Proceedings of the Microgravity Transport Processes in Fluid, Thermal, Biological and Materials Sciences III
Davos, Switzerland.
September 14 to 19, 2003

ECI: MTP-03-34

MICROGRAVITY ACTIVITIES FOR THE VINCI ENGINE RE-IGNITION CAPABILITY

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ABSTRACT

The VINCI engine will power the Ariane 5 ESC-B upper stage and contribute to providing a 12-ton payload capability in geostationary transfer orbit to the Ariane 5 launch system. VINCI is a cryogenic expander cycle engine and produces a 180-kN thrust using liquid oxygen (LOX) and liquid hydrogen (LH_2). It is designed to be restartable up to 4 times on orbit, which broadens the array of possible missions.

Before a reignition, the gravity level onboard the stage is very low and this may have an effect on several crucial steps in the reignition process. The main concerns are fluids behavior (filling of the injection cavity) and heat transfer during chilldown (pool boiling and convective boiling in pipes of various dimensions). Predicting the magnitude of these effects is of prime importance in order to take them into account in the design and eventually justify the reignition capability. This paper describes the expected effects of microgravity on the VINCI engine and the plan of dedicated studies that are foreseen.

INTRODUCTION

In June 1998, the European Space Agency (ESA) took the decision to develop a new cryogenic upper stage, named ESC-B, powered by a new cryogenic engine, the VINCI (figure 1). These programs are part of the Ariane 5 Evolution program, a continuous upgrade of performances of the Ariane 5 launcher. The ESC-B and VINCI developments are programs of the European Space Agency (ESA) whose management has been delegated to Centre National d'Etudes Spatiales (CNES), the French Space Agency.

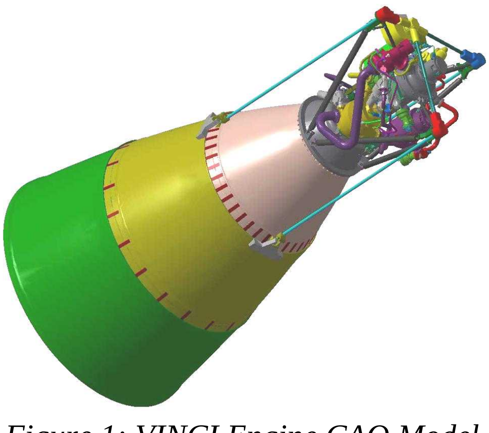

Figure 1: VINCI Engine CAO Model

The VINCI overall system design and integration is under the responsibility of Snecma Moteurs in Vernon, France, as well as the functional propulsive system of the VINCI (pressurization equipment, helium command system, etc). Major subsystem contractors are EADS-ST (Ottobrunn, Germany) for the combustion chamber and Avio (Turin, Italy) for the oxygen turbopump.

From the beginning of the project, the requirements for low cost, high performance, multiple ignitions (up to 4 restarts on orbit) and high reliability have led to the choice of an expander cycle for the VINCI (figure 2).

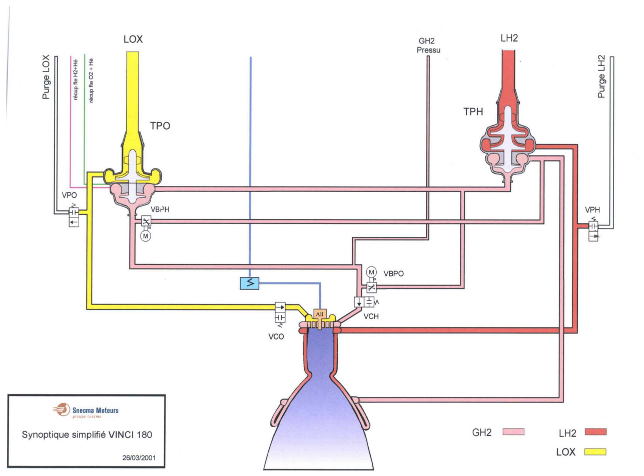

Figure 2: Simplified VINCI flow diagram

The VINCI uses liquid oxygen (LOX) and liquid hydrogen (LH_2) to produce a 180kN thrust with 464 seconds ISP. But what is more, the VINCI introduces the concept of versatility: with its multiple-firing capability, it gives Ariane 5 the possibility to perform a broad array of missions. For example, in the GTO/GTO+ mission, a first payload is injected on a GTO orbit; then a 5.5-hour ballistic phase occurs before the VINCI is restarted. At the end of this second boost, a second payload is injected on another GTO orbit (figure 3).

