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Atomization chill-down demonstrator for the next generation cryogenic rocket engines: experiments and first results

Duri Davide, Kreit Patrick[§], Bozet Jean-Luc[§], Le Martelot Sebastien[†]*
[*] ArianeGroup,
BP806 Forêt de Vernon – BP806, 27207 Vernon, davide.duri@ariane.group
[§] ULG,
Site cryotechnique ESA B17b, quartier des Urbanistes 2, B4000 Sart Tilmann,
p.kreit@uliege.be, jlbozet@uliege.be
[†] CNES, Direction des Lanceurs - DLA/SDT/EPM,
52 rue Jacques Hillairet, 75612 Paris Cedex, sebastien.lemartelot@cnes.fr

Abstract
This paper describes the results of the cryogenic demonstration of an innovative technique to chill-down the turbopumps of a rocket engine as part of an endeavour to optimize the performance of the thermal conditioning phase as long as contributing to the launcher propellant load management in order to increase the payload capacity. By combining the state-of-the-art ALM metal powder printing for rapid prototyping with the highest heat transfer rates achievable from the boiling impinging two-phase spray cooling, we developed, manufactured and tested a fully integrated demonstrator simulating a cryogenic turbopump housing. This demonstrator was used to validate experimentally the performance of the novel chill-down method under representative thermal conditions for the next generation cryogenic rocket engines.

1. Introduction

The constant quest for the optimization of a rocket launcher performance in terms of payload requires the efficient use of the propellant to reduce the initial reserve tankage load and the end-of-flight residuals. Within this framework the reduction of the non-propulsive propellant load carried in the launcher tanks and allocated for the thermal conditioning of the cryogenic propulsive system (in what is normally called the "chill-down phase") can lead to substantial mass savings and payload gains especially for a versatile cryogenic upper stage capable of multiple engine re-ignitions for maximum mission flexibility.

The chill-down is mandatory prior to any rocket engine start-up as the propellant feeding lines, the turbo-pumps and their bearings must be properly preconditioned and cooled down to the specific temperature criteria within a predetermined duration in order to assure a reliable and reproducible start-up transient. Liquid sub-cooled fluid shall be assured at the pumps interfaces and chamber feed valves. Considering that the propellant used to cool down the engine is carried on-board but is normally dumped overboard during the process, therefore not contributing to the launcher final velocity increment (ΔV), a high efficiency of the chill-down is paramount to reduce this load penalty in favour of the payload. The cooling sequence must be optimized to achieve the minimum consumption of propellants within the established duration and temperature criteria whilst taking into account every extreme external boundary and functional condition scattering and the physics of boiling heat transfer.

The thermal conditioning process involves complex unsteady two-phase cryogenic flow due to the low boiling point of the propellants. The complexity of the problem results from the non-linear interaction of the fluid dynamics and heat transfer during the liquid-to-vapour phase-change which evolves temporally and spatially throughout the circuit depending on the temperature difference between the fluid saturation temperature and the wall temperature as presented by the boiling curve in figure 1 (left). These phenomena are inherently unstable and can lead to extreme flow and pressure fluctuations. The flight hardware may also be subject to mechanical stresses due to thermal differential contraction. The initial phase of chill-down is dominated by the massive evaporation of the cryogens. As the system cools down, slugs of liquid entrained by the gas stream, flow through the system in a two-phase film boiling mode followed by the propagation of the liquid quenching front accompanied by nucleate boiling until the sub-cooling

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temperature is reached. The limiting factor contributing to the overall propellant consumption and cooling duration is the film boiling regime which is characterized by the lowest heat transfer rates as the liquid is separated from the wall by a thin vapour layer acting as an insulator [3].

