Getting Sloshed in Outer Space

Liquid Behavior in Microgravity

N Ananthkrishnan

We document some basic facts about how liquids behave in the low gravity of outer space and how this poses challenges to space scientists and engineers who need to design and test systems that handle fluids in outer space while working in the 1-g environment on Earth.

Who has not seen an image of an astronaut chasing a drop of water (or some other drink) while floating free in a spacecraft in outer space – or better still, using a pair of chopsticks to pick up a blob of tea and popping it in his mouth[1].

All this is possible because of the very low gravity in outer space, technically called microgravity (see *Box* 1). Then other forces such as surface tension (capillary effects) become dominant and liquids behave in ways that we are not used to seeing on gravity-dominated Earth.

On Earth, liquids accumulate at the bottom of the container, and take the shape of the container, but in gravity-free space, they could just be anywhere in the container, may be in several disconnected lumps. Or they could stick to the sides of the container leaving a gas bubble in the center. On Earth, hotter liquid rises to the top to be replaced by colder liquid, forming what are called convection loops. But in the 'zero-gravity' of outer space, the hotter liquid is really no lighter than the colder one, the effects of buoyancy are absent. So boiling water in outer space is a different 'cup of tea' altogether. See the contrast between boiling on Earth and in outer space in *Figure* 1. In outer space, the colder liquid stays cold, while the hotter liquid keeps on getting hotter and evap-

N Ananthkrishnan is Director, Coral Digital Technologies (P) Ltd, a Bangalore-based company working in the area of multidisciplinary simulation and system integration of aerospace, naval and surface vehicles, and in the design and development of autonomous unmanned/micro air vehicles.

Keywords
Low gravity, microgravity, unmanned aircraft, sloshing.

---

[1] http://science.nasa.gov/ppod/y2003/07apr_hightea.htm

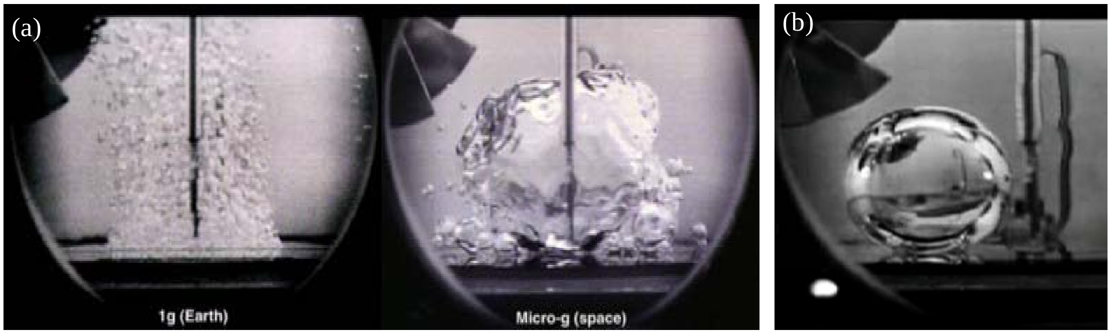

Figure 1. (a) Boiling liquids in outer space (right) behave differently than on Earth (left).
(b) The bubbles instead of rising individually may agglomerate into a single large bubble.
(Courtesy: NASA)

orates, but the bubbles of vapor do not rise all the way to the top. They may even agglomerate to form a single large bubble that remains suspended in the liquid.

Thus, ordinary issues such as determining the volume of liquid in a tank, or venting bubbles of vapor in the liquid, become challenging tasks in outer space.

