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FLOW VISUALIZATION STUDY ON TWO-PHASE CRYOGENIC FLOW

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ABSTRACT
In cryogenic fluid cavitation phenomenon is similar to boiling. Generally, these two processes can be distinguished by the fact that cavitation is the process of nucleation in a liquid when the pressure falls below the saturated vapor pressure, while the boiling is the process of nucleation that occurs when the temperature is raised above the saturated vapor temperature. In cryogenic fluids is very difficult to distinguish between these two different causes of phase change, and a lack of experimental investigations is present in literatures. In aerospace field, cryogenic fluids are usually used as rocket propellant obtained as mixture of liquid oxygen (LOx) and liquid hydrogen (LH2). These fluids can be employed under particular conditions as low temperature, microgravity and the environmental space, but they are susceptible to cavitation phenomena, because to a few change of temperature is combined to a change of phase. The aim of this paper is to examine the results of a flow visualization study on two-phase cryogenic flow passing through a internal nozzle. The transient growth process of the cloud cavitation induced by flow through the throat is observed using high-speed video images and analyzed by pressure and accelerometer signal.

INTRODUCTION

Cryogenic two-phase flows are present in many engineering applications as superconductivity technology, liquefied natural gas plants, aerospace components, and many other fields. Thus, the investigations of these flows is very interesting and important not only in the basic study of the hydrodynamics of cryogenic fluid but also for providing solutions to problems related to practical engineering applications of cryogenic two-phase flow.
In a hydrodynamic flow field, the beginning of two-phase flow and so the triggering of cavitation phenomenon are events more frequent, due to timing of engine mechanical components, leading to unsteady fluctuations in pressure and mass flow. Valve systems in rocket propulsion systems and testing facilities are constantly subject to dynamic events resulting from the timing of valve motion leading to unsteady fluctuations in pressure and mass flow. Such events can also be accompanied by cavitation, resonance, system vibration leading to catastrophic failure. Also in components of liquid rockets, mainly used to launch satellite systems, cavitating two-phase flows are present. In the rockets, the propellants (liquid hydrogen LH2 and liquid oxygen LOX) are supplied propellants to a combustion chamber with high pressure by a very fast turbopump, where cavitation occurs around the inducer , it induces disturbances that can result in substantial performance losses and/or in strong unsteady forces acting on the pump components [1].
More than water, cryogenic fluid transfer presents the problem of pressure drop. A probably cause of pressure drop is the design of interior pipe wall, in particular, a decrease of area puts the flow at a higher velocity and, as a consequence, at lower pressure. This process characterizes the liquid behavior; however, the decrease of temperature is a possible cause that is more specific for cryogenic flow [2].
Usually, the development of cavitation in a liquid flow is modeled as a phase change from liquid to vapor at almost constant temperature. This is a good approximation for water and other fluids, for which the temperature variation due to phase change is very small. However, the cavitation is accompanied with a non-negligible temperature variation in the case of cryogenic fluids [3].
This different behavior depends greatly upon physical properties of this fluids. Cryogenic fluids are characterized by large compressibility as compared with fluids, such as water, at room temperature, with a small difference in density between vapor and liquid phases and with a small latent heat of vaporization. These unique characteristics of cryogenic fluids can be utilized to realize high performance in fluid apparatuses, such as the two-phase operation of inducers for liquid rocket turbopumps.
In literature several studies have been focused on cavitation flow in liquids such as water [4]; while there is a lack in literature about cavitation phenomenon in cryogenic liquids.
Cryogenic flow has been investigated; however, there is a lack of information useful for clarifying the fundamental cryogenic fluids behaviors, obtained by theoretical or experimental studies [5-6]. One of the main reasons for the lack of information is that the available experimental results are insufficient for the validation of mathematical models because of the difficulty nature of techniques for visualizing two-phase transient flow. Dedicated experimental investigations should be done to identify and quantify the main parameters controlling the phase change in order to obtain more generalized models.
In particular the concentration of nuclei contained in the fluid affect the inception, development and scaling of cavitation.
The aim of this study is to conduct a experimental analysis of liquid nitrogen cavitation in an orifice nozzle, to clarify the fundamental characteristics of the nucleation and transient

growth process bubbles. This study was performed by the analysis of pressure signals and accelerometer signals.

