DOI: 10.13009/EUCASS2022-4643

Experimental study on the effect of cryogenic two-phase flow inlet conditions on the suction capacity of a high speed centrifugal pump equipped with an inducer: first results on saturated pure liquid and GHe/LN2 mixtures

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Abstract

The development and operation of cryogenic liquid propulsion systems for launcher upper stages may be considered as a pinnacle of technical complexity arising from challenging performance requirements, cryogenic propellant management and microgravity conditions. To such endeavour the physics and the phenomena involved in operating the upper stage pumps under variable flow conditions and for longer durations have to be considered, mastered and reliably controlled in order to assure the success of the mission. Within this framework fundamental research activities are carried out by ArianeGroup, CNES at AREELIS Technologies™ and focused on the suction capacity of high speed centrifugal pumps with non-null void of fraction at the inlet. Experiments carried out by injecting a finite amount of non-condensable helium are performed in order to identify the different behaviour induced by the accumulation of the non-condensable phase within the pressure and velocity field of the pump elements. Qualitative comparison of the results with available references and futures experimental perspectives and opportunities are presented.

1. Introduction

High performance cryogenic propulsion systems typically used in launcher upper stages which handle low boiling fluids such as oxygen, methane and hydrogen normally require the use of high speed centrifugal pumps with low net positive suction head requirements in conjunction with pressurized tanks. Pressurization gas mass requirements and margins with respect to the tanks stratification and saturated flow handling are also included in the functional design process contributing to assure a smooth pump behaviour in the entire flight domain. New trends in cryogenic proposition systems flexibility and applications both for space applications and earth-bound applications (i.e. for cryogenically stored liquid hydrogen powered low emission aircrafts and ships) require the development of pumping systems capable to handle a broader range of inlet conditions imposed by the operational constraints and margin-reduction policies for increased efficiency.

To such extent the so-called “zero-tank NPSP” handling capabilities may be required thus leading to the design, development and testing of pumps working with inlet saturated conditions hence with non-null void of fraction inlet flows as long with the presence of non-condensable gas bubbles which may be present. In order to contribute to the fundamental understanding of these issues and to contribute to the design, verification and validation process of high performance centrifugal pumps a dedicated experimental test campaign has been carried out by ArianeGroup and CNES at AREELIS Technologies™ in liquid nitrogen. A specific test setup has been integrated, coupling a state-of-the art centrifugal pump equipped with an inducer and an unshrouded impeller with an in-line, low disturbance and high dynamic response void of fraction capacitive sensor at the inlet, to measure the effect of a broad range of inlet conditions under repeatable testing conditions.

This article is structured as follows: at first an overview is presented concerning the problem of operating a centrifugal pump under non-null inlet void of fraction complemented by the state-of-the art analysis which led to the test campaign.

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Secondly the experimental cryogenic setup layout is presented and detailed as long as the void of fraction measurement system and calibration procedure. Finally the preliminary results obtained with pure liquid nitrogen flow at subcooled and saturated inlet conditions as long as by injecting non-condensable helium are presented and discussed.

2. On the two phase suction capability problem

The suction capacity of a pump refers to the net positive suction head margin with respect to the loss of pressure head (or an admissible percentage degradation with respect to the nominal head) due to the cavitation phenomena occurring at the inducer and/or in the downstream elements such as the impeller, this latter case leading to the flow blockage. Historically, the net positive suction head (NPSH) requirements of rocket propellant pumps have been steadily reduced by mean of CFD modeling and experiments to improve the launcher performance. This improvement was focused at lowering the vehicle structural dry mass resulting from the reduction of the tank operating pressures and wall thickness down to the asymptotic limit of NPSH reduction which is the condition in which the NPSH is equal to the fluid velocity head. At this condition a regime is entered in which the inlet pressure is equal to the fluid saturation pressure and two-phase flow (liquid, gas) will exist at the pump inlet.