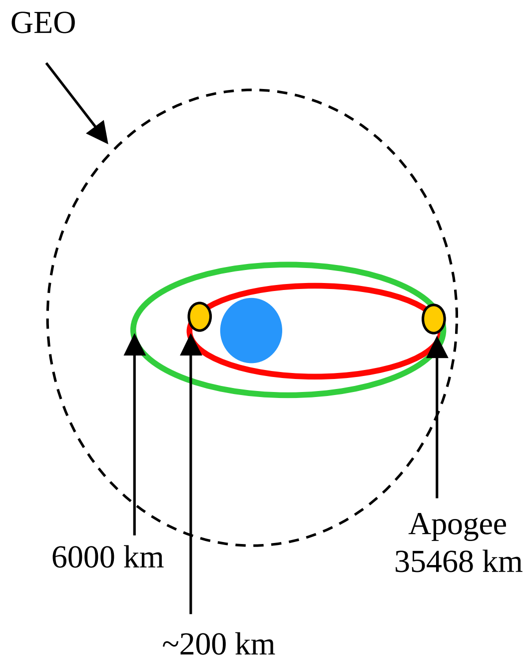

Figure 3: ESC-B mission with 1 restart (VINCI boosts are symbolized by ○)

VINCI is the first-ever European cryogenic engine designed to be restartable. Therefore, some specific design issues arise and are presented hereafter.

RE-IGNITION ISSUES

The first VINCI boost occurs just after the first stage jettisoning. Then, after the 5.5-hour ballistic phase, several operations have to be performed under reduced gravity (around 10^{-4} g) before the engine can be restarted:

- Tanks reconditioning: the tanks are slowly depressurized to bring the propellants temperatures down. Then they are repressurized to the nominal start pressure.

- Engine chilldown: given the very low temperatures of the propellants (around 90K for LOX and 20K for LH_2), propellants must be flowed through the engine in order to cool down the subsystems (lines, valves, and especially turbopumps) to their nominal operation temperature.

- Finally, the VINCI ignition sequence itself: this includes filling the LOX dome (figure 4), a cavity located just upstream the injectors which atomize the LOX in the combustion chamber.

Figure 4: LOX dome

Problems that may occur during these phases in microgravity are:

- Propellant behavior in the tanks (sloshing, ingestion of liquid in pressurization lines);
- Fluid flows in pipes and systems with a complex geometry;
- Boiling and heat transfer during chilldown in microgravity.

The most common way of dealing with these problems is to produce a thrust using acceleration devices, usually hydrazine thrusters. They create an artificial gravity level which settles the propellants. However, such an additional propulsion system is heavy: it requires specific propellant tanks (hydrazine bottles for example), feed lines, a control system, and the thrusters themselves. This affects the performance of the whole upper stage of the launcher in terms of payload capability. It also adds to the recurring cost.

A better knowledge of fluids and heat transfer phenomena in microgravity may prove that such a system is not necessary. Specific microgravity studies are therefore needed and will lead to a better optimized design of the engine and its propulsive system.

In the following paragraphs, details about the microgravity issues placed under the responsibility of Snecma Moteurs, the engine and propulsive system prime contractor, are provided. Activities and studies that are currently under consideration are also described.

SLOSHING AND INGESTION

It is a very old concern (some references are dating back to the 1960's). Several causes can explain propellant sloshing:

- Shut down of propulsion;
- Structures relaxation;
- Attitude control, spin;
- Inertia, viscosity and surface tension forces.

Consequently, the location of the liquid phase in the tank changes. Various configurations are possible: vapor at the center of the tank and liquid around it, liquid in the center and vapor around it, liquid on one side of the tank or the other… The free surface may even break up into drops of various sizes.

Risks linked to these phenomena are:

- Unexpected loads perturbing the stage attitude and trajectory;

- Impossible venting if liquid is present at the venting line connection: liquid propellant drops could be ingested in the lines and eventually go through the attitude control system and to the pressurization plates, which are not rated for such a two-phase flow and may be damaged. Moreover, the pressurization loop and the stage attitude control rely on predictions that were made using a gas-only flow, and having a two-phase flow instead would compromise the accuracy of such predictions. An unstable behavior of the pressurization loop could also occur.