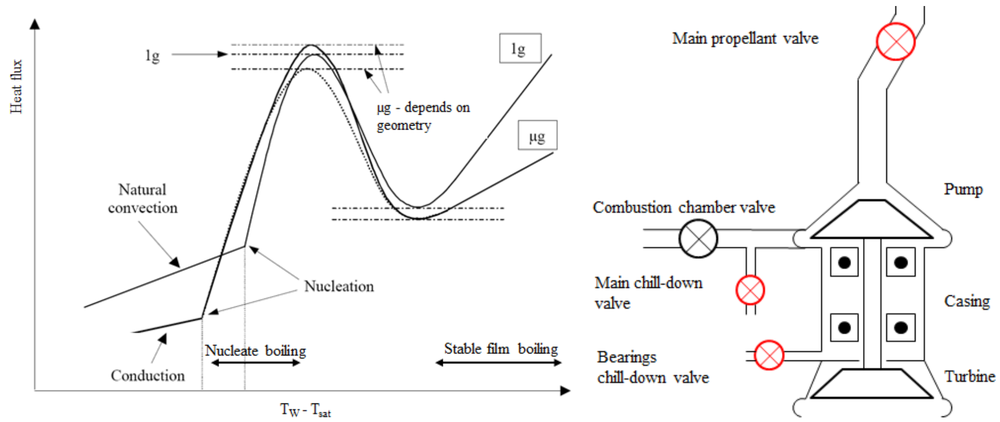

Figure 1: Boiling curve under 1-g and µ-g conditions presenting the heat flux as a function of the wall to saturation temperature difference (left) and cryogenic turbopump classic chill-down architecture (right)

Such poor cooling performance are worsened under low acceleration levels as the surface tension and capillarity forces become relevant with respect to the inertial contribution of the mass flow rate. The reduced gravity condition strongly changes the flow patterns (with respect to the 1-g gravity level) and accordingly affects the heat transfer rate. Boiling and two-phase flow behave differently when the gravity levels vary, leading to a significant reduction in heat exchange and therefore to a less efficient chill-down process with higher consumption and longer cool down durations [2].

2. The state of the art

The design of the chill-down architecture and the methodologies are the result of trade-off between the launcher architecture, the flight performance and constraints. Its optimization shall consider the scattering and uncertainties associated with the boundary conditions (tank pressure, heat fluxes etc.) and the heat transfer rates (µ-g vs 1-g effects). Several flight-worthy methods have been developed in the past to overcome these difficulties. Such methods are:

- Full flush and trickle flow chill-down,
- Pulsed flow,
- Charge-hold-and vent chill-down (CHV),
- No-bleed chill-down,
- Two-phase thermosiphon,
- Recirculating pumps,
- Ground chill-down.

The simplest chill-down method is the full flush that uses the turbopumps secondary circuit internal flow paths fitted with dedicated bearing chill-down valve (figure 1 – right) to let the propellant drain from the launcher tanks to the inner parts of the turbopumps. The mass flowrate is therefore obtained by the pressure gradient established between the tanks and the external vacuum and metered by calibrating orifices. Such method implies high mass flow rate and unacceptable propellant consumption whereas its alternative, called the “trickle down” chill-down, by letting a constant low mass flow rate trickle of propellant through the feed lines, allows for a better propellant mass flow rate management by taking full advantage of the latent heat of vaporization but at a price of a longer duration to reach the functional temperature criteria. Normally the full flush method is applied on the booster stage engines during the ground hold down sequence. The STS Shuttle orbiter, for example, during ground hold prior to the lift off maintains a constant bleed of 2.4 kg/s of liquid oxygen which is vented overboard through a flight-rated valve.

The trickle down method is more suited for upper stages thermal conditioning. Standard propulsion system architecture modifications to implement the trickle down method requires the implementation of an additional purge valve coupled with a calibrating orifice to meter the reduced mass flow rate to a lower bound limited by the microgravity-induced effects on the heat transfer rates. Such technique has been extensively studied with liquid oxygen and tested under 1-g and microgravity acceleration conditions by means of sounding rockets experiments within the framework of the H-IIA/LE-5A upper stage propulsion system upgrade [20].

The pulse flow method consists in cycling the main propellant valve with the purge valve being maintained open. Slugs of liquid propellant are forced by the pressure gradient between the tank and the external pressure at regular time intervals. Comparative experiments have been carried out in LH2 [11] on a vertical channel representing a cryogenic transfer line demonstrating the advantages of such technique with respect to the trickle down method as lower consumptions were obtained. The results showed the possibility to optimize either the consumption or the chill-down duration by choosing the appropriate valve duty cycle to achieve the steady state temperature conditions depending on the mission constraints. The main disadvantages are associated with the reduction of the flight-rated valve lifespan due to the repeated cycling and the intrinsic complexity in predicting the actuation frequency in order to achieve the required efficiency.