The analysis of the suction capacity under saturated conditions requires some initial definition in order to discriminate between the different thermodynamic states of the propellant and the operational conditions in flight. We examine the phenomenology of the centrifugal pump behavior considering the following thermodynamic conditions of a cryogenic propellant at the tank outlet once the temperature (T) and pressure (P) are known.
The two-phase pure saturated flow in such case consists of a flow of saturated liquid and saturated vapor with volume fractions (or void of fraction -VF) ranging from 0 to 1 (100% liquid to 100% vapor). As one thermodynamic variable is redundant as T=T_sat(P) and conversely P=P_sat(T) the exact value of the void of fraction can be known only by measurement or by knowing the initial condition and the path followed by the fluid (assuming a constant enthalpy process) through pressure reduction devices such screens and/or heating elements. This is typically the case for liquid hydrogen upper stage tanks when during propellant positioning before firing and thermal management operations are carried out in flight. Such latter case normally involves the depressurization of the tank in order to cool the propellant to the Tsat(P) value targeted.

Additional complexity arise when non-pure cases are considered. The use of GHe pressuring gas to provide a positive NPSH in the launcher liquid oxygen (LOX) tanks imply the necessity to consider the absorption and desorption of the non-condensable GHe in the propellant bulk and/or the presence of GHe bubbles mixed with the propellant. The non-condensable gas bubbles can be either mixed with the single phase propellant or with the two phase propellant. As the treatment of the GHe absorption/desorption process is too complex and besides the scope of this analysis we focus our inquiry only on the matter of a mass flow rate of GHe in the form of clouds of bubbles mixed with the propellant in the attempt of mimicking the void of fraction effect on the pump suction performance induced by a pure fluid two phase flow. This cloud, assumed at thermal equilibrium is advected towards the pump inlet by the main bulk flow [R1, R2].

The operations under two-phase flow conditions at the inducer inlet are a longstanding topic with widespread applications not only confined within the astronautical engineering realm but to all industrial processes where the low boiling fluids are involved or saturated flow conditions may be reached and high suction capabilities are required. Seminal analysis and reports can be traced back to the 60’ and 70’ when experimental and theoretical analysis were carried out (see [R3] and [R4]) to evaluate the vapor- to mixture-volume ratio present in the inlet line to a pump when the fluid is pumped at or near zero net positive suction head. One-dimensional flow, thermodynamic equilibrium, and a homogeneous mixture of liquid and vapor were assumed to exist in the pump inlet line and analytical results were compared with those obtained from experimental studies in liquid hydrogen using a "workhorse" pump to generate flow in the test annulus. The vapor- to mixture-volume ratio in the inlet line upstream of an inducer can be calculated using a heat balance and one-dimensional flow relations under the assumption of thermodynamic equilibrium and a homogeneous mixture of liquid and vapor. Similarly, the velocity of the liquid-vapor mixture and the static pressure in the inlet annulus were estimated if the static pressure in the inlet line is assumed equal to the local vapor pressure. The volume ratio can also be evaluated experimentally from measurements of the static pressure in the inlet annulus.
Additional experimental data are available for a certain number of centrifugal pumps from NASA programs devoted to the reduction of the NPSP margins as long as to reach the “zero tank-NPSP” start-up capabilities. Data from the J-2 upper stage engine fuel and oxidizer turbopumps (Mark 15, Mark 29 and Mark 25) were tested in LH2, LOx and water with specific experimental setups and post-processing methodologies to correlate the inducer performance to the inlet void of fraction.

The Mark 15 LH2 pump was tested in two-phase hydrogen at Rocketdyne under the J-2X engine program. Two-phase hydrogen was generated by a Frantz screen (meshed screen introducing localized pressure losses) that was installed

upstream of the pump inlet. The vapor fractions were determined from measurements of pressure and temperature in the pure liquid upstream of the screen and in the two-phase fluid downstream of the screen. Assuming a constant enthalpy process in thermal equilibrium the void of fraction was inferred at each testing point but never measured. It shall be noted that the pressure drop screen has been positioned far upstream with respect to the inlet diameter in order to avoid any interaction between the recirculation structures of the inducer
Rocketdyne's Mark 25 hydrogen pump was tested in two-phase hydrogen. The method used to generate and measure vapor at the pump inlet was similar to that used in the previously discussed Mark 15 LH2 pump two-phase hydrogen testing. The model Mark 29 LH2 inducer was tested in water at Rocketdyne under the J-2s engine program. No pump inlet vapor fractions were obtained because these were standard cavitation tests (hence not aimed at zero-tank NSPS) and the test fluid was water. However, the wide range of flow coefficient over which this inducer was tested provided data on the effects of the blade blockage.