EXPERIMENTAL SET-UP

A schematic illustration of the experimental set-up, used to investigate the internal nozzle flow, is shown in fig. 1 and fig. 2. The liquid nitrogen has been chosen as the cryogenic working fluid.

The set-up consists of a nitrogen supply tank, at a temperature of 77 K, two on-off valves and a flow visualization test section. A global view of the entire test section (bulk flow) is given in fig. 3. The test section is an assembly of a central internal nozzle, in which the fluid flows; two vacuum chambers, for the thermal isolation and two flanges. In order to perform the continuous monitoring of cavitation phenomenon, 4 quartz glass are fitted between the assembly components. The supply tank is connected to the visualization chamber by a 2 m long pipe.

Geometrical details of the flow channel are shown in fig. 4. The test section is a 15 mm-long rectangular orifice nozzle with a throat cross section 2 mm by 8 mm. After the visualization chamber, the nitrogen liquid is ejected in atmosphere as gas.

The line is filled with pressurized cryogenic liquid at a pressure of 2 bar and flow immediately occurred when the first on-off valve after the nitrogen pressure tank is opened.

The cavitation phenomenon can be observed within the flow, at a certain flow rate, in the throat section. If the pressure is below the vapor pressure at the flow temperature, cavitation occurs.

The acquisition and data elaboration system is based on:

- Two KISTLER 701A piezoresistive pressure sensors, with a sensibility of -80 pC/bar and a temperature range of -190/200°C. They are placed according to figure 5.
- A KISTLER piezoresistive amplifier, used for pressure signals
- A NI-DAQCard-6024E acquisition board at 200KS/s, used for the pressure signals.
- A KISTLER 8702B100 accelerometer.
- A NI-DAQCard-6020E acquisition board up to 1.25Ms/s, used for accelerometer signal.
- A high speed camera CCD Kodak Motion Corder Analyzer FASTCAM-Super 10k.

The imagines have been acquired at 125 fps and then have been downloaded and stored on a pc to be subsequently processed digitally.

For the different test cases, the pressure and accelerometer signals have been acquired at a maximum frequency of 100 kHz and 100000 samples, for a total data period of 1s. Then the signals have been amplified, filtered and collected into the two boards.

The voltage working range, for our test cases, was between -2 V and 2 V; it was been possible to obtain a gain in order to acquire also a minimum voltage variation of 2.44mV.

The acquisition programs were developed in-situ using the software Labview and the signal processing code was developed using MATLAB® software. Part of uncertainty is inherent to the flow conditions: the flow velocity, the pressure in the test section, the cavitation number. The uncertainty on the pressure is about 3%. The resulting cavitation number variability is estimated to be $\Delta\sigma=\pm0.05$. For the pressure transducers calibration, the deviation toward linearity was about 250 Pa ~0.25% of the measurement range.

The test conditions are summarized in Table 1.

Figure 1: Experimental set-up

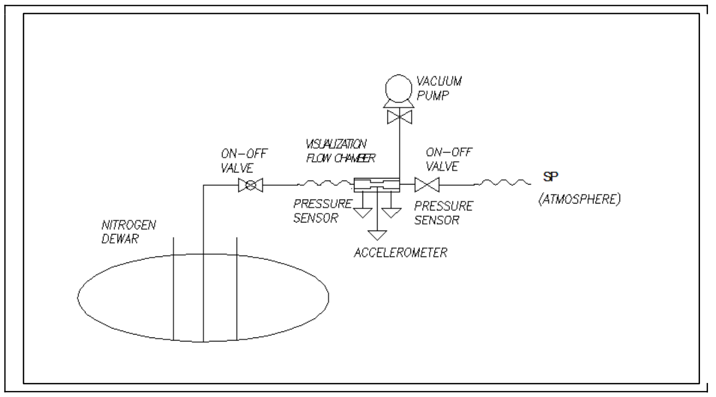


Figure 2: Sketch of the experimental setup.