Foreseen activities/studies: the tank contractor is responsible for sloshing limitation and non-ingestion of liquid propellant in the pressurization lines. The current baseline solution is to use a specific diffuser at vent lines inlets (under the responsibility of EADS-ST, Bremen, Germany), and to settle the propellants at the tank bottom before reignition by creating artificial gravity and/or using phase-separation devices. Moreover, a study group called COMPERE and led by CNES works on propellant behavior in tanks.

As the propulsion system and engine designer, Snecma Moteurs is concerned by these issues in order to be able to contribute to the definition of the appropriate sequence of operations before restarting the VINCI: if artificial gravity is needed for propellant retention and settling, what would be the level of thrust to be produced? Could the propulsive system be designed in some way to produce this thrust without the need for a specific system like hydrazine thrusters?

More knowledge on the behavior of fluids in microgravity will help answer these questions.

INJECTION CAVITY FILLING

When the LOX chamber valve (VCO) is opened during the reignition sequence, the LOX enters the "LOX dome", which is a cavity just above the thrust chamber (figure 5). At the bottom of this cavity, injectors lead the propellant into the thrust chamber. While LH_2 injection is almost unaffected by gravity and acceleration due to its low density, the LOX dome cavity filling may be affected: injection mass flow and repartition of the flow among the LOX injectors may be different from what happens on the ground. Moreover, helium injection just downstream the VCO plays an important role in atomizing the LOX.

This whole sequence of operations is critical to ensure a correct ignition in the thrust chamber. There is consequently a need to know better the nature of the flow downstream the VCO and to make sure all injectors in the LOX dome cavity are fed properly. Given the high velocities of the LOX (5 to 20 m/s) and of the Helium (flow rate of 10 to 15 g/s), the engineering feeling is that the LOX dome filling is driven more by fluid momentum than gravity, so the process should not be affected a lot by microgravity. But the injection process is so critical that a verification test is mandatory for qualification purposes.

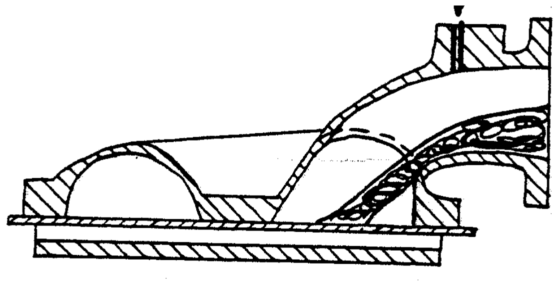

Figure 5: LOX dome cavity filling

Possible activities/studies: the goal is to characterize the flow downstream the VCO ("flash vaporization" of the LOX, influence of helium injection and of the specific geometry of the VCO, impact of the flow on the LOX dome walls, …)

Experimental work is proposed by EADS-ST Ottobrunn (thrust chamber contractor) and numerical studies by Snecma Moteurs. The proposed activities are to:

- conduct simulations with a 3D, two-phase flow simulation tool taking into account microgravity and both the complex physical phenomena *and* the complex geometry;
- verify experimentally the injection flow pattern in microgravity, and especially point out the differences, if any, with what happens in 1g; propose an adaptation of the filling sequence if needed.

Experiments could be conducted in a drop tower and a very preliminary concept was defined to that end. It is shown on figure 6; the idea is to feed the dome with pressurized LOX and visualize the flow profile downstream of the injectors during the drop tower free-fall time.