This extensive body of work was used to derive empirical correlations and design rules in order to develop, within the experimental domain of validity, inducers capable to work up to 20 or 30% of inlet void of fraction. Considering the state of the art of the computational fluid mechanics of the 70’ no correlation with experimental results were performed. More recently in [R5] an electric pump with an inducer of 60 mm in diameter and an 130 mm in diameter impeller with an outlet blade angle of 25 degree was tested in LN2 at a rotating speed of 1800 rpm. A two phase flow inducer is applied to achieve zero-NPSH. Designing the inducer, it is necessary to establish the inlet flow velocity, the peripheral velocity and the blade angles to avoid any separation of boundary layer on the blade suction surface. Pump suction performance in terms of NPSH versus pump head curve are presented in the article. This test was performed with varying the inlet valve position and LN2 level in the run tank at constant rotating speed of 1800 rpm. The authors demonstrated the performance of two phase flow inducer. The suction head was achieved at “zero tank NPSH” and two phase flow of approximately 10-25% void of fraction was recorded.

The importance in achieving almost “zero tank NPSP” and the need for a precise characterization of the pump performance under a non-null void of fraction at its inlet led to the planning and execution of a dedicated R&T AGS/CNES experimental campaign in LN2 at the AREELIS Technologies™ test facility with a centrifugal pump specifically equipped with a two-phase flow void sensor (VOF) at its inlet. During this campaign two type of tests are carried out:

- The pump performance characterization with a void of fraction generated by injecting non-condensable helium gas (GHe) in the LN2 bulk.
- The performance characterization with pure LN2 at saturation conditions. The aim is to verify the difference in behavior between the GHe-generated void of fraction and the pure saturated fluid as long as to determine the maximum inlet void of fraction acceptable by the pump under reasonable pressure head losses. Differences in behavior are expected as the GHe bubbles will behave differently within the inducer and impeller pressure field.

3. Experimental facility

The tests are carried out at the AREELIS Technologies™ taking advantage of the team know-how with respect to the development of customized cryogenic systems. The test campaign used an open loop liquid nitrogen test bench which is composed of the following elements (see Figure 1):

- Liquid nitrogen Dewars with average capacity of 450 liters with autonomous pressure control are normally used for a test run. The liquid nitrogen is delivered the day before the test and thermally conditioned during the night. As the 1st Dewar is depleted a manually operated swap is required hence variation of the temperature of the LN2 feeding the pump may be encountered due to the stratification of the liquid in the tank.
- The injection port for the pressurized helium with a mass flow meter with digital readout. The resolution is of the order of 0.1 NL/min with a maximum range of 12 NL/min. The control of the mass flow is performed with a hand-operated valve from the test facility control room. Standard B50 pressurized bottles are used of the He supply and the temperature is fairly constant at 300 K.
- The ArianeGroup high speed electrical centrifugal pump positioned vertically and protected by a thermal insulation blanket as for the other components of the installation.
- Two Coriolis mass flow meters Emerson type 55M with resolution up to 1 g/s are installed at the inlet and the outlet of the centrifugal pump.
- The inlet (outlet) temperature and pressure sensors based on two PT100 platinum resistors (with a resolution of +/-0.04 K at 77 K) and a Keller PAA-33X absolute pressure sensor (with a resolution of 0.15% on the full 0- 30 bar range).

DOI: 10.13009/EUCASS2022-4643

- A back pressure valve is operated remotely by the AREELIS Technologies™ test bench command and control system in order to change the circuit characteristics and the circulating mass flow rate. The nitrogen circulating the open loop is dumped outside to a retention pool and safely evaporated.
- Data is acquired at high (up to 50 kHz) and low frequencies (100 Hz) depending on the experimental needs by the bench digital and acquisition (DAQ) system and stored in a redundant server for data reduction and analysis. Real time data was monitored from the facility control room in order to chill-down the bench and the cryogenic pump whereas the test sequences were pre-programmed and executed automatically.