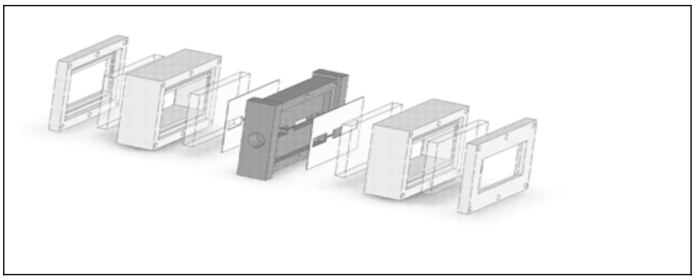


Figure 3: Visualization flow test section.

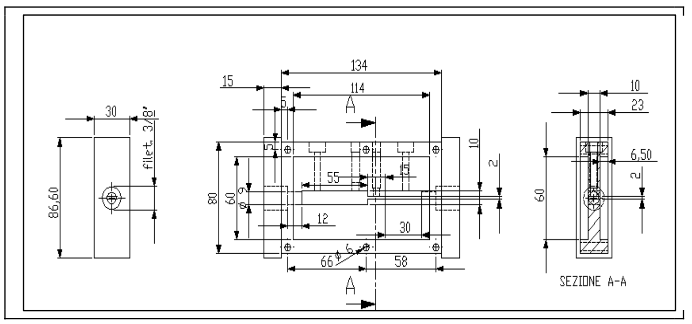


Figure 4: Test section particular.

Table 1: Operating condition of experimental case.

	Upload Pressure [bar]	*Download Pressure [bar]*	*Q [m³/s]*	*σ*
Case 1	1.08	1.0015	0.0011	1.364
Case 2	1.49	1.0226	0.0008	1.104
Case 3	1.77	1.0234	0.0006	1.066
Case 4	2.04	1.0223	0.0003	1.047
Case 5	2.05	1.0236	0.0002	1.034
Case 6	0.95	0.9320	0.0011	0.990
Case 7	1.06	0.9275	0.0010	0.986
Case 8	1.35	0.9216	0.0008	0.980
Case 9	1.80	0.9177	0.0005	0.977
Case 10	2.01	0.9167	0.0004	0.976

RESULTS

The aim of these experiments is to characterize the cavitating cryogenic flow in term of time occurrence, space, and intensity for various hydrodynamic conditions.

The experimental methods used in the study are:

— Accelerometer measurements.

— Upstream and downstream pressure measurements the contraction area.

— Optical observations (CCD).

A number of experiments have been carried out in order to determine the characteristics of the cavity length at different cavitation numbers defined as :

$$\sigma = [(p_{up} - p_v)/(p_{up} - p_{dw})] \quad (1)$$

where p_{up} and p_{dw} are, respectively, the upstream and the downstream pressure. The p_v is the vapour pressure at the flow temperature, that, for the test cases, is considered as the Dewar temperature, so T=77K, and consequently $p_v = 0.9744$ bar.

The acquired signals have been studied in time domain and frequency domain, in order to obtain information correlated to the cavitation phenomena.

It is well known that cavitation inception in a liquid is due to the explosive growth of microscopic bubbles or nuclei initially present in the liquid; the inception of cavitation happens when the local pressure drop below a critical low pressure. The determination of the number of these nuclei is important to control the phenomena and to validate the numerical modeling.

