CORRELATIONS BETWEEN NEUTRAL BUOYANCY TESTS AND CFD

by

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Abstract : Neutral buoyancy testing is a well known test capability in Matra Marconi Space for the functional validation of surface tension devices. In order to validate the new Eurostar 3000 PMD, and compare its performances to those of the E2000+ PMD, a complete reservoir has been tested in a neutral buoyancy test bench. Moreover, numerical simulations have been performed in order to correlate and improve our knowledge about transient and stationary capillary phenomena. A discussion and a correlation of the different results is presented. The limits of the different tools are shown and a brief example of the E3000 improvement is modelled

1. INTRODUCTION

During its in-orbit life, a spacecraft tank encounters a variety of gravitational environments created by the station-keeping manoeuvres thrust. Many techniques exist for the ground simulation of low-gravity positioning and reorientation, one among them being neutral buoyancy, which will be presented in the first part of this paper. This technique has been used by Matra Marconi Space for the study of the functional aspect of the lower part of a Eurostar 2000 and 2000+ propellant tank and the Propellant Management Device (PMD) since 1988. In particular, PMDs with different bottom shapes were studied.

Due to the insufficient accuracy of the neutral buoyancy technique for the study of dynamic responses, numerical simulation is a good complement for a complete study of the capillary phenomena.

FLOW3D, a three dimensional free surface computational fluid dynamics model developed by Flow Science Incorporated, and Surface Evolver, a minimum energy solver for surfaces in multidimensions, developed by the Geometry Center, were used for the simulation of interface positioning and PMD behaviour.

2. NEUTRAL BUOYANCY

2.1. PRESENTATION OF THE NEUTRAL BUOYANCY TECHNIQUE

Neutral buoyancy is one of the most representative on-ground simulation techniques for a liquid capillary behaviour, and in particular here, propellants. This technique is based on the consideration that on Earth, gravity, which everything is submitted to, can be balanced by buoyancy. This remark can be exploited for the simulation of propellant and pressurant in low gravity, through the use of two non-miscible liquids having almost equivalent densities.

In our case, helium was simulated by demineralized water, and propellant by a mixture of different organic components. This mixture has been chosen for its density, close to that of water, so that small accelerations can be simulated through density variations induced by thermal control.

Since capillary forces are predominant in neutral buoyancy, a great attention must be given to the preparation of the wet surfaces. Once being sure of these boundaries, the correspondence between simulation and real results will be based on the Bond number similarity. The Bond number of a system is dependent on the characteristic dimension l, the surface tension σ and the density ρ of the liquid, submitted to the acceleration g :

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

Thus, with considerations based on the Bond number, we can determine the simulated acceleration by knowing the density difference between the two fluids through the relation :

$$\gamma_{real} = \frac{\rho_{NB} - \rho_{water}}{\rho_{propellant}} \times \frac{\sigma_{propellant} \cos\theta_{propellant}}{\sigma_{NB} \cos\theta_{NB}} \times g$$

where γ_{real} is the simulated acceleration, ρ_{NB}, ρ_{water} and $\rho_{propellant}$ are the respective densities of each liquid, NB states for the propellant simulating mixture, $\sigma_{propellant}$ and σ_{NB} the respective surface

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tensions of each liquid, and $\theta_{propellant}$ and θ_{NB} the wetting angles.

The use of full scale models avoided the use of a geometrical correlation. Two transparent plastic models of PMDs (a classic E2000+ design and an improved design) and a complete E2000+ tank also machined in transparent perspex, were set inside a 4000l aquarium filled with water and thermally controlled with heaters and water injectors for mixing purposes (see Figure 2-1).

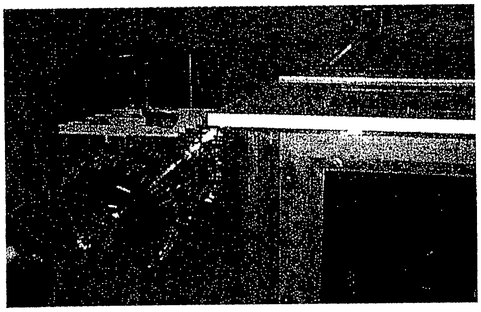


Figure 2-1 Neutral buoyancy test bench

The tank was dismountable in order to change the configuration of the PMD, the vanes or the membrane.