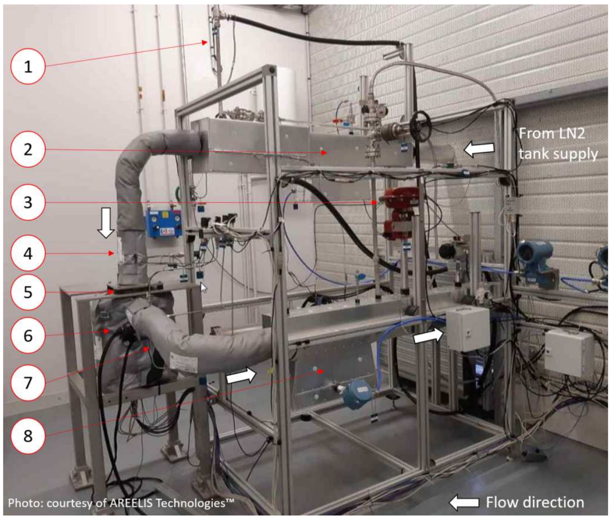

Photo: courtesy of AREELIS Technologies™

Figure 1: Liquid nitrogen open loop test facility at AREELIS Technologies™ under the thermal insulation blanket. Legend: 1) gaseous helium injection port, 2) inlet Coriolis flowmeter, 3) back-pressure valve, 4) VOF sensor, 5) pump inlet P-T sensors, 6) cryogenic electric centrifugal pump, 7) pump outlet P-T sensors, 8) outlet Coriolis flowmeter.

3.1 High speed electric pump

A high speed cryogenic centrifugal pump developed and manufactured by ArianeGroup and has been used during the entire test campaign. Driven by a brushless electric motor the pump rotor components consist of an integrated component having an integrally CNC-machined aluminum three-bladed inducer followed by a centrifugal impeller. A stainless steel casing with an integrally-machined vaneless diffuser houses the ball bearings which are qualified for cryogenic propellants and are cooled by a secondary circuit which uses the pressurized nitrogen tap-off at the diffuser. This secondary circuit may be configured to be recycled at the pump inlet or dumped overboard depending on the experimental setup. The characteristic dimensions of the order of 20 mm for the pump inlet diameter and 60 mm for the impeller. When used in liquid nitrogen the inlet mass flow rate is of the order of 100 g/s with a maximum rotational speed of 16 000 rpm and a pressure head of 8 bar (absolute). The electric motor is driven by a dedicated controller and power source working at 110 V.

3.2 Void of fraction sensor

A novelty in the test setup is the use of a cryogenic capacitive VOF (Void Of Fraction) sensor developed by ArianeGroup and positioned at the electric pump inlet (Figure 2). The sensor is composed of a stainless steel body housing three independent ring electrodes flush-mounted within the inner 29 mm in diameter, 300 mm long tube in which the liquid nitrogen flows. The sensor works by measuring as a condenser the variation of the bulk dielectric constant induced by the presence of vapor bubbles within the measurement volume (the value is averaged within the sensing zone). The electrodes are electrically insulated while the stainless steel body of the sensor acts as an electromagnetic shield and suppresses electrical noise coming from the external environment and the electric pump motor. The variations of the potential between the anode and the cathode rings are measured by a capacitance meter through a coaxial cable and recorded as 0-10 V DC signal by the test facility DAQ system.

Due to the novelty of the experimental setup the first tests were aimed at calibrating the VOF sensor electronics and output in order to take into account the variation of capacitance of the sensor electrodes. Such deviations are due (1) to the thermal shrinking of the assembly between 300 K and (2) to the liquid nitrogen dielectric constant dependence on the temperature and pressure of the liquid bulk. Whilst the first contribution is considered as negligible after verification of the sensor dry wall temperature, the latter is considered and accounted for in the data reduction procedure.

Figure 2: Void Of Fraction (VOF) capacitive sensor developed by ArianeGroup and installed at the cryogenic centrifugal pump inlet

Tests run with sub-cooling temperature of 2 K with respect to the saturation temperature at the inlet pump pressure led to the measurement of the VOF raw signal constant bias coupled with a temporal evolution of the signal inversely correlated with the inlet temperature (an example is given in figure 3). The raw data shows that the liquid fraction does not reach 100% (this is the effect of the constant bias) and that it decreases (hence some vapor bubbles are generated) despite the sub-cooling temperature being 1 K lower that the saturation temperature within the first 80 s of the test. This behavior can be understood by considering the effects of the variation of the dielectric constant of the nitrogen due to the temperature of the bulk. The liquid permittivity increases when the pressure increases or when the temperature decreases as seen in [R6, R7].