The vapor bubbles contain non condensable gas and vapor, so it is assumed that both sides of the bubble interface is in thermodynamic equilibrium [2]:

$$p_g + p_v = p_\infty + (2S/R) \quad (2)$$

in which p_g and p_∞ are, respectively, the pressure of non condensable gas and the liquid pressure, while *S* is the surface tension and R is the bubble radius.

Considering that the p_g can be re-written in function of bubble radius and a *K* factor, that is proportional to the mass of non condensable gas, it can be defined an equilibrium curve, characterized by a minimum point denominated "critical point" with the following values of pressure and radius:

$$R_c = \sqrt{\frac{3K}{2S}} \quad (3)$$

$$p_c = p_v - \frac{4S}{3R_c} \quad (4)$$

If the nuclei undergoes a pressure drop below the minimum p_c, they also grows indefinitely without reaching a new equilibrium and form a cavitation bubble. When these bubbles travel across a high pressure zone, they implode with a correspondent local max in the pressure signal. For this reason from temporal analysis, it has been possible to count the concentration of nuclei (fig. 5), during their transit through the nozzle, at different cavitation number. It is possible to observe a higher density of nuclei for lower cavitation number, because the liquid pressure is low, that allows the bubble growing and collapsing. Also the standard deviation of the downstream pressure signal (fig. 6) shows a higher oscillation for lower number cavitation, less than 1. It seems that the cavitation number =0.99 is a critical value, below that the cavitation increases, showing a high number of activated nuclei and so a higher standard deviations. The pressure signals, measured upstream and downstream of the contraction area in the orifice, and the accelerometer signal, have been processed to calculate the characteristic frequency content of the aforementioned signals. The formation of cavitation bubbles and their collapse generate observable pressure fluctuations. The Fast Fourier Transform of the measured signals was carried out considering the pressure fluctuations components around the time integrated mean value.

In figures 7, 8 and 9 the amplitude spectrum of Fourier Transform of upstream and downstream pressure and of accelerometer are showed at different flow conditions (different cavitation number, σ).

The complete development of cavitation phenomenon can be related to fluctuations measured before and after the throat. It is noticeable that for the upstream flow the main frequency content is in the range of low frequencies, up to 500 Hz, especially for low cavitation number, related to the impacts due to the vapor bubbles implosion. The frequency spectrum of the downstream pressure signals can be related to the characteristic behavior of the different cavitating regimes. In fact, the spectra show different characteristic frequencies with the variation of the cavitation number. At higher cavitation numbers, the spectra reveal relatively high dominant frequencies distributed in broad ranges of few hundred Hertz width. At lower cavitation numbers, less than 1, the spectra show sharp dominant spectral peaks also at higher frequencies. The increasing of some typical frequency component amplitudes, at small cavitation number is related to a sharp increase in the length of the cavitating zone, as evident also by the flow visualization by the CCD (fig. 10).

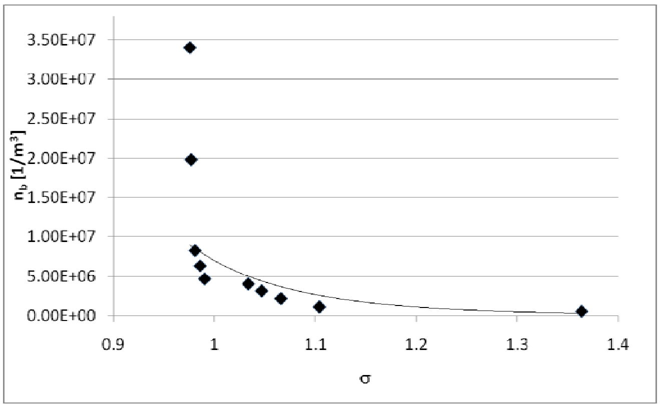


Figure 5: Distribution of density of activated nuclei density for different cavitation numbers.