2.2. SIMULATIONS ON A LOWER E2000+ TANK

A first series of simulations was performed on the transparent perspex model of the lower part of the Eurostar 2000+ tank. This model was submitted to drastic functional conditions. The overall in-orbit life sequence was performed with a complete draining of the tank. The working of the PMD was validated and the volume of residuals estimated. We show below (see Figure 2-2) for a 150 Bond number based on the tank radius, and a 30% filling ratio the shape of the interface corresponding to a station keeping manoeuvre.

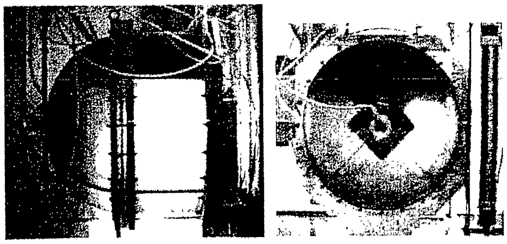


Figure 2-2 Propellant position under acceleration

It can be seen that the curvature of the interface is low due to the high value of the acceleration, and similarly noticed a more pronounced curvature is generated for lower accelerations. Nevertheless we can still notice the position of the residuals under the PMD, along the vanes and in the corner between the cylinder and the internal membrane. Failure cases were also simulated and the compliance of the PMD demonstrated.

2.3. SIMULATIONS ON A PMD ALONE

2.3.1. First design

The PMD studied is a standard E2000+ PMD, as sketched on Figure 2-3. The experiments consisted in filling the sponge with propellant simulating mixture, and then draining the sponge as much as possible. Thus, we could study the maximum expelled volume under a variety of accelerations, and also the behaviour of the tank bottom, which was machined in transparent perspex. Since the PMD had its inlet corner grids closed to avoid vane alimentation, the expelled volume corresponds to the useful sponge volume.

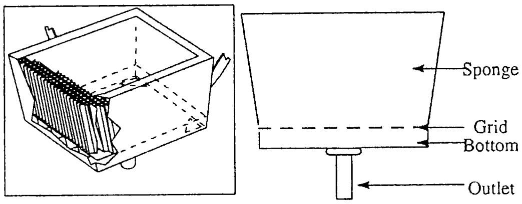


Figure 2-3 E2000+ PMD

The results of the test campaign, with a Bond number based on the PMD's width, are summarised in the table below (the expelled ratio is the useful sponge volume / sponge volume) :

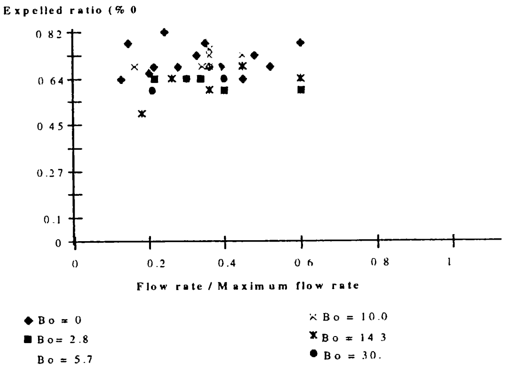


Figure 2-4 Sponge expelled volume

The conclusion to these experiments is that :

The mean expulsion ratio is, for the standard PMD : **66%**

Consequently, the mean static residuals in the standard PMD are : **34%**

The global standard deviation is, for all the experiments on the standard PMD : **7.2%**

This residual value is only the static sponge residual in the worst case with no vane alimentation.

This design complies to the specification of a mean expelled volume of 50%. The residuals were shown to be located in the corners of the PMD.

Another result of this test campaign was the visualisation of the sponge depletion ending with the explosion of a meniscus which appears for conditions worst than the real specifications. This phenomenon occurs when no more propellant can be expelled from the PMD. It can be described in three phases :

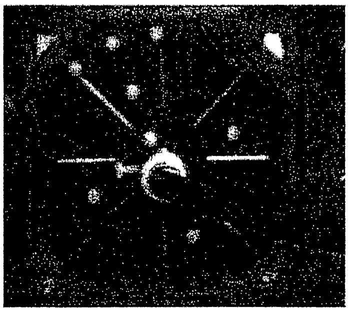


Figure 2-5 Normal draining in E2000+

In the first phase, shown in Figure 2-5, the draining proceeds normally, with no bubble in the bottom.

