Microgravity PMD investigations by miniaturization of the test sample

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The main objective of the presented work was to recreate the effect of a microgravity environment in conventional ground-based laboratories by decreasing the scale of the test sample. In order to assess the viability of such a technique, an experimental study of a sponge-type control PMD (Propellant Management Device) was carried out.

For the purpose of the study, a dedicated test rig was developed and built to perform tests at different sponge's scales at the research laboratory of fluid mechanics CMEFE of HEPIA in Geneva. The miniaturization of the sponges was performed by Wire Electrical Discharge Machining (WEDM) which allowed to manufacture the miniaturized sponges.

For steady state investigations, experimental tests were performed and compared with theoretical data, based on the dimensionless number analysis. In order to reproduce physical similarity of the microgravity behavior, a known Bond Number was imposed in the experimental campaigns.

Nomenclature

a	Acceleration
D	Characteristic length
FR	Fill Ratio
g	Gravitational acceleration
PMD	Propellant Management Device
U	Velocity
WEDM	Wire Electrical Discharge Machining

Symbols

θ	Contact angle of the liquid with the solid
ρ	Density
μ	Dynamic viscosity
σ	Surface tension

I. Introduction

In the PMD related research, microgravity experimental investigations are of paramount importance to validate numerical and theoretical data. Moreover, in the framework of industrial contexts, experiments are often important in order to perform qualification tests on models physically representing the actual flight

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PMD. The cost of good quality microgravity investigations is usually quite high and can become prohibitive when a lot of information has to be collected for statistical purposes.

Parabolic Flights are seldom successfully used to investigate capillarity-driven flows due to the poor quality of the microgravity. In this framework, parabolic flights are rather used to validate the concept of complex investigation systems aimed to fly in sounding rockets or in on-orbit tests.

Drop Towers are more often used to investigate capillarity-driven flows. In these facilities, only few seconds of microgravity can be simulated by the free-fall. Most tests on the PMD physics can be adapted to be performed in this time range, but often PMD qualification tests require a longer microgravity time.

Plateau Tanks, basins filled with immiscible liquids of approximately the same density and working according to the principle of buoyancy, allow unlimited microgravity time. They are used both for physical investigations and qualification tests. Nevertheless, due to the differential change in density of the two fluids with the temperature, it can be relatively complex to impose a precise level of microgravity. Moreover, the liquid choice can be complex and subjected to security restrictions. Furthermore, dynamic investigations are seldom performed by this technique because of both viscosity and density of the liquids used.

Sounding rockets and on-orbit tests are good instruments for the investigation of capillary-dominated flows. They can allow up to several minutes of microgravity or, in the case of on-orbit tests, indefinite time. Of course, the cost of a massive experimental campaign can be prohibitive and flight campaigns are sometimes coupled to other microgravity tests to widen the investigation range for a more affordable cost.

The miniaturization technique presents many advantages with respect the other methods: provided that the necessary manufacturing capabilities are available, it allows low cost experimental campaign in conventional ground-based laboratories, relatively fast change of geometry and flow configurations, easy access to experiments, and, basically, unlimited microgravity time. On the other hand, manufacturing technology limits the minimum dimensions of the scale samples.

The main objective of the here presented study is evaluate the accuracy of the miniaturization technique by comparing the theoretical model[1] and experimental data for static phenomena. To be in accordance with the theory proposed by Jaeckle, the gaps between the sponge's panels communicate with each other. Liquid passage is guaranteed by a gap between the panels and the central pole. In order to reproduce different micro-gravity levels, different Bond numbers were investigated and different miniaturized sponges were manufactured.

II. Physics background

When performing capillarity PMD studies, due to the all the facility constraints, mockups and models have to be used in the investigations. This means that physical similitude is obtained by the use of dimensionless numbers. Moreover, depending on the investigated phenomenon, some of the test facilities can be more suitable than others.

Some of the most commonly used dimensionless numbers +in the PMD capillary investigations are:

- The Reynolds Number (ratio of inertial to viscosity forces)

$$Re = \frac{\rho U D}{\mu}$$

- The Bond Number (ratio of gravitational to capillarity forces)

$$Bo = \frac{\rho a D^2}{\sigma \cos\theta}$$

- The Froude Number (ratio of inertial to gravitational forces)

$$Fr = \frac{U^2}{aD}$$

where ρ is the density, U is the velocity, D is the characteristic length, μ is the dynamic viscosity, a is the acceleration, σ is the surface tension and θ is the contact angle of the liquid with the solid.