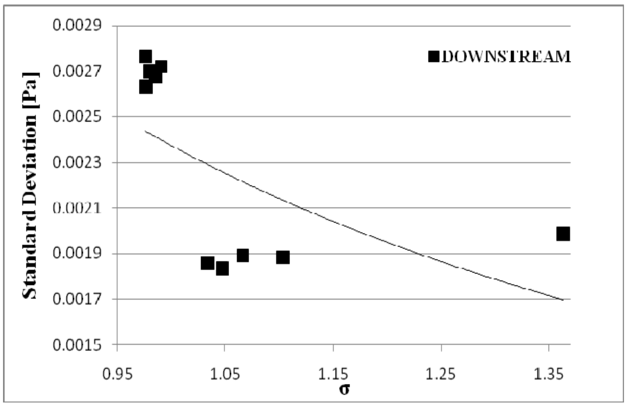


Figure 6: Standard deviation of downstrem pressure signals for different cavitation numbers

In particular, a characteristic frequency is at values close to 400 Hz, peaks at this frequency are present only in the downstream pressure signals and not at the upstream section. The amplitude peaks at this frequency has an increasing behavior at low cavitation numbers, as shown in fig. 11.

For the accelerometer signal it is not possible to locate a range of frequencies, probably due to the high implosion intensity.

Starting from the amplitude spectrum of Fourier Transform, it is interesting to calculate the function S(f1-f2):

$$S(f_1,f_2) = \int_{f_1}^{f_2} s(f)df \qquad (5)$$

This equation represents the area between the spectrum and the frequency axis and between the f_1 and f_2 frequencies. So it possible to confirm the FFT spectrum results. In fact, the figures 12 shows the S(0-10kHz) function for the downstream pressure signal at different cavitation numbers; it is evident and increasing of areas corresponding a decrease of cavitation number .

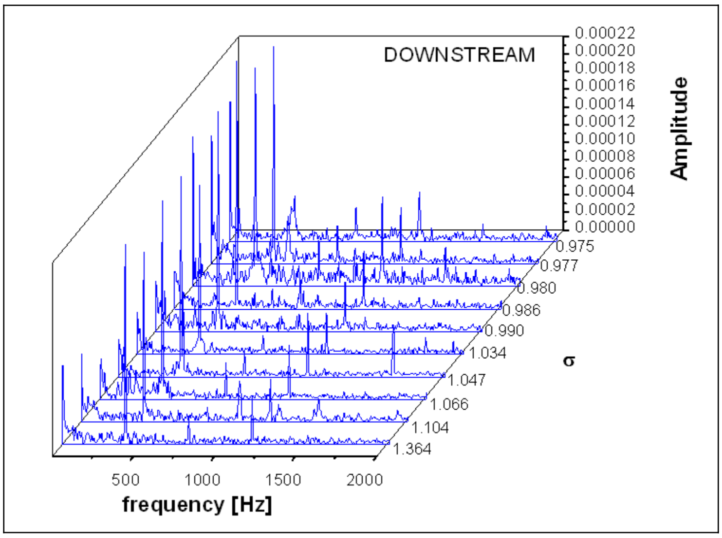


Figure 8: FFT Amplitude Spectrum of the downstream pressure for different cavitation numbers.