The charge-hold-and vent chill-down (CHV) technique is aimed at taking advantage of the latent heat of vaporization of the cryogenic propellant by aiming at the complete vaporization of small quantities of propellant trapped within the feed lines and the turbopumps. Slugs of liquid are introduced into the lines by opening the main propellant valve (MPV) and the purge valve (PV) valves. Then both MPV and PV are closed to hold the slug until the pressure in the volume exceeds a predetermined value. At this point the PV valve is opened to vent the cavity and the process is repeated. This technique allows an efficient use of the propellant latent heat and it consumes the least amount of propellant consumptions but it requires additional sensors (with redundancy) to monitor the pressure evolution and the valve opening logic and introduced risks of over-pressurization in the event of a PV failure to open [11].

The no-bleed chill-down relies on the natural convection and pool boiling of the propellant filling and cooling the drain lines by opening only the feed valve. This technique is attractive as it involves no moving part or additional flight-rated component the flow phenomenology is intrinsically tri-dimensional and difficult to predict reliably by means of numerical tools without extensive experimental and code anchoring efforts. Such setup is also prone to the onset of unsteady geysering which introduces complex flow management techniques and requires the careful handling of the launcher tank loading procedure [9][10]. This technique is limited to ground chill-down sequence for the booster engines or during high acceleration flight phases as the counter-flow between the vapor phase rising towards the tank and the liquid phase is driven by the gravity field.

The two-phase thermosiphon method improves the no-bleed method by introducing a secondary un-insulated recirculation line which provides a direct path for the venting of the vapor phase. With this architecture an open-loop thermosiphon is established thus reducing the risks of geysering by enhancing the natural circulation of the propellant liquid phase towards the engine. As for the no-bleed chill-down method, the two-phase thermosiphon works thanks to the gravity field and cannot be used during the upper stage ballistic phase [7].

Active chill-down architectures rely on electrically driven canned or submerged pumps and dedicated valves to control the mass flow rate and the routing of the propellant in order to optimize the cooling. On the Saturn S-IVB upper stage equipped with the Rocketdyne J-2 engine prior to the start-up sequence the chill-down sequence was performed using two independently actuated electric a-c centrifugal pumps to recirculate liquid oxygen and liquid hydrogen propellant from the tanks through the feed lines to the turbopumps and back to the main tank. Closed loop circuits allow some propellant savings even if during the initial chill-down stages the vapor and saturated liquid propellant is mixed with the subcooled propellant potentially increasing the thermal residuals. De-stratification of the propellant layers shall also be taken into account. A sound fitting of horizontally oriented diffusers at the circuit outlet is sufficient to prevent such problems as demonstrated in the post-flight analysis [19] of the AS-203 Saturn V mission during which the closed-loop system was repeatedly tested under microgravity conditions. It shall be stressed out that nevertheless an adequate acceleration level must be assured by the reaction control system (RCS) secondary propulsion system in order to settle the propellant at the tank bottom to prime the recirculating chill-down pumps. The STS Space Shuttle also used a LH2 recirculation pumps for the liquid hydrogen SSME fuel pump chill-down before the lift-off [7].

The ground assisted chill-down is a one-of-a kind method which has been extensively used on the Pratt&Whitney RL-10 expander rocket engine turbopumps on the Centaur upper stage by means of liquid helium (LHe) supplied to the launcher from a dedicated ground circuit prior to the lift off [18]. The pressurized liquid helium is supplied from a dewar to the RL-10 turbopump through a dedicated umbilical on the launch pad. The helium circulating through the turbopump casing it then vented overboard. Neither the cool-down duration nor the quantity of helium consumed were the constraining factors in the early stages of the Centaur development. The only cooldown constraints are that the fuel pump must be maintained below 35 K, and the LOX pump must be below 150 K for the last five minutes before launch. Helium flow is stopped about eight seconds before launch, and no cooling is provided during the boost phase. The period before launch after the helium flow is stopped and the time during the boost phase of the mission amounts to approximately 250 seconds, during which time the pumps warm slightly to about 65 K on the fuel side, and 140 K on

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the oxidizer side. Immediately after staging, the engine inlet valves are opened (known as prestart), and propellants are allowed to flow through the fuel pump for five seconds and the LOX system for nine seconds before engine start. This prestart flow consumes approximately 10 kg of oxidizer, and 3 kg of fuel per engine. Whereas such method enables a reduction in the chill-down duration of approximately 75% resulting in an increase in payload capacity by 23 kg, several drawbacks are identified [1]. The handling of significant quantities of expensive liquid helium to maintain the temperature criteria within the pre-launch bounds requires complex (and costly) ground equipment. An adequate LHe supply shall be available to assure the preconditioning during the entire launch window.

