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Comparison between water and liquid nitrogen pressure surge experiments to analyze cavitation induced noise growth

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Abstract: Water hammer phenomena play a major role in the design of rocket engine feed line systems. High amplitude pressure waves, generated by rapidly closing a valve to stop the chill down process or shut down the engine, can lead to acoustic cavitation inside the fuel delivery system. Since most liquid rocket engines are run by cryogenic fluids, but experiments with water need much less effort, it is of interest to understand the differences between the behavior of these fluids in rocket engine feed line systems. For that, several water and liquid nitrogen hammer tests have been performed at the Fluid Transient Test Facility (FTTF) at DLR Lampoldshausen. The aim of this paper specifically is to compare the grow rates of noise due to acoustic cavitation in order to make a statement about using water as a replacement fluid for cryogenic fluids.

Keywords: Water hammer, Cavitation, Liquid Nitrogen, Noise growth, Cryogenics

1. Introduction

The water hammer effect appears when a flow is stopped abruptly, causing a pressure wave to travel upstream. This effect has already been extensively studied, especially in hydraulic engineering and the oil industry, an overview about research activities can be found in [1,2]. In rocket engines the effect can appear while shutting down an engine or stopping the chill down procedure before start. The loss of the fourth flight of the N1 rocket is attributable to the shock wave after shutting down several engines in flight [3]. In the development of the ATV spaceship pressure peaks up to 220 bar [4]. Because most liquid rocket engines are operated with cryogenic fluids, fluid hammer experiments with liquid nitrogen (LN2) were performed and compared to numerical simulations by Gouriet et al. [5]. Since cryogenic experiments are more elaborate than water (H2O) experiments, the FTTF was build to analyze the main difference between these types of fluids. Previous work treated the influence of cavitation as an acoustic boundary condition (H2O only) [6], while this paper aims on the difference between H2O and LN2 in noise growth due to the occurrence of acoustic cavitation.

2. Testbench and Methods

The FTTF was built in two configurations, one for H2O (FTTF-1) and one for LN2 (FTTF-2). Both are comparable in size, mass flow and pressure level. A schematic of both configurations is shown in **Figure 1** and a detailed description of the FTTF-1 can be found in [7]. Each configuration includes two pressurized tanks (HP tank & LP tank). These tanks are connected via a pipe with a one and a half spiral, a fast closing valve and a coriolis flow meter. The test section contains three sensor positions S1, S2 and S3, each is equipped with a static pressure sensor ($f_{s,P}$ = 10 kHz), a dynamic pressure sensor ($f_{s,Pdyn}$ = 150 kHz) and a thermocouple. The test bench is made out of steel 1.456. The main dimensions can be found in **Table 1**, which are the inner diameter d_i, the wall thickness e, the length of the pipe l, the position of the sensors x_i and the time till the valve closes Δt.

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Table 1 : Dimensions of the FTTF

Parameter	FTTF -1 (LN2)	FTTF-2 (LN2)
Inner diameter $\boldsymbol{d_i}$	19 mm	19 mm
Wall thickness $\boldsymbol{e}$	1.5 mm	1.5 mm
Length (valve – HP tank inlet): $\boldsymbol{l}$	7,671 m	9.294 m
Position S1 ($\boldsymbol{x_1/l}$)	3.9 %	6.46 %
Position S1 ($\boldsymbol{x_2/l}$)	88.8 %	47.3 %
Position S1 ($\boldsymbol{x_3/l}$)	97.8 %	81.8 %
Time till valve closure $\boldsymbol{\Delta t}$	4.6 s	10 s

The main differences between the configurations are the isolation at the FTTF-2, the sensor position S2 and the change of the LP-tank inlet from the bottom to the top, as shown in **Figure *1*:** Schematic of the FTTF - 1/2. Left: H2O configuration without isolation. Right: LN2 configuration with isolation. **Figure *1***. This change has the advantage that the fluid can be pumped back and forth between the tanks, which is necessary for the chill down of the system. To minimize heat entrance, the FTTF-2 is completely isolated, jackets filled with boiling LN2 at nearly ambient pressure are used at the tanks, the pipeline is isolated by a vacuum hose and the valve and surrounding piping is wrapped in foam isolation.

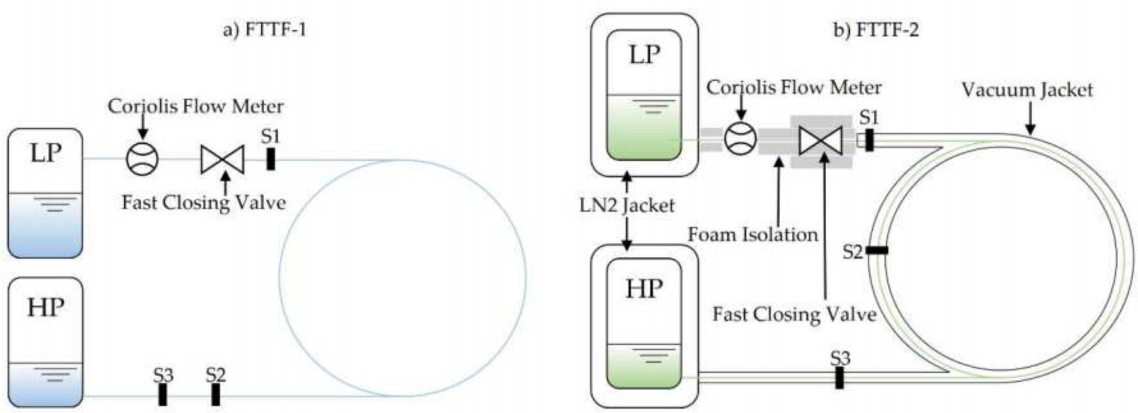

Figure 1: Schematic of the FTTF - 1/2. Left: H2O configuration without isolation. Right: LN2 configuration with isolation.

Pressurizing both tanks ($P_{HP} > P_{LP}$) leads to a flow from HP to LP, which is stopped after a certain amount of time by closing the valve. This time is chosen to be longer in LN2 experiments due to warming of the fluid in the pipe between experiments. A fluid hammer occurs and is measured at the sensor positions. Cavitation at the valve is detected by measuring vapor pressure at S1. The pressure wave is reflected by the HP tank inlet and starts oscillating between the closed valve and the HP tank inlet.

In total 251 tests with H2O and 106 tests with LN2 were performed. Here, cavitation occurred in 225 H2O tests and 84 LN2 tests. To analyze the difference of cavitation induced noise in cryogenic and non-cryogenic fluids, all four data sets (H2O no cav., H2O cav., LN2 no cav., LN2 cav.) are considered. In order to measure the amount of noise in the liquid part of the pipe, the sensor position S2 in H2O and S3 in LN2 will be used, which have a similar relative position (x/l).

3. Results

The pressure trace close to the valve (S1), and where the noise is measured (H2O: S2, LN2:S3), is shown in **Figure 2**. The pressure before valve closing is $P_0 = 5$ bar and the first peak reaches an amplitude up to

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nearly $p_1 = 60$ bar. Since the amplitude $\Delta P_1 = P_1 - P_0 = 55$ bar is greater than P_0 the vapor pressure is reached in the first wave trough and cavitation is formed close to the valve. Therefore the pressure in the valley is constant until the next pressure peak. The pressure trace can be split into two areas: Area 1 "while cavitation" and area 2: "after cavitation", before and after the last valley with occurrence of cavitation. To get this splitting, the pressure trace is compared to the vapor pressure $P_{v,H2O}(t = 291\text{ K}) = 0.0234$ bar. For LN2 a buffer is added, here the corrected vapor pressure is $P_{v,LN2,c} = 3$ bar.

To get the amount of noise in the liquid part of the pipe, a high pass filter with $f_{HP} = 250$ Hz is used on the signal of the dynamic pressure sensors. The absolute value of the filtered signal is used as a measure of the amount of noise, which is shown in **Figure 2** as a grey line. The black line between each peak is the mean value of the absolute noise. As expected the amount of noise in the first area is significantly higher than after the end of cavitation in area two.

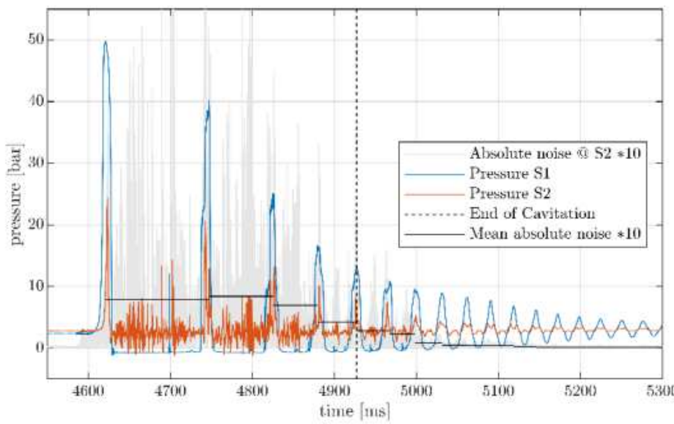

Figure 2: Pressure trace at Sensor S1/S2 for H2O. The plot is split into two areas with the dashed line, before and after cavitation. The mean amount of noise is shown between each peak.

To analyze the influence of the cavitation on the noise growth, all tests with occurrence of cavitation are considered and compared to refence cases without cavitation. The peak number is counted from the last peak with cavitation, that is why peaks in area 1 have negative numbers. To achieve better comparability, all pressure traces are normalized to the maximum pressure of the largest peak of S1. The mean value, with 68% quantile as an error bar, of each wave trough is shown in **Figure 3**. The plots a) and b) show the reference cases without occurrence of cavitation. It is to be recognized that the amount of noise decays exponentially for both fluids, in LN2 a bit faster but with a higher spreading. The values of H2O are an order of magnitude larger than in LN2, therefore water tests are noisier than LN2 tests.

The cases with cavitation are shown in plot c) and d). The exponential decay of the curves after the last wave trough with cavitation (blue curve) is comparable with the one in plot a) respectively b) for both fluids. Both (after cavitation in c/d) start at a lower value but with greater spreading than their counterparts in a/b, especially for LN2 the values are much lower. The amount of noise remains at a high level while there is cavitation (red curve) in H2O, in contrast to LN2, where the amount of noise decays linearly.

4. Conclusions

Water hammer tests with and without the occurrence of cavitation using H2O and LN2 were performed at the FTTF at DLR Lampoldshausen. The amount of noise was analyzed by splitting the data into two areas: "while cavitation" and "after cavitation" and calculating the averaged amount of noise between each pressure peak. The mean absolute noises were compared and differences in the noise behavior between water and liquid nitrogen were identified:

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