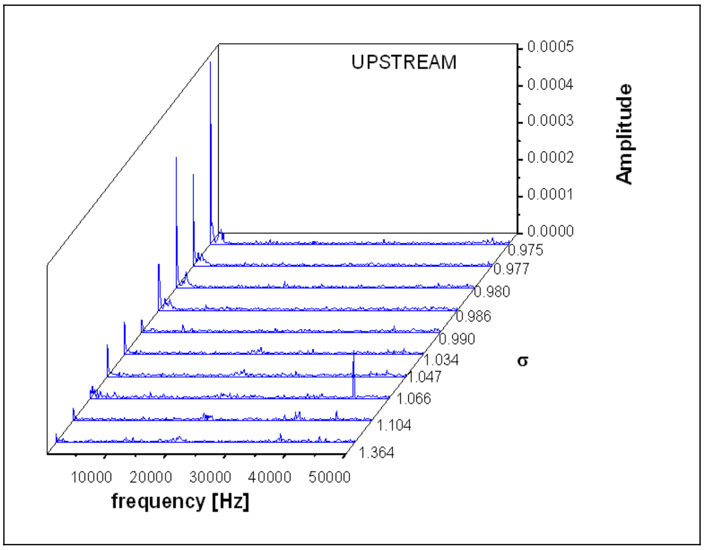


Figure 7: FFT Amplitude Spectrum of the upstream pressure for different cavitation numbers

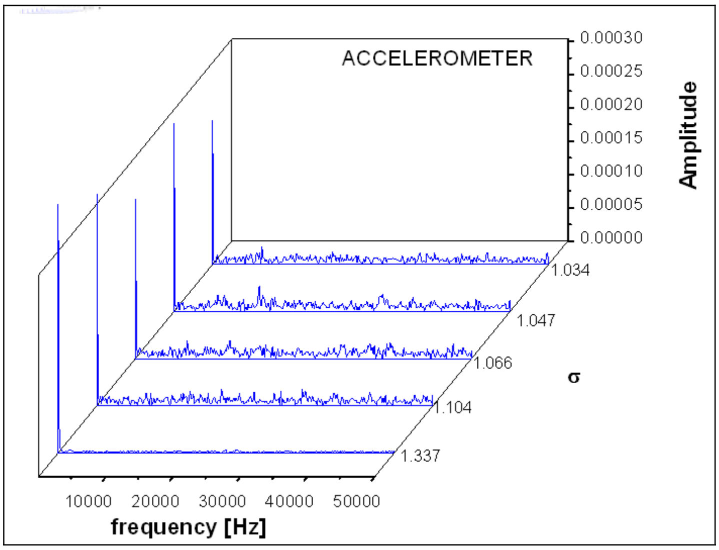


Figure 9: FFT Amplitude Spectrum of accelerometer for different cavitation numbers.

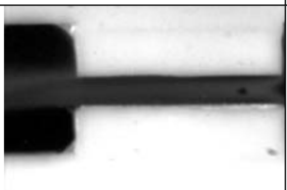
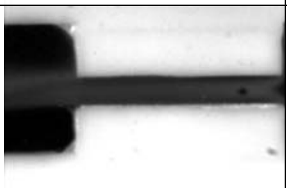
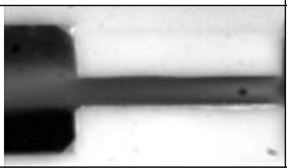
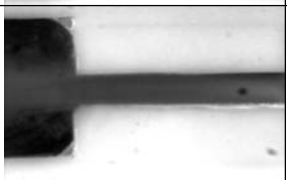
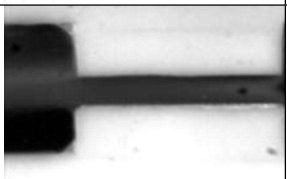
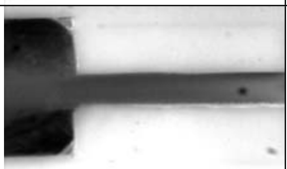
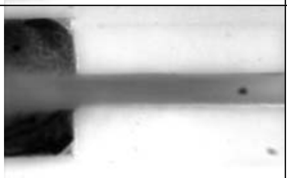
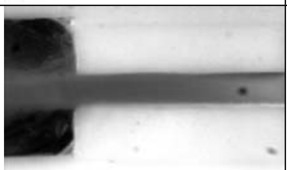
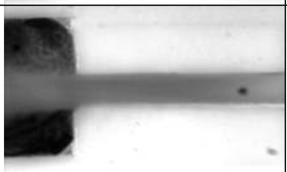
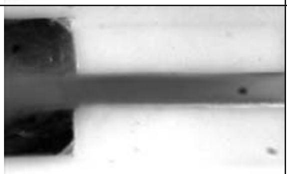
	Upload Pressure [bar]	*σ*
Case 1		1.364
Case 2		1.104
Case 3		1.066
Case 4		1.047
Case 5		1.034
Case 6		0.990
Case 7		0.986
Case 8		0.980
Case 9		0.977
Case 10		0.976

Figure 12 : Flow visualizzazions at different cavitation numbers σ.