Dedicated interfaces with the rocket launcher on the launch pad shall be added (check valves and quick disconnect valves on the break-away side of the airborne disconnect as long as on the umbilical ground section) increasing the complexity of the system. The effectiveness of this techniques applies only for the chill-down of the upper stage engine prior to the first boost flight phase as the multiple re-ignition capability of versatile upper stages requires ad-hoc chill-down sequences thus reducing the global effectiveness of the ground thermal conditioning. This method can be nevertheless useful if the duration criteria for the in-flight conditioning during the first boost phase cannot be met. Some of the above mentioned disadvantages can be offset by the use of liquid or gaseous nitrogen to perform the chill-down of the booster engines.

3. Spray chill-down

Experience in the selection, design and sizing of the chill-down has shown that several factors shall be compounded such as the architecture mass (from valves, batteries etc.), recurring costs, reliability and availability of the single-point failure components and intrinsic uncertainties in the heat transfer process. From mission-to-mission various factors such as tank pressure, initial thermal gradient, heat fluxes and launcher staging duration can combine to create variations in the boundary conditions affecting the chill-down during the launcher flight. In order to cope with the scattering of the control parameters current practice is to bound the expected variation of the boundary conditions with 3σ maximum and minimum levels of heating, where σ is the standard deviation derived from the flight heating data, numerical thermal models and knowledge-based assumptions. Since these combined factors often lead to unacceptable high propellant tankage loads to satisfy the mission objectives we investigated a broad range of innovative cryogenic cooling solutions to reach for a tenth-fold increase in the heat transfer rate while demanding a high degree of functional integration within the propulsion system.

The two-phase spray impinging cooling technique was selected as the most promising solution to obtain spatially and temporally localized cooling of the turbopumps bearings and housing. By forcing a propellant spray stream to impinge a targeted surface we were able to combine the boiling and phase change heat removal of the cryogenic fluid with the inertial forcing of the flow stream thus eliminating the loss of efficiency induced by the low gravity acceleration levels typical of the upper stage ballistic flight phases. By taking advantage of the liquid high latent heat, liquid impingement spray cooling has already demonstrated to be an effective way of removing high heat power from surfaces, requiring only a small surface superheat as well as low mass flow rate, which are essential requirements for a compact cooling system design [15]. Spray cooling is widely used in various fields: fire protection, thermal protection of hypersonic reentry vehicles nosecones [12], high power laser diodes [13], quenching and heat-treatment of metal components [17] and high performance electronic devices [16]. The heat transfer mechanisms occurring in a spray cooling process basically combines all the two-phase heat transfer mechanisms that contribute to its high heat removal rate and the combination and interference of these mechanisms make the spray cooling unique compared to other conventional cooling methods such as forced convection. Such performance allows for the reduction of the upper stage tankage load by a combination of cooling duration reduction and the minimization of the uncertainties on the microgravity heat transfer rate.

In order to achieve the complete functional integration with the turbomachinery components the spray orifices and the distribution manifold were manufactured directly within the turbomachinery stator housing using the additive layer manufacturing techniques (ALM) to simplify the process and to reduce costs [8].

3.1 The spray chill-down demonstrator

Given the complex nature of the spray cooling and the novelty of the technique we decided to first demonstrate the feasibility by directly performing a proof-of-concept demonstration aimed at the following test objectives:
1) To validate the manufacturing feasibility of the integrated manifolds and the injection orifices,
2) To perform cryogenic spray chill-down experiments under realistic thermal and functional boundary conditions,
3) To quantify the performance of the spray chill-down with respect to the standard full-flush method.

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A fully integrated atomization chill-down demonstrator was designed and manufactured by taking full advantage of the Ariane Group in-house ALM manufacturing capabilities as long as standard manufacturing techniques and off-the shelf components to achieve a quick prototyping-to-test turnaround time interval while assuring a geometrical and size coherence with the next generation high performance turbo pumps. The demonstrator was designed around a decommissioned hydrogen turbopump ball bearing which was selected as the target to be cooled down. The design loops after three iterations led to the final configuration which consisted in two parts: a lower assembly and an upper assembly.