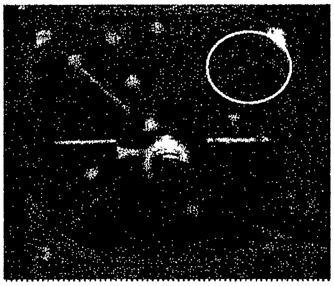


Figure 2-6 Meniscus breaking in E2000+

In the second phase, shown in the Figure 2-6, a meniscus explodes in the circled zone. The bubble then grows progressively, and after about one minute, we reach the stage shown in the Figure 2-7.

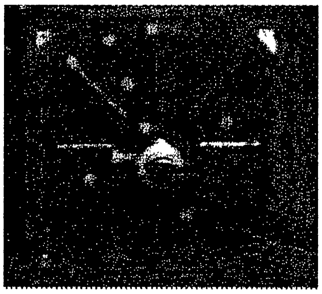


Figure 2-7 Gas invasion in E2000+

At this stage, only very little propellant remains in the bottom, and all of it is sucked back into the sponge. Consequently absolutely no further propellant can be expelled.

The fact that the equilibrium position shows no propellant remaining in the bottom was puzzling, since this prevents the broken menisci to reappear. An analytical calculation linking the dimensions of the bottom, the capillary pressure in the sponge and the equilibrium shape of the interface leads to the following curves, Figure 2-8, giving the bubble surface ratio (bubble surface / bottom PMD surface) versus the PMD under-grid height.

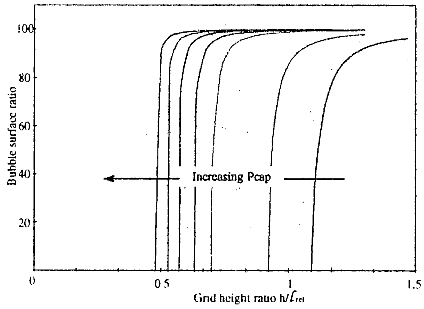


Figure 2-8 Gas bubble invasion versus grid height

Therefore, we could understand the equilibrium shape we obtained in neutral buoyancy and estimate an ideal value, giving the best compromise between propellant covered area and dimensions.

2.3.2. Improved design

The PMD design was optimised for the sponge draining and the bubble ejection using the results of the first campaign. In particular, the PMD configuration was adapted to the exact pressure drop we needed and the ability to expel bubbles out of the PMD. The results of the tests with this new design are summarised in the Figure 2-9:

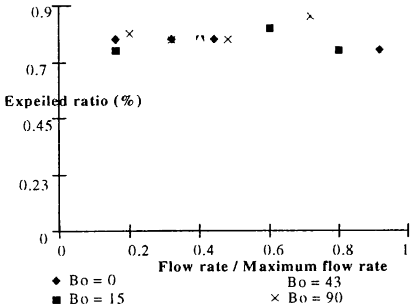


Figure 2-9 Sponge expelled volume

The conclusion to these experiments are :

The mean global expulsion ratio for all the experiments on the modified PMD is : **77 %**

Consequently, the mean static residuals in a modified PMD are : **23 %**

The standard deviation is : **4 %**.

This results confirms the improvement of the design.

Moreover the meniscus breaking phenomenon was also different. The first phase of the draining is shown Figure 2-10.

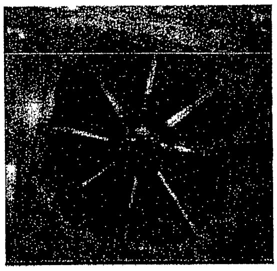
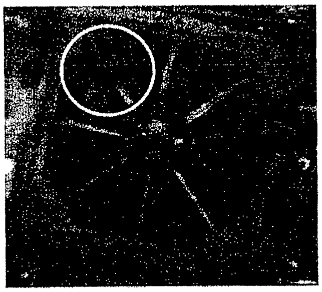


Figure 2-10 Normal draining

In the second phase, bubbles are generated from the broken meniscus located in the circled zone in the Figure 2-11. The draining is then stopped, and the equilibrium position, is reached in about 10 s.



The final equilibrium position is different showing lower bubble surface ratio. The final shape which is representative of the improvements of the PMD was also analytically predicted.

The neutral buoyancy test campaign has clearly demonstrated the improvements of the design of the different tank capillary devices. It was also useful to confirm these improvements by the numerical tools used in Matra Marconi Space.