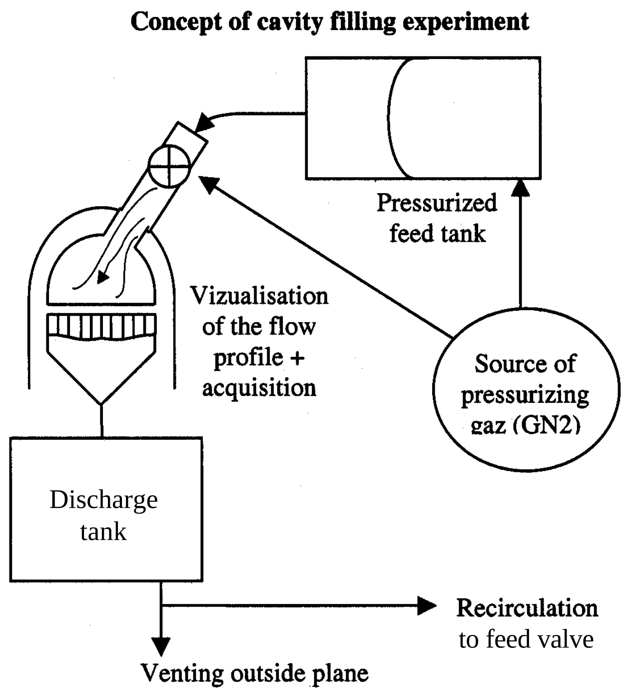

Figure 6: LOX dome experiment concept

CHILLDOWN

Context

In order to chilldown the turbopumps before reignition, liquid propellants must be run through them. The problem is to limit the mass of propellants used to this end while still ensuring a good chilldown in all parts of the turbopump (in the main circuit but also in "dead ends"). Moreover, there should be only liquid in the turbopumps (no "trapped bubbles"). Once the turbopumps temperature has reached predefined criteria, the rest of the reignition sequence can be launched.

Using very preliminary assumptions, the current baseline sequence (in GTO/GTO+) aims at limiting the propellants consumption to 125 kg of LOX and 35 kg of LH_2. The scenario is to open the feed and purge valves, let propellants flow (heat transfer is then mainly done through forced convection, except in the dead ends) and close the purge valves when consumption reaches respectively 100 kg and 20 kg.

Chilldown continues by percolation (pool boiling in microgravity), and purge valves are reopened just before reignition, the remaining 25 kg of LOX and 5 kg of LH_2 being consumed at that moment.

It is important to be able to confirm that this chilldown scenario will effectively enable the turbopumps to reach their operating temperature. In order to do so, current codes must be updated with thermal correlations on the heat transfer coefficients in microgravity, as shown on figure 7. Indeed, available codes currently use 1-g correlations and it is suggested in the literature that heat transfer in microgravity may be less efficient than on the ground. In that case, chilldown in microgravity may require more propellant consumption than demonstrated in 1 g and last longer than expected.

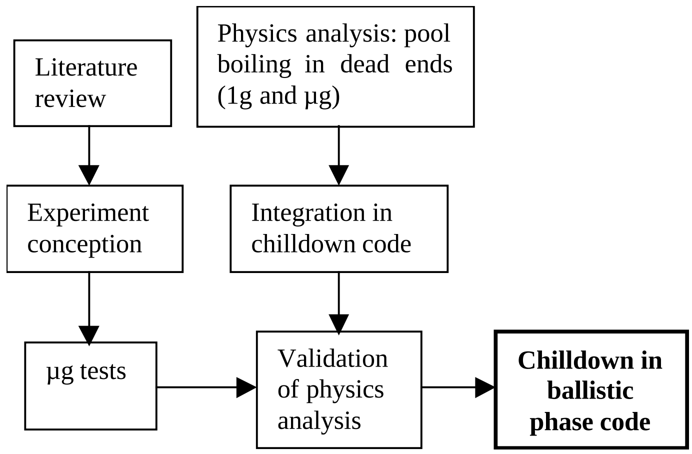

Figure 7: Taking microgravity into account in the current simulation tools

Consequently, the need associated with this problem is to conduct dedicated activities to answer the following questions:

- how (quantitatively) does convective heat transfer in microgravity (forced convection in the main canal, natural convection in the dead ends, pool boiling) compare to? What is the importance of the convective speed: high speed flows are probably not very affected by microgravity, but is there a threshold effect?

- what is the motion of gas bubbles in the turbopumps, especially during the percolation phase? Do they go up to the tank, or do they stay trapped in the turbopumps, in the dead ends? What could cause them to disappear? How do they behave in the presence of zones of various flow velocities?

- from the system point of view, how can the chilldown scenario be optimized for both low propellant consumption and good chilldown?

Literature review

A literature review was conducted on pool and convective boiling in microgravity.

On pool boiling, the review showed that despite the lack of a unified theory, some tendencies could be defined, as in articles of Straub [1], Merte & Lee [2,3], DiMarco & Grassi [4]. The geometries in literature are small wires and plates ; the difference concerning boiling between these two geometries is pointed out.