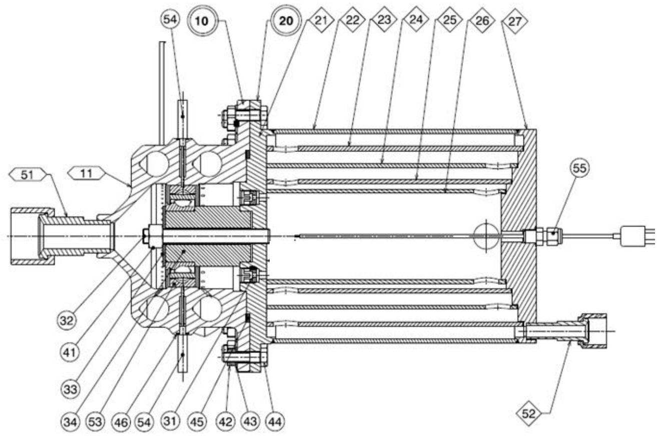

Figure 2: Cutaway of the spray chill-down demonstrator (labels are included in the text)

The lower assembly (component 10 in figure 2) is designed to house the spray orifices oriented against the ball bearing (53). Manufactured using an EOS290 ALM printer using Inconel 718 in Vernon it consists in two independent annular manifolds which allows feeding two rows of 23 and 53 orifices, 2 mm and 1 mm in diameter, respectively. The liquid oxygen is supplied to each manifold by a welded ½' Swagelock™ VCR fitting and it is evacuated either through a 1' Swagelock™ VCR fitting at the bottom (51) or through the upper component. Interfaces are provided in each manifold to install thermocouples measuring the liquid temperature. Two additional interfaces are available to install thermocouples measuring the ball bearing outer racetrack temperature during the chill-down. For this purpose two Kayme™ type K thermocouples with spring-loaded sensing element (to assure the contact with the bearing racetrack across the entire temperature range regardless of the thermal contraction at cryogenic temperatures) were installed (54). The component was manufactured according to the dimensional specification and after the cleaning procedure it passed the non-destructive inspection where only one orifice was detected as obstructed. Such event was foreseen and adequate redundancy of the spray stream pattern was assured by the number of orifices.

The upper assembly (20) was designed from standard 304L stainless steel flanges (21 and 27) and rolled plates (22 - 26) to represent in terms of mass and surface the turbopump inlet walls while reducing the manufacturing costs. A flange with a Teflon-plated C-ring seal (45) provided the interface with the lower part and a makeshift turbopump cantilevered shaft (32 - 34) holding the ball bearing. Two fluidic interfaces were fitted to allow the circulation of the liquid cryogenic flow during the chill-down sequences: a standard Swagelock™ VCR fitting at the top (52) and 6 calibrating orifices 1 mm in diameter (31) simulating the cross section of the flow path within the turbopump secondary circuit. These orifices were screwed to allow for changes in the internal flow-path layout according to the test plan. A thermocouple (55) is installed to measure the filling of the upper part.

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Figure 3: Lower assembly after the ALM-manufacturing process (left) and assembled demonstrator (right) undergoing a standard full-flush chill-down test sequence (right)

Once assembled the demonstrator was completed by a by-pass line and additional calibrating orifices simulating the generic turbopump internal layout of the secondary flow forming the escape pathway for dumping the vapor phase during the cooling. The assembled demonstrator is presented in figure 3 (right) where it can be seen undergoing a full-flush chill-down sequence. No thermal insulation was added to the external surfaces of the demonstrator.

3.2 Experimental facility

The chill-down test campaign were carried out at the cryogenic ULG University test site in Liège (Belgium) taking advantage of the laboratory know-how on handling of pressurized liquid oxygen. The ULG test team was also in charge of supervising the final assembly of the demonstrator lower part fluid interfaces as long as the manufacturing responsibility of the upper component. The team also supervised the final mechanical integration of all the fluidic interfaces, the sensor fitting and the final check-out prior to the test campaign.

The chill-down demonstrator was installed within the existing test facility complex which provided the pressurized liquid oxygen at the prescribed temperature (87 K to 90 K) and pressure (4 to 6 bar) ranges specified by Ariane Group. The final experimental setup, which is presented in figure 4, consisted in the demonstrator and the supporting facility required for remotely handling the pressurized LOx.