3. NUMERICAL SIMULATION

As in Neutral Buoyancy, numerical simulations were led at two different scales :

- the tank scale, including the study of the global behaviour of the interface with different filling ratios and acceleration levels.

- the PMD scale, with the study of the draining phase of the PMD and the volume of the residuals.

Several important results were obtained at both scales. We summarise hereafter some of them and the comparison between two numerical software.

3.1. TANK SIMULATION

3.1.1. Flow3D model

FLOW3D is a CFD software which solves the complete Navier Stokes' and energy balance equations with a VOF technique [1]. This software has been for a long time validated for on-ground and transient sloshing [2], [3]. From Authors' knowledge it has not been done for pure capillary stationary problems. Thus it was important to estimate the ability of FLOW3D to solve this kind of problem. We used a 45x45x60 grid to mesh the lower part of a Eurostar 2000+ tank. We show below, Figure 3-1, the free surface position in the bottom of the tank for a 35 Bond number and a 30 % filling ratio.

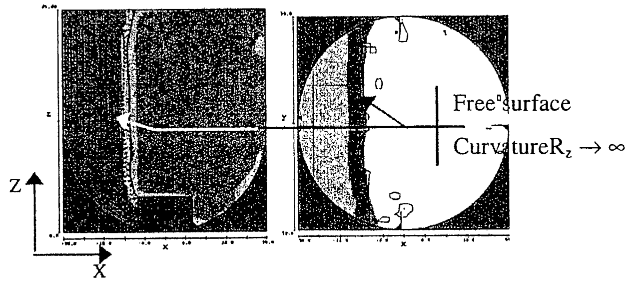


Figure 3-1 Propellant position under acceleration

We can notice a low curvature of the interface, which is nearly flat, and the fact that the PMD is mostly uncovered. We can also notice some residuals near the vanes which were shown by neutral buoyancy testing. The more complete validation of these results needs the use of a capillary dedicated software such as Surface Evolver including a Boundary Element Method more adapted to this kind of problem.

3.1.2. Surface Evolver model

Surface Evolver is a freeware which uses a boundary element method in order to minimise the surface energy [4]. For this study, we used a 16292 vertices model. The results of the simulation for the same case as the one studied with FLOW3D is shown below Figure 3-2.

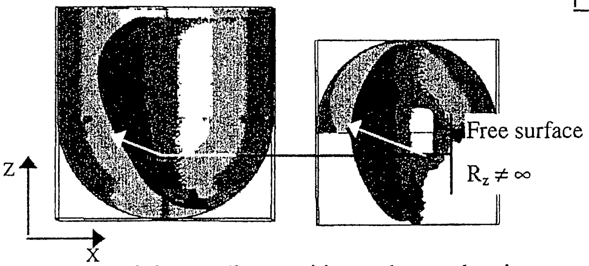


Figure 3-2 Propellant position under acceleration

As in neutral buoyancy the fluid residuals are located along the vanes and in the membrane cylinder corner.

Moreover we can notice that the curvature of the free surface is more important and that the PMD is more covered than in the FLOW3D simulation. The main reason which explains this discrepancy is the use of a VOF technique (FLOW3D) which does not take accurately the surface tension and wetting angle phenomena into account.

The stationary results obtained with Neutral Buoyancy tests were well predicted by Surface Evolver. The residuals positioning, the bubbles curvatures, and the free surface position under acceleration were compared and showed a good correlation.

However the transient behaviour, which can not be studied with Surface Evolver, was predicted with FLOW3D and comparisons to other studies [5] demonstrated the good comparisons.

Thus, in order to simulate the draining of the sponge a numerical model of the PMD was set with FLOW3D.

3.2. PMD SIMULATION

The PMD model set up for this study takes into account the capillary pressure in both the sponge and the grid. The system was meshed with a 25x25x40 grid, and a fixed flow rate was set as a boundary condition. The pressure drops in the PMD were compared to experimental measurements done in several points of a real PMD, in order to have the same flow losses. The gas-liquid interface shape inside the sponge is shown in the Figure 3-3.