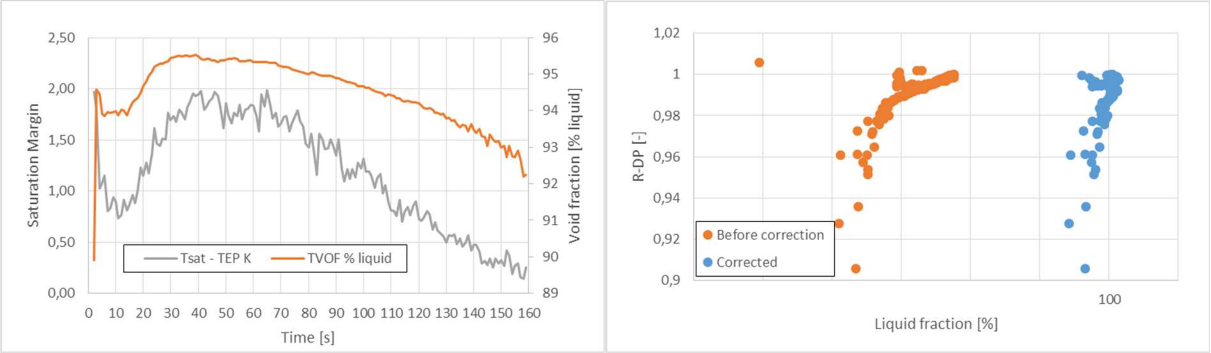

Figure 3: Temporal evolution of the void of fraction raw signal and the saturation margin in LN2 (left). Evolution of the relative pressure head (R-DP) as a function of the liquid fraction for the raw and the corrected data (right).

A correction methodology has been therefore developed for the VOF sensor data reduction to take into account the variation of the temperature of the liquid nitrogen either due to the effect of the external heat fluxes, of the thermal stratification in the LN2 tanks and the heating due to the helium mass flow rate injected at approximately 300 K (resulting at the higher mass flow rate to a temperature increase of 1 to 1.5 K). The variation of the nitrogen liquid phase dielectric property has been considered in this work only as a function of the temperature as the pressure is kept constant within 2%. The signal is processed as follow:

1. The temporal evolution of the inlet temperature TEP is compared with the evolution of the saturation temperature margin
2. We identify a time instant in which the saturation margin is at least greater than 1 K and we define a reference inlet temperature TEP_ref at this instant t0 as follows TEP_ref=TEP(t=t0). At this time instant we assume that the liquid fraction is 100% (fully liquid). The bias of the VOF sensor reading at t0 is also identified as VOF(t0) and supposed constant during an individual test run which typically lasts 300 to 600 s. A low pass filtering of the inlet temperature is performed with a sliding centered average over 10 data-points over the dataset sampled at 100 Hz.

DOI: 10.13009/EUCASS2022-4643

3. A temporal gain G(t) is calculated as: G(t)=TEP(t=t0)/ TEP(t).
4. The VOF reading is corrected by applying the gain on the temporal data and the initial bias as: VOF_c(t)=VOF(t)/G(t)+VOF(t0). The application of the different steps is performed on a pure LN2 run which ends with the depletion of the tanks culminating with the loss of pressure head.

Data compiled in figure 3 (right) shows the normalized pressure head R_DP (the ratio between the pressure head with GHe and the nominal pressure head without the helium injection) as a function of the liquid fraction. We can observe how the deviation of the liquid bulk density affects the VOF signal and also the evolution of the VOF vs pressure head since, after the correction of the data, a higher sensitivity to the presence of bubbles is detected as the same pressure head loss is measured for an ostensibly lower liquid fraction value.

4. Preliminary results

Once the test setup was declared operational and the instruments calibrated, several runs were performed by reaching at first a pure liquid nitrogen set point (in terms of inlet mass flow rate and rotational speed). Then by injecting an increasingly higher mass flow rate of gaseous helium until the pressure head decrease was reached ending to an abrupt flow blockage. The procedure was repeated until the depletion of the tanks reaching normalized inlet flow coefficients Φ/Φ_d ranging from 0.59 to 1.42 and rotational speed within the 5000 to 16 000 rpm range. The normalized flow coefficient defined as:

$$\Phi = \frac{Q_e}{\rho \omega \pi {R_t}^3 \left(1 - \left(\frac{R_h}{R_t}\right)^2\right)}$$

where Q_e is the inlet mass flow rate, $R_h$and R_t are the hub and tip inducer inlet radiuses, ω the rotational speed and ρ the inlet density. The reference flow coefficient Φ_d corresponds to the pump design point flow coefficient. The reduced flow coefficient ϕ_e^+ [m^3] is defined as $\phi_e^+ = Q_e/(\rho_e \omega)$ whereas the reduced pressure head coefficient ψ_e^+ [m^2] is defined as $\psi_e^+ = \Delta P/(\rho_e \omega^2)$ where ΔP is the pump pressure head.