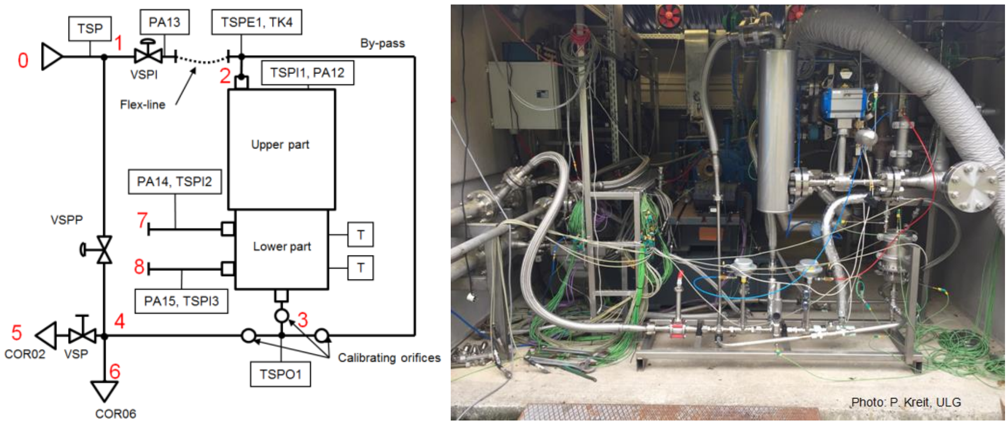

Figure 4: layout of the experimental setup (left) and view of the ULG facility (right). Legend included in the text.

The demonstrator was connected to the test bench through a dedicated feedline (points 0 – 1 in figure 4) and bench chill-down valves (VSPP and VSP). Three interfaces to the demonstrator were available (2, 7 and 7 corresponding to the upper part inlet and the upper and the lower manifolds respectively) to which a flexible line was connected according to the test plan. When the spray tests were performed the specific manifold was selected by connecting its port to the ULG facility by means of a flexible cryogenic piping. Taps were installed when an interface was not used. The liquid oxygen was vented through the circuit point 3 down to the dump trench trough the Coriolis mass flow meter. Additional instrumentation was integrated to the demonstrator and its bench to complete the existing array. The additional sensors consists of 5 type K thermocouples calibrated over the 300 K – 77 K temperature range (uncertainty

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of +/-2 K at 1σ on the full scale, named TSPIx where x is an incremental number), two Coriolis mass flow meters (a CMF200 and a CMF100 with a mass flow range of 0-4.5 kg/s and 0-3 kg/s, respectively) to measure the spray injection mass flow rate and Keller absolute pressure transducers (0-60 bar full range with an uncertainty of +/-0.05 bar) positioned at each interface of the manifolds and at the venting outlet (sensors named PAx in figure 4).

The measured data was digitally acquired and stored at a frequency of 10 Hz and included the test facility status as well as the pneumatically-activated valves position to assure the repeatability and consistency of the different chill-down sequences. The real time data was monitored from the facility control room in order to regulate the injection pressure within the prescribed test corridor especially during the initial phases of the chill-down when high pressure spikes are normally expected due to the flash evaporation of the cryogenic coolant.

3.3 Test sequence and test parameters

During the demonstration program 10 experimental chill-down sequences have been tested in order to vary the design parameters and their range. An initial full flush chill-down sequence test was conducted with the goal of establishing a comparison with respect to the spray chill-down method. For such purpose the LOx feed line temperature was set at 89 K+/-2 K with an injection pressure of 4 bar. Six tests were devoted to the exploration of the performance and the efficiency of the spray chill-down method by increasing the pressure (up to 6 bar) and the orifices type while 3 tests focused on the effect of the ground configuration (internal vapor pathway, orientation etc.) upon the liquid-vapor phase separation and the cooling of the upper part as long as the internal calibrating sections on the pressure spike occurrence. Each test started at ambient temperature (approximately 300 K) with the opening of the injection valve VSPI (see figure 4-left) until a complete thermal steady state was reached on all thermocouple readings. The modularity of the facility and the test set-up allowed for short turnaround time to reconfigure the demonstrator according to the test plan and to perform more than 2 tests per week.