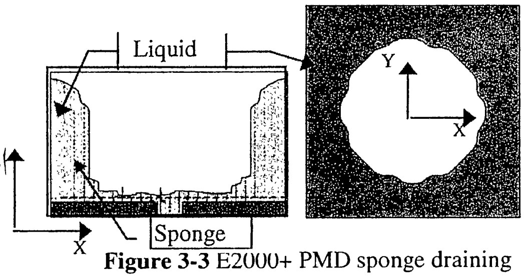


Figure 3-3 E2000+ PMD sponge draining

We can notice the axial symmetry of the draining, the location of the residuals after the meniscus breaking, and the non-homogeneous distribution of the liquid. Through pressure drop considerations, a meniscus breaking was detected for an expulsion ratio of 60% which is closed to the neutral buoyancy test results (66% of average expulsion ratio).

In order to study the effect of the acceleration on the PMD behaviour, another simulation was led with Bo= 13 , result is shown in Figure 3-4.

We can see here the displacement of the liquid-gas interface due to the side acceleration

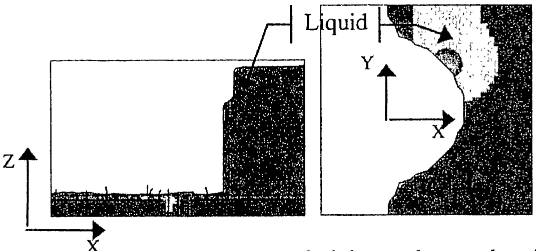


Figure 3-4 PMD sponge draining under acceleration

The grid remains efficient, the expelled volume is almost the same as without acceleration which is also predicted by the neutral buoyancy experiments.

Finally the improved PMD was simulated with FLOW3D. We show Figure 3-5 the shape of the gas-liquid interface.

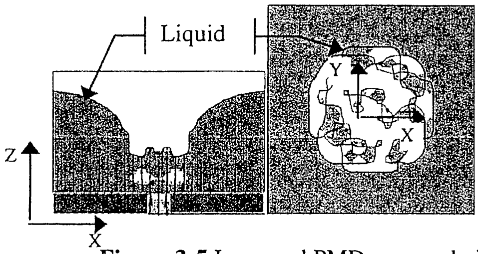


Figure 3-5 Improved PMD sponge draining

We can notice a more homogeneous distribution of liquid, due to the different flow losses in the bottom, which results in a greater expelled volume.

For all these cases, numerical simulation and neutral buoyancy tests were found to be very complementary approaches. In particular numerical simulations allowed the user to obtain physical values everywhere, and to perform accurate transient capillary sloshing.

4. GENERAL CONCLUSION

The capillary behaviour of liquids has been studied for a long time in Matra Marconi Space, which now has a complete tool panel on its disposal. MMS has now a great ability, based on experimental (Neutral Buoyancy test bench) and numerical (Surface Evolver and FLOW3D and in-house) tools, to perform and design capillary devices such as those used in propellant tank.

The neutral buoyancy technique is now well controlled with a laboratory equipped with a 4000 l aquarium and a complete transparent perspex tank model.

Development and validation of numerical tools has been performed. The correlation with neutral buoyancy has demonstrated the need of using each numerical tool in its particular field of application. Moreover the numerical results have been well correlated with neutral buoyancy.

These complementary approaches allowed the validation and improvement of the E2000+ propellant tank, shown in Figure 4-1 and is now a key-stone of the development of the forthcoming E3000 platform.

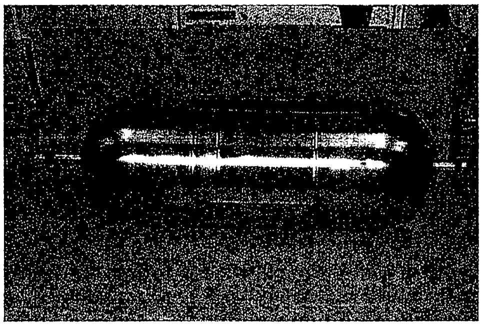


Figure 4-1 E2000+ reservoir

Thus using a precise mechanical design and an accurate functional analysis, MMS has designed a very efficient and competitive propellant tank.

References :

[1] FLOW3D users manual, Flow Science Inc.

[2] Analysis of cryogenic propeilant behaviour in micro-gravity and low thrust environments, M.F. Fischer, G.R. Schmidt and J. J. Martin

[3] Propellant tank forces resulting from fluid motion in low gravity field, J. Navickas, C.R. Cross and D.D Van Winkle

[4] Surface Evolver users manual, K.A. Brakke

[5] Low gravity bubble reorientation in liquid propellant tanks, AIAA-87-0622, J.J. Der and C.L. Stevens