Spacecrafts use liquid fuel to fire thrusters that direct them to the correct orbit or allow them to control their orientation (the direction in which they face) with respect to the Earth. Space scientists need to consider the behavior of liquid fuel in tanks, the feed system that carries the fuel to the engines (thrusters), and the way in which the fuel reacts to produce thrust in the engines, all under low gravity conditions. Simple things such as determining how much fuel is left in a tank can be a complicated exercise in outer space. As the effect of gravity decreases, the shape of the liquid-free surface changes, as is captured for example in *Figure* 2 for various values of a non-dimensional number called *Bond number*. The Bond number, defined as follows:

$$Bo = \frac{\rho g l^2}{\sigma}$$

is the ratio of gravitational effects (more generally, body forces, with g replaced by any acceleration a) to surface tension effects, σ (ρ is density of liquid, l is a characteristic length scale). High Bond numbers indicate significant effects of gravity while low Bond numbers (usually

Box 1. Microgravity

Strictly, microgravity is a level of gravitational acceleration that is of the order of a millionth of that experienced on Earth, usually called 1-g. Small levels of gravity, of the order of 0.01-g or lower are referred to as 'low gravity'. However, the word 'microgravity' is often used to cover situations of low gravity, as defined above, as well.

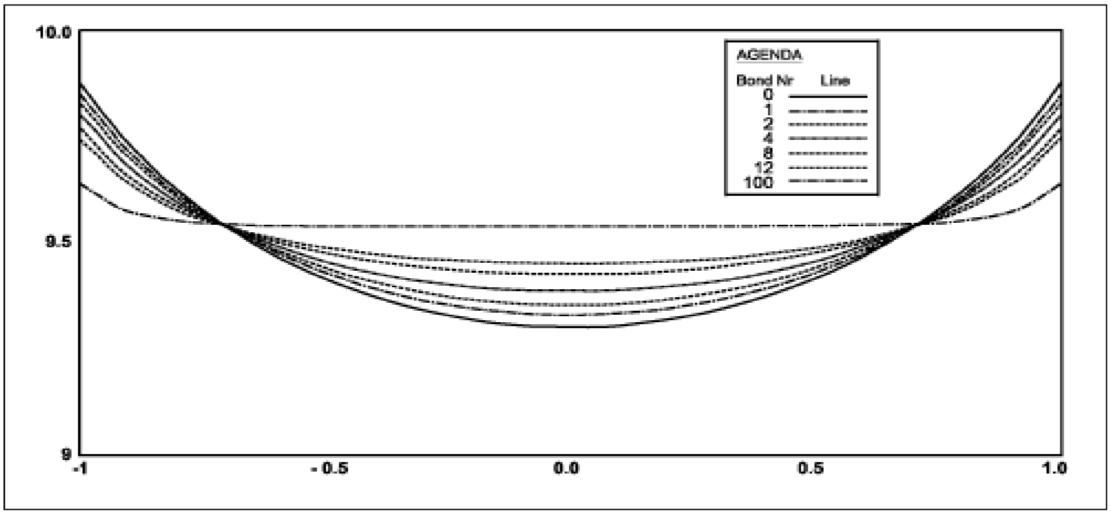

Figure 2. Changing shape of the liquid-free surface in a container as the effect of gravity is decreased; Bond Number reducing from 100 to 0. (Courtesy: ESA)

less than 1) signify flows that are surface tension dominated. Under low gravity conditions, *Figure* 2 shows that the fluid tends to creep up the sides of the container while bottoming out at the center. A probe introduced at the center of the tank that judges the amount of fuel left in the tank by measuring the height of the free surface will wrongly indicate a lesser fuel volume under low gravity!

Surface tension is the effect that is responsible for the rise (or fall) of liquid in the capillary tube as every high school student would have seen (*Figure* 3). Depending on the relative strength of i) the adhesion between the tube walls and the liquid molecules and, ii) the cohesion between the liquid molecules, the liquid either rises up or is depressed in the capillary tube. The adhesion between the liquid and a solid surface determines whether the liquid spreads out on ('wets') the surface, like oil on water, or forms a bead ('non-wetting') like water on wax (*Figure* 3). The cohesive force, the surface tension, tries to draw the liquid into a spherical ball. It is not difficult to show that the height of the free surface in the capillary tube of radius r in *Figure* 3 is given by