4. Results

The preliminary results from the full flush reference test and the spray chill-down method carried out at the same injection pressure (4 bar) are presented in figure (5) which shows the temporal evolution of the ball bearing outer racetrack temperature, the temperature of the makeshift inlet in the upper assembly (TK4 in figure 4 - left), the manifold internal temperatures and the mass flow rate. The propellant temperature evolution inside each manifold is also measured to assess the duration of the filling of these cavities. To perform a quantitative comparison of the results given the difference in flow topology between the spray vs full-flush configurations we defined 3 temperature criteria (set arbitrarily at 95 K) to be met with a 3/3 logic: the 2 ball bearing racetrack temperatures and the inlet volute temperature.

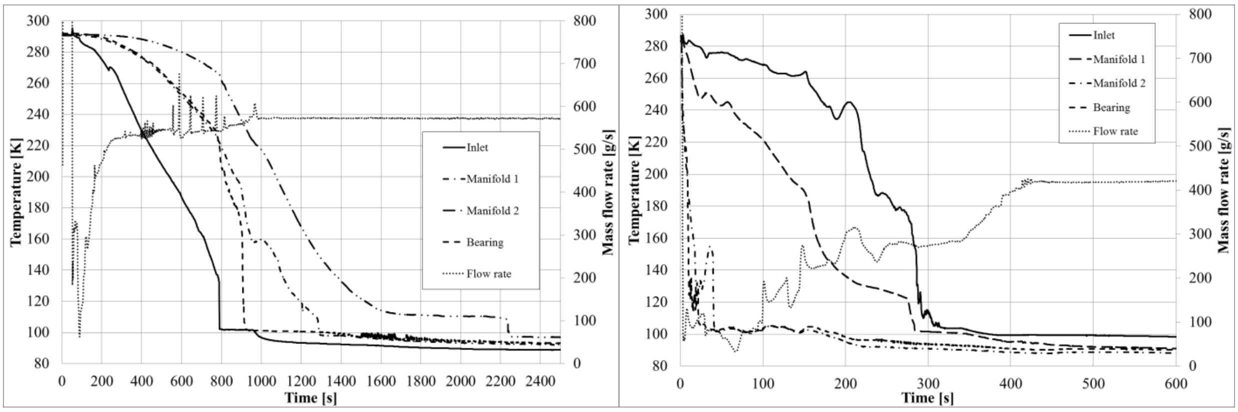

Figure 5: Temperature and mass flow rate temporal evolution during the standard full-flush chill-down (left) and during the spray chill-down (right).

In each case the initial temperature of the demonstrator is 280 K and the cooling process starts at t=0 s by opening the VSPI valve. On the reference chill-down case (figure 5 – left) we can observe the slow cooling rate of the order of -0.5 K/s which is the result of the film boiling heat transfer regime occurring within a wall temperature interval between 280 K and 130 K. A sudden drop of the temperature occurring at 900 s corresponds to the signature of the transition from the film boiling regime to the more efficient nucleate boiling regime once the wall temperature reaches the Leidenfrost temperature of the oxygen. All the temperature criteria are met within 1500 s while the propellant total

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consumption is of the order of 900 kg. As a result of the film boiling heat transfer rate, the liquid flow rate surrounded by a vapor blanket reaches an almost steady state value of 550 - 600 g/s in only 250 seconds hence leading to such high final propellant consumption.

The spray chill-down method allows for a better and faster cooling as illustrated in figure 5 (right). The ball bearing criteria are met in only 50 s while the inlet criteria is met in approximately 400 s after the beginning of the sequence resulting in a cumulative propellant consumption of only 160 kg due to the combination of high cooling rate and limited steady state mass flow rate of 400 g/s. The performance of the spray cooling can be examined by considering the boiling curve for each test configuration (under the assumption of a negligible thermal resistivity within the ball bearing racetrack corresponding to a characteristic Biot number Bi=hL/k<<1 where h is the heat transfer coefficient, L a characteristic length scale and k the thermal conductivity). As the wall temperature history is measured by using the heat balance equation (1):