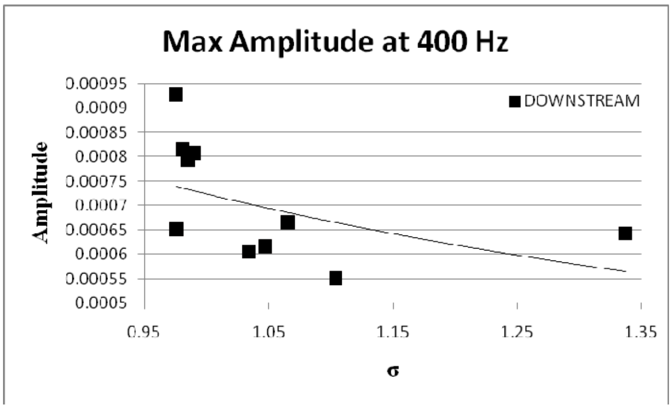


Figure 10: Max Amplitude obtained at 400Hz of downstream pressure signal at different cavitation numbers.

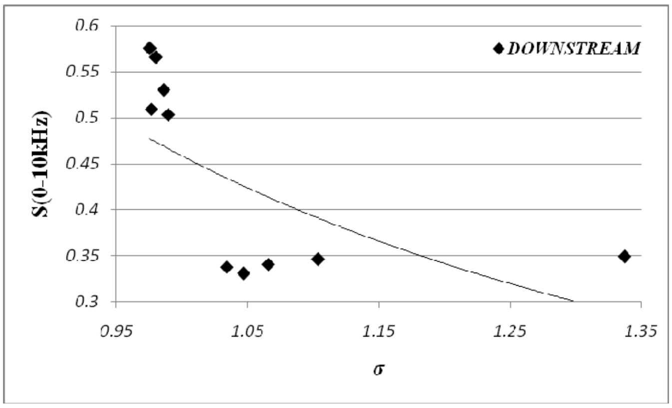


Figure 11: S(0-10kHz) function for the downstream pressure signal at different cavitation numbers.

CONCLUSIONS

Some experimental results on the cavitation of cryogenic fluids are presented. In particular, a flow visualization and pressure measurements on two-phase cryogenic flow passing through a an orifice nozzle installed in a horizontal pipe is carried out to clarify the fundamental characteristics of the cavitating structures.

Pressure signals have been analyzed both in time domain and in frequency domain, to characterize the cavitating cryogenic flow in term of time occurrence, space, and intensity for various hydrodynamic conditions.

The concentration of activated bubbles nuclei has been obtained, this could be useful for modeling validations. An increase of nuclei due to a decrease of cavitation number has been observed. Then the standard deviation of the pressure signals, recorded downstream the restricted nozzle area has been studied in order to obtain an evaluation about the oscillation of pressure signals due the development of cavitation.

By means of the Fourier Transform, it has been possible to locate a range of characteristic frequencies for the upstream pressure and downstream pressures.

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NOMENCLATURE

K	Factor proportional to the non condensable gas mass	
p_c	Critical pressure	[Pa]
p_g	Non condensable gas pressure	[Pa]
p_{dw}	Downstream pressure	[Pa]
p_{up}	Upstream pressure	[Pa]
p_v	Vapour pressure	[Pa]
p_∞	Liquid pressure	[Pa]
R	Bubble radius	[m]
R_c	Critical radius	[m]
S	Surface tension	[N/m]

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