The preliminary results of this test phase are presented in figure 4 (left) showing the variation of the normalized pressure head as a function of the liquid fraction. The preliminary data set reveals a dependency of the capability of the centrifugal pump to maintain an almost unaltered pressure head (the limit is set at R_DP=0.95) when the pump is operating at low mass flow rates up to liquid fraction predicted by analytical assessments. These measurements corroborate previous estimations obtained without the VOF sensor on the same facility but further work is necessary to identify the dependency on other performance parameters such as the rotational speed and the carrier liquid sub-cooling.

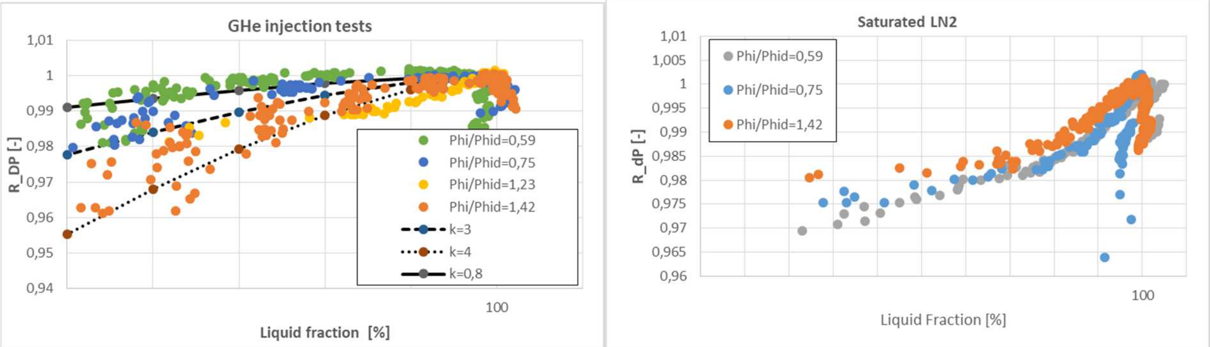

Figure 2. Left: Pump normalized pressure ratio as a function of the liquid fraction generated by injecting GHe. The fitting curves are based on the Murakami model [R9] with exponent 0.8, 3 and 4. Right: Pump normalized pressure ratio R_DP as a function of the liquid fraction generated in pure LN2.

In figure 4 (left) we can observe the scattering of the normalized pressure head decrease as a function of the liquid fraction and as a function of the normalized flow coefficient Φ/Φ_d from 0.59 to 1.42 and for liquid fraction quite consequent. We observe a non-monotonous dependence in ϕ_e^+ whereas a clear dependency in the LN2 mass flow rate seems to occur. Lower flow coefficient shows that the pump can sustain a pressure head for higher liquid void of fraction than for nominal flow coefficient. The analysis of centrifugal pump performance operating with an air-liquid mixture [R8][R9] shows that at low flow coefficient churn flow may be present thus leading to the modification of the flow distribution of helium within the liquid bulk due to the effects of buoyancy. According to the literature a decrease of pressure head is expected which is not what is observed in our case. A fitting is attempted considering the correlation proposed by Murakami et al. [R9] for small gas-to-liquid value ratios (less than 10%), which reads:

$$\psi^{*} = 1 - k\,\alpha^{1.5}$$

where $\psi^{*}$is degradation factor versus the inlet void fraction (all assumptions and development can be found in [R8-R10]). The value of k depends on the number of blades. Correlation proposed by Murakami leads to k = 3 for six blades whereas our pump impeller as 6 blades and 6 splitter blades. No additional analysis of the K factor dependency on the blade number is given by the Murakami. Assuming a k value between 3 and 4 we observe that the high flow coefficient dataset fits satisfactorily the correlation. These values are consistent with the observed literature.