Generally speaking, the heat flux is found to be a function of R' = R / L, where R is a characteristic length and L is the capillary length :

$$L = \sqrt{\frac{\sigma}{(\rho_l - \rho_g)g}} .$$

Concerning small wires, the influence of microgravity is quite well known and a Nukiyama curve can be plotted (figure 8). However there are no explicit correlations of heat flux with respect to gravity.

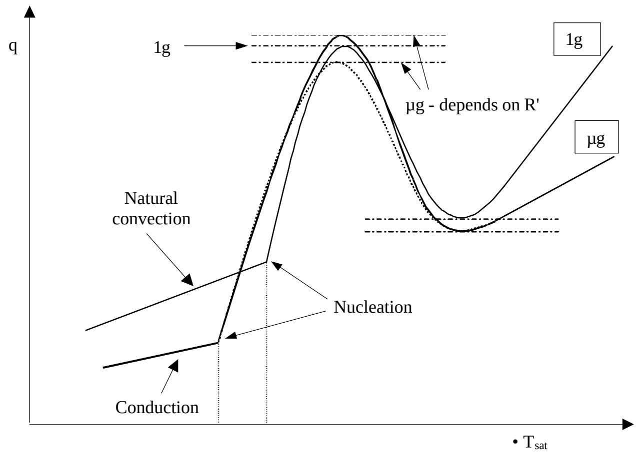

Figure 8 : Preliminary pool boiling curves on a wire

According to Straub [1], maximum heat flux is not so decreased by microgravity ; it can even be increased in some cases. Stable film boiling exists and heat transfer in this regime is highly affected by microgravity. Correlations exist but depend on the range of gravity : influence of gravity is not the same at 10^{-4} g or 10^{-2} g. DiMarco & Grassi suggest to rely on the wavelength of the oscillations during film boiling and its dependence on R'. This method should lead to a global correlation for film boiling in microgravity on wires.

Concerning plates, only nucleate boiling and boiling crisis are treated. Work of Merte [2,3] or Kim [5] enables to plot a boiling curve up to the maximum heat flux. The results of Merte are shown on figure 9.

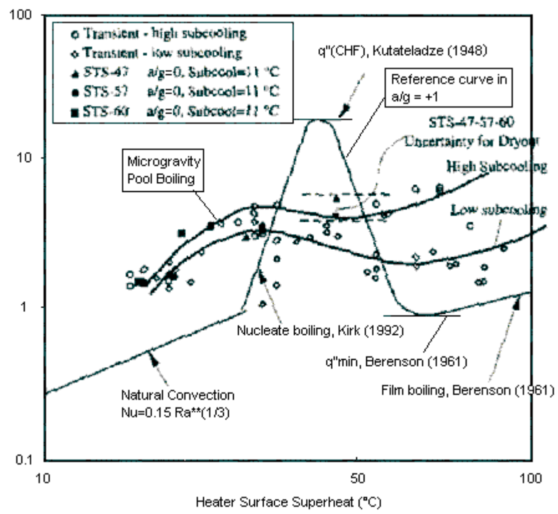

Figure 9 : Pool boiling curve on a plate for R113 [reference 3]

One particularity of subcooled boiling on plates in microgravity is the heat pipe phenomenon (figure 10): a stable, huge bubble forms upon the plate; evaporation takes place at the bottom of this bubble and condensation at the top. This enables to increase heat transfer in nucleate boiling compared to normal gravity.

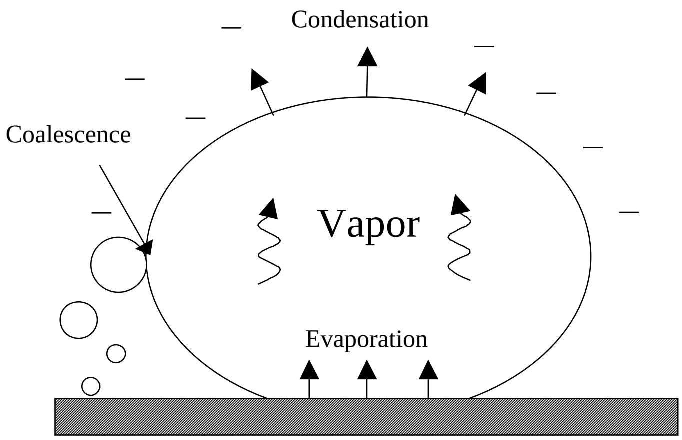

Figure 10 : Heat pipe phenomenon

On the contrary, maximum heat flux is highly reduced; but the relation between this flux and gravity level is not established. Boiling for high superheat is not studied but it seems that no stable film boiling exists on plates.