$$\frac{Q}{A} = \frac{mC(T)}{A}\frac{dT}{dt} \tag{1}$$

where m is the bearing racetrack mass, A is the reference surface and C(T) is the temperature-dependent specific heat of the Inconel 718, it is possible to calculate the instantaneous heat flux per unit area Q/A. The figure 6 (left) presents the evolution of the heat flux Q/A as a function of time for the reference chill-down case showing the peak heat fluxes corresponding to the transition from the film to the nucleate boiling regimes in good agreement with the available literature [3]. The Biot number evaluated for the flush and the spray chill-down sequences is estimated at 0.026 and 0.23, respectively thus validating the initial hypothesis. By plotting the heat flux as a function of the wall temperature we can compare the two-phase boiling curve (figure 6 - right) of the reference flush chill-down with respect to the spray chill-down showing the performance enhancement granted by the spray cooling over the standard inertial forcing technique.

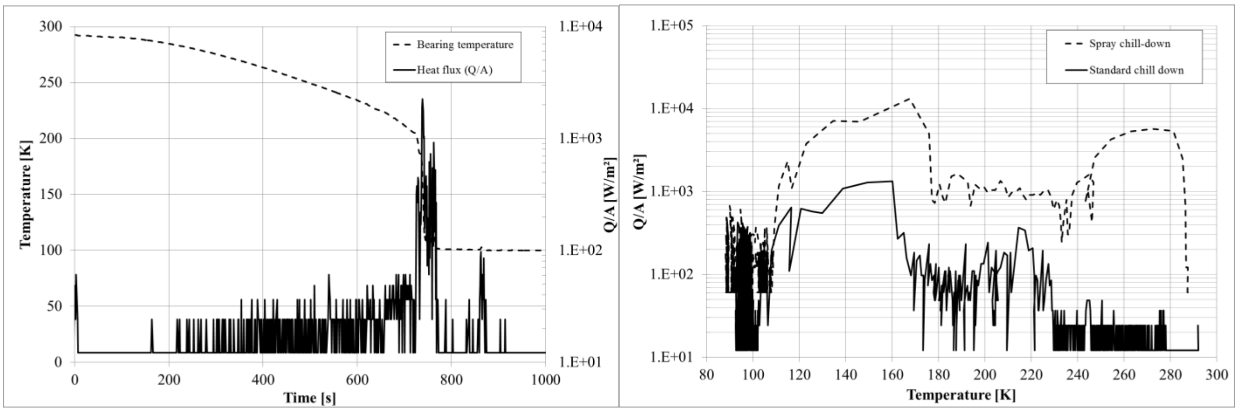

Figure 6: Ball bearing temperature and heat flux temporal evolution (left) and comparison of the boiling curves as a function of the chill-down methodology (right).

Considering the 300 K to 240 K temperature range which corresponds to the stable film boiling regime the heat flux is increased by the two-phase spray by almost 3 orders of magnitude whereas in the 240 K to 130 K temperature range one order of magnitude increase is observed. The former effect is attributed to the impinging cooling of the high pressure high velocity oxygen gaseous phase generated by the chill-down of the manifolds while the latter is attributed either to the result of the phase change boiling transfer from the two-phase flow impinging the bearing surface or the reduction in heat transfer induced by the flooding of the bearing cavity. Under such conditions the flow assumes a submerged jet configuration [21]. At lower wall temperatures the nucleate boiling is detected even if the temporal resolution is insufficient.

5. Conclusions and further developments

The first experimental campaign of the integrated spray chill-down system was carried out successfully at the ULG test site with the accomplishment of all technical objectives showing the potential of the cooling concept in reducing the chill-down duration and consumption with respect to a standard thermal conditioning method. The successful manufacturing of the first ALM housing prototype with fully integrated manifolds and orifices allowed identifying the manufacturing, cleaning and inspection procedures to meet the flightworthy hardware requirements and industrial processes. The preliminary experimental results under fully representative cryogenic conditions showed the several order of magnitude increases in the heat transfer coefficient that will be implemented in the numerical chill-down models [4] for further sizing and thermomechanical analysis. Further efforts will be focused on the integration of the spray system at first within a cryogenic turbopump assembly and secondly within a complete propulsion system associated with the flight mission analysis and the industrial cost analysis. Particular attention will be devoted to the interaction between cavities in the closely-packed turbopump housing and the associated structural and thermal interaction as long as the pressurized supply system trade-off at upper stage/launcher level that is required for controlling the mass flow rate and the pressure of the injected propellant.

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