The same procedure was repeated without GHe in order to observe the pressure decay under the effect of the non-null inlet void of fraction measured with the VOF sensor. The thermal divergence of the inlet temperature was obtained by setting the rotational speed and the initial mass flow rate then by gradually decreasing the opening section of the back pressure. The mass flow rate was reduced up to the point that the parasitic heat fluxes led to a two-phase flow at the pump inlet. The preliminary results of this test phase are presented in figure 4 (right) showing the variation of the normalized pressure head as a function of the liquid fraction. Plotting the data in terms of dimensional coefficients and comparing the evolution of the pressure head with respect non cavitation condition leads to Figure 5 which presents the pump performance deviation from the non-cavitating characteristics dimensional coefficients $\phi_e^{+} = f(\psi_e^{+})$ as a function of the inlet liquid fraction.

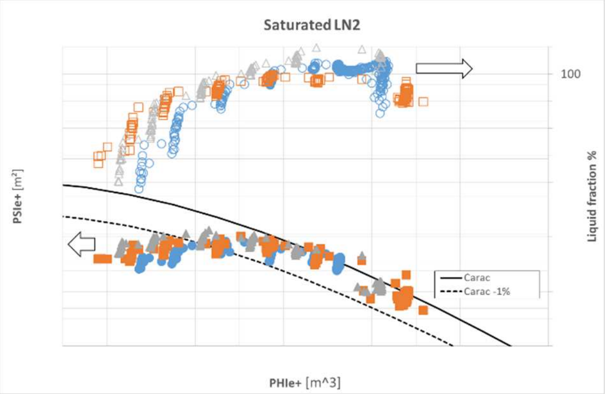

Figure 3. Pump performance deviation from the non-cavitating characteristics as a function of the inlet liquid fraction. Filled symbol: Phie+ vs Psie+, empty symbols: Phie+ vs liquid fraction.

The pure LN2 test shows that a relative pressure loss of 2% was reached for a void of fraction of approximately 8%. Despite not covering the same pressure head ranges due to the intrinsic limitation of the test setup and the difficulties in controlling all driving parameters (especially the flow temperature). The preliminary analysis of the dataset revealed unsurprisingly that the pump behaves differently when the void of fraction is generated by means of an injection of GHe or in pure two-phase flow. This is due to the different and mutually exclusive phenomena that take place (condensation in a two-phase pure system through the inducer opposed to the GHe bubble behavior driven by the pressure gradients within the flow filed inside the pump).

It shall be stressed out that the latter case is, in any case, not representative of the pump behavior when two-phase flow (meaning the coexistence of both phases of the propellant, liquid and vapor, due to thermodynamic saturation of the bulk) is available at the inlet. The effects of the non-condensable gas dispersed in the liquid on the impeller performance are controlled by a combination of opposing phenomena which depends on the size of the bubbles, the pressure gradient, the Coriolis force and the shear forces between the phases as long as the individual history of the bubbles. Geometry and internal casing-to-impeller clearances also play an important role as the gas phase accumulates in low pressure regions. All these effects combined defy any analytical and computational engineering effort to develop a predictive model to assess the performance loss. The effect of the non-condensable gas on the impeller performance correspond to a global decrease of the pressure head until the gas locking effect takes place even if, as reported in [R8] and [R9] for low void fractions sometimes an increase of pressure head of the order of 2 to 5% is observed due to the modification of the velocity vector by the non-condensable gas accumulation.

DOI: 10.13009/EUCASS2022-4643

5. Conclusions and further perspectives

An experimental test campaign has been planned and it is currently executed in order to gain further insight when CFD simulations are deemed unfeasible in the interaction between the pump inducer and impeller and the two-phase void fraction which may be ingested during a microgravity flight phase of an upper stage with saturated propellant. The preliminary results allow to verify the capability of the void of fraction sensor and to assess the performance of the pump but further tests and more data analysis are still required. Results show a behavior of the inducer-impeller pump consistent with the literature when GHe is injected whereas a total pressure loss under saturated conditions is measured with sufficient accuracy to be consistent with analytical predictions. Further analysis will be focused at improving the accuracy of the experiment. Additionally the versatility of the inlet sensor and its flush configuration opens up to broader possibilities in terms of real-time monitoring and control of the electrical pumps.

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