We have plotted a preliminary pool boiling curve which could be used in chilldown codes (figure 11).

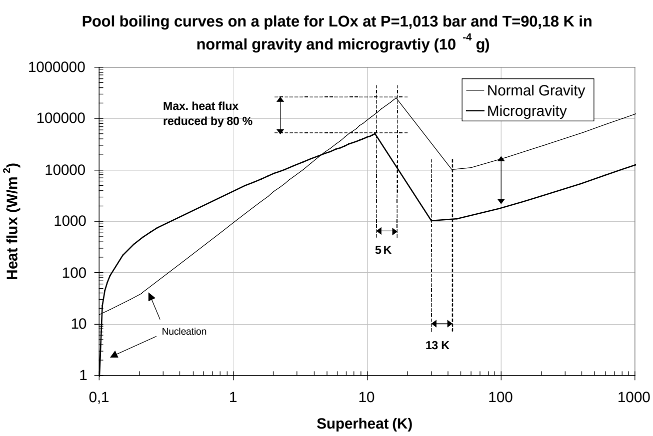

Figure 11 : Preliminary pool boiling curves for LOX

As regards convective boiling, it is obvious that the effect of microgravity decreases as the fluid velocity increases. However, the range of velocities in which microgravity has on effect on convective boiling is not easy to determine, especially for cryogens.

Westheimer & Peterson [6] show the transitions between regimes of flow boiling of water are dependent of gravity level. According to Ma & Chung [7], heat transfer on a wire in a crossflow of FC72 can decrease in microgravity. Work of Kawanami et al. [8] shows that microgravity can increase heat flux in case of an upstream flow of LN_2. But only one value of mass flow rate is tested. It should be the contrary in the case of a downstream flow as it is the case on the VINCI engine.

Specific needs

Experiments in the literature are dedicated to study heat transfers in satellites devices.

The result is that none of the studies that were found in the literature are directly applicable to the VINCI engine chilldown because:
- they deal with simple geometries (heated wires or plates), while in the turbopumps the problem is an *internal* flow in a complex geometry (figure 12);
- they usually study "common" fluids (water or CFCs), while VINCI uses cryogenic LOX and LH_2;
- they are not focused on boiling for high superheat while this is the main regime during the VINCI chilldown.

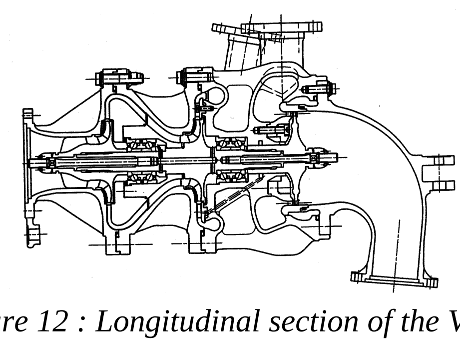

Figure 12 : Longitudinal section of the VINCI hydrogen turbopump

Quantitative results on convective boiling are available for ducts but data for oxygen / hydrogen and for various velocities lack.

Consequently, there is a need to perform specific experiments and simulations. Assuming an internal flow of a cryogen in cylinders of various diameters and inclinations, the objectives are the following:

- to determine the effect of microgravity on pool boiling with high superheats;
- to determine the effect of a shape factor on heat flux in all the boiling regimes (compare with boiling on a plate : for example does the same heat pipe phenomenon exist?);
- to determine the effect of microgravity on convective boiling with respect to the flow velocity.