$$\frac{h}{d} = \frac{\theta}{Bo},$$

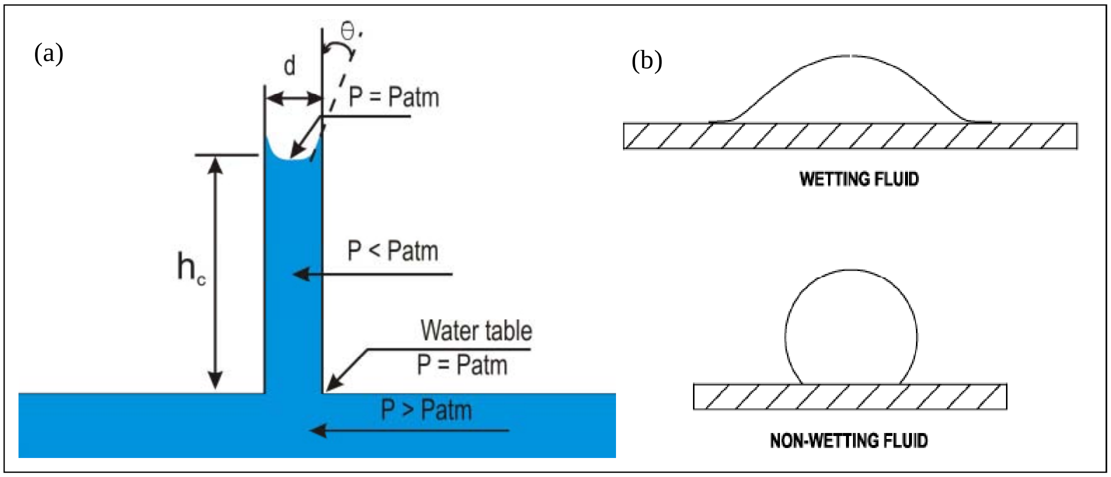

Figure 3.
(a) Effect of surface tension seen in a capillary tube.
(b) Drop of liquid on a surface.

where θ is the contact angle made by the liquid at the solid wall and Bo is the Bond number. Under microgravity conditions ($Bo \ll 1$), the liquid-free surface climbs up the tube wall ($h/r \gg 1$). Experiments to demonstrate this effect were carried out on early space flight missions.

Another problem that often bothers scientists is the motion of the liquid free surface, called sloshing. Sloshing motion in spacecraft fuel tanks, can dissipate energy reducing the useful life of the satellite. Unfortunately, under the microgravity conditions in outer space, the liquid sloshing frequencies are rather low, usually of the order of $0.01 - 0.1$ Hz. They could excite oscillations in the structure, for example, in large solar arrays, or interfere with the control system that manages the satellite attitude. Hence, forces and moments caused by liquid sloshing is a critical input to the team analyzing the dynamics and control of satellites.

> Another problem that often bothers scientists is the motion of the liquid free surface, called sloshing. Sloshing motion in spacecraft fuel tanks, can dissipate energy reducing the useful life of the satellite.

How do scientists create outer space-like conditions on Earth to test under low-gravity? Short periods of reduced gravity (from a hundred to a million times lesser than the normal gravity on Earth) can be created by setting objects in a state of 'free fall' on Earth. Just let the experimental apparatus fall from a drop tower and it will encounter a few seconds of 'zero gravity' during its descent. Another way is to use an airplane to fly a series of parabolic trajectories, each parabolic segment can offer some 20 seconds of low gravity. NASA now employs a C-9B airplane to carry out low gravity tests and also to train astronauts. Or one can fly a parabolic trajectory using a sounding rocket (*Figure* 4). Special sounding rockets meant for microgravity experiments have been designed and flown. However, all these technologies are very costly to set up, maintain and use. A cheaper and