Others dimensionless numbers arising from the combination of the preceding are:

- The Weber Number (ratio of inertial to capillarity forces)

$$We = \frac{\rho U^2 D}{\sigma \cos\theta} = FrBo$$

- The Capillarity Number (ratio of viscosity to capillarity forces)

$$Ca = \frac{\mu U}{\sigma \cos\theta} = \frac{BoFr}{Re} = \frac{We}{Re}$$

If Reynolds, Bond and Froude numbers are identical between the model and the real PMD, a complete physical similitude is established, but the constraints due to the facilities bring to the impossibility to attain this ideal condition. In these cases, a reduced similitude is established and one or more of the dimensionless parameters is not satisfied. In this case, particular attention has to be paid to insure that the physics investigated is correctly represented.

A Reynolds similarity is usually difficult to be obtained, mainly because of the reduced scale of the models. Nevertheless, the gravitational acceleration has no direct effect on it.

On the other hand, the gravitational acceleration has a direct effect on Bond and Froude numbers, which are more likely important to be respected in the microgravity capillary investigations. For this reason, in order to control the microgravity behavior of a capillary system, depending on the phenomenon to be investigated, it is usually of paramount importance to impose the Bond number, the Froude number, or both.

In the here presented cases of static tests (U = 0), only the Bond number similarity needs to be imposed in the experimental tests. The Bond number is a measure of the importance of surface tensions compared to hydrostatic forces. A high Bond number indicates that the system is relatively unaffected by surface tension effects. A low number (typically less than 1) indicates that the surface tensions are predominant, thus the system can be considered in micro-gravity. Intermediate Bond numbers indicate a non-trivial balance between the two effects.

III. The miniaturization approach

Low Bond numbers, usually obtained by a free-fall or by buoyancy effects, can be also obtained by reducing the size of the model D. The present work aims at showing the viability of this technique and discussing the accuracy of the results obtained with this approach.

The machining of the samples was performed by WEDM. This technique uses a metallic wire (electrode) to cut a contour in a workpiece. This procedure can be used to machine conductive materials of any hardness (for example titanium). The minimum scale of the sample which can be manufactured is limited by the diameter of the wire used in the cutting process. In the present project, three scale sponges were manufactured (see figure 1, left side) and a picture of a microgravity experimental test is given in figure 1.

Due to the optimal materials characteristics (high surface tension and low contact angle), and due to their non-toxicity, the authors chose to use titanium as solid material and water as wetting liquid.

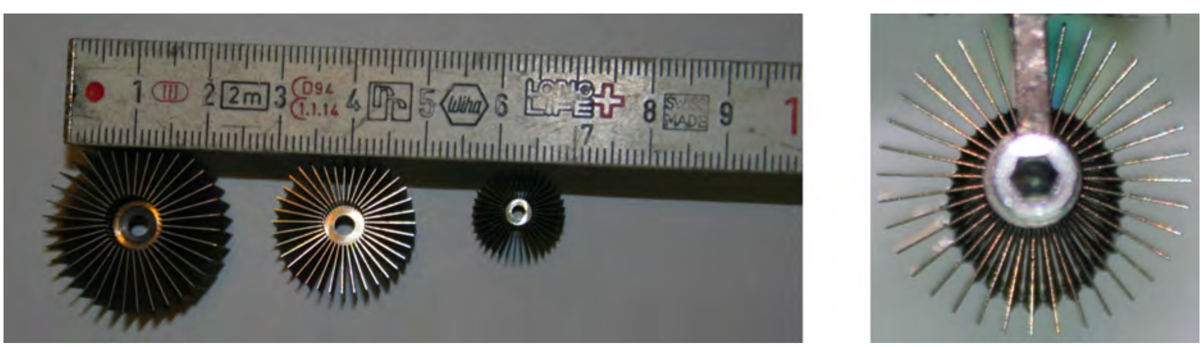

Figure 1. Miniaturization of the titanium sponges: different scale sponges (on the left side) and microgravity experimental behavior (on the right side).