What is finally needed is the heat flux coefficient h(fluid, T, P, g, geometry: characteristic length, diameter, shape factor, orientation …), with:
- fluid: hydrogen, oxygen
- Tp - Tsat = [0, 300 K]
- P = [1 bar, 5 bar]
- g = [10^{-3} m/s² ; 10 m/s²]

Possible activities/studies

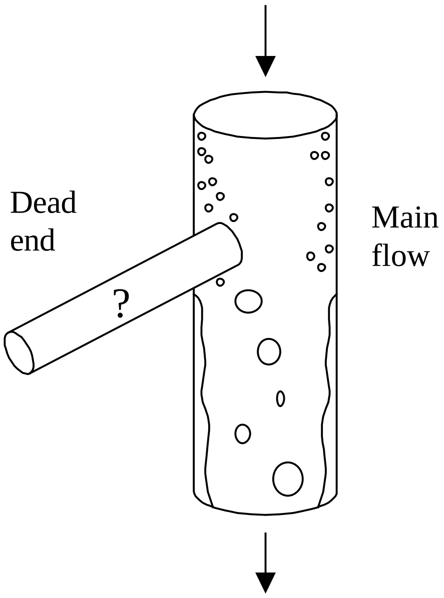

Figure 13 : Experimental configuration to be tested

Snecma Moteurs proposes to conduct a dedicated experiment about heat transfer in microgravity. A typical situation in which correlations are needed is the one shown on figure 13, where the main flow presents the classical regimes of convective boiling. The boiling regime in the dead end is not defined.

The experiment should allow to find out the necessary correlations in order to determine the temperature evolution of such a system.

The main difficulty is that the boiling curve must be determined for a wide range of superheats, especially for high superheats (> 100 K). This means that a constant heat flux source cannot be used because of burnout.

The only way is to initially heat the sample and to measure the temperature drop as the fluid flows through it (convective boiling) or is in contact with the walls without flowing (pool boiling) : this is the quenching technique.

This method has already been employed by Merte [2] for pool boiling but the surface was very simple. It was also used by Kawanami et al. [8] for convective boiling but the influence of velocity has not been studied.

Problems to address

A lot of questions ought to be solved in order to design an experiment :

- Is it possible to treat pool and convective boiling in microgravity on the same device?
- What is the best experimental means for this purpose: Zero-G plane or drop tower?
- Similitude: as experiments are difficult to do with LH_2, a method to extrapolate results to other fluids is needed.
- How can we predict the value of heat flux in order to design the experiment :
    - Is there a heat pipe phenomenon?
    - What is the expected regime with high superheats?
    - What is the effect of subcooling?

CONCLUSION

In this paper, the main problems concerning the reignition process of a cryogenic upper stage engine in microgravity were presented. When these problems are solved, an auxiliary propulsion system (usually required to create artificial gravity) may not be needed anymore, thus saving mass and cost.

A dedicated work logic with theoretical analyses, experiments and simulations is therefore being set up. In 2002, an extensive literature review was conducted; it is summarized in this paper. In 2003, contacts with specialized laboratories are being established, in order to refine the needs and the experimental concepts. Finally, synergies and partnerships with these laboratories are under consideration.

REFERENCES

[1] Johannes Straub, *Boiling Heat Transfer and Bubble Dynamics in Microgravity*, Advances in Heat Transfer, Vol. 35, pp 57-172.

[2] Herman Merte Jr., *Nucleate Pool Boiling: High Gravity to Reduced Gravity; Liquid Metals to Cryogens.*

[3] H. S. Lee, H. Merte & F. Chiaramonte, *Pool Boiling Curve in Microgravity*, Journal of Thermophysics and Heat Transfer, Vol.11, No. 2, April-June 1997.

[4] P. DiMarco, W. Grassi, *Pool Film Boiling Experiments on a Wire in Low gravity: Preliminary Results*, Proceedings of the Microgravity Transport Processes in Fluids, Thermal, Biological and Material Sciences, Banff, Alberta, Canada, September 30 to October 5, 2001.

[5] J. Kim, J. F. Benton, D. Wisniewski, *Pool Boiling Heat Transfer on Small Heaters: Effect of Gravity and Subcooling*, IJHMT, 2002.

[6] D. T. Westheimer & G. P. Peterson, *Visualization of Flow Boiling in an Annular Heat Exchanger Under Microgravity Conditions*, Journal of Thermophysics and Heat Transfer, Vol.15, No. 3, July-September 2001.

[7] Y. Ma, J.N. Chung, *An Experimental Study of Critical Heat Flux in Microgravity Forced-Convection Boiling*, Int. Journal of Multiphase Flow 27, pp. 1753-1767, 2001.

[8] O. Kawanami, T. Hiejima, H. Azuma, H. Ohta, *Experimental Study of Boiling Phenomenon for the Transfer of Cryogenic Liquid under Different Gravity*, Jpn. Soc. Microgravity Appl. Vol. 18, Supplement, 2001.