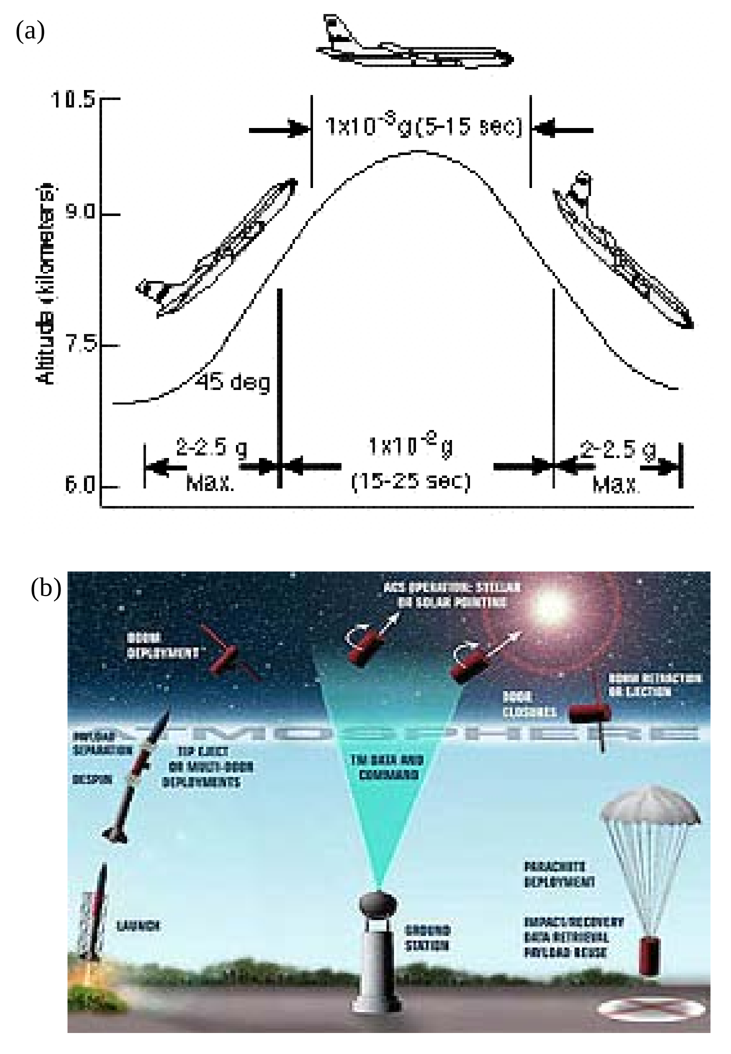

Figure 4. Parabolic flight profiles of (a) a KC-135 airplane. (b) a sounding rocket, to create low gravity conditions.

(Courtesy: NASA)

more attractive option perhaps is to use unmanned aircraft flown autonomously or remotely from the ground for low gravity testing.

A cheaper and more attractive option perhaps is to use unmanned aircraft flown autonomously or remotely from the ground for low gravity testing.

Strictly speaking, creating low gravity conditions is not the only way to reproduce phenomena that occur in outer space on Earth. Rather, what is needed is to conduct experiments with appropriate values of nondimensional numbers, such as the Bond number described earlier. For instance, while reducing g by 6 orders gives a certain Bond number, the same effect can be obtained by reducing l by 3 orders, keeping g unchanged. Thus, microscale experiments conducted on Earth under normal gravity can show similar phenomena as expected in the low gravity of outer space. This is a challenging area of work for researchers in microfluidics and micro electromechanical systems (MEMS).

Acknowledgements

Figure 1 from http://science.nasa.gov/headlines/y2001/ast07sep_2.htm, last accessed Nov 13, 2007.

Figure 2 and 3(b) from www.esa.int/esapub/bulletin/bullet85/klein85.htm, last accessed Sep 13, 2007.

Figure 3 (a) hydram.epfl.ch/VICAIRE/mod_3/chapt_2/text.htm

Figure 4 (a) hydram.epfl.ch/VICAIRE/mod_3/chapt_2/text.htm

Figure 4(b) from www.nasa.gov/missions/research/f_sounding.html, last accessed Nov 19, 2007.

Address for Correspondence
N Ananthkrishnan
C-146, CSRE C-Type Bldg
Indian Institute of Technology
Bombay Campus, Powai
Mumbai 400 076, India.
Email:dr.akn.19@gmail.com
akn@aero.iitb.ac.in