable to have highly automated facilities with washing machines and fluid regenerators).

Finally, from the operations point-of-view, and taking into account the very limited crew support to be available, the requirement of a large infrastructure for telescience operations is set forward, with special emphasis for FS research, where the on-site characterisation of the sample and the ease of quick-look analysis, render this approach most rewarding. The development of this infrastructure should be carried out by the operations team and not by the individual investigators, which should help in the effort.

The following list summarises the general requirements that the FS community may pose to the definition of a FS laboratory for Columbus:

- microgravity time;
- personalised test volume (fluid containment, isolation, supply, stimuli);
- modular equipment (fluid management, optical diagnostics, data processing);
- sophisticated diagnostic tools (imaging, field velocimetry, thermography);
- advanced housekeeping (selfconfigure, autotesting, autologging);
- crew support (at least for set-up and clean-up);
- telescience (remote, interactive experiment execution).

The FS community looks eagerness to the space station era, when experiments under microgravity would no longer be rare events, when investigators do not need to register a decade ahead to have an opportunity, investing years of preparatory work to get minutes of experimental time (which are then devoted to trouble-shooting components, equipment, or the whole laboratory); FS investigators would rather wish to concentrate their efforts on scientific matters, and this can only happen if the proper Columbus infrastructure, both in orbit and on ground, is developed and made available to the users with full assistance from managers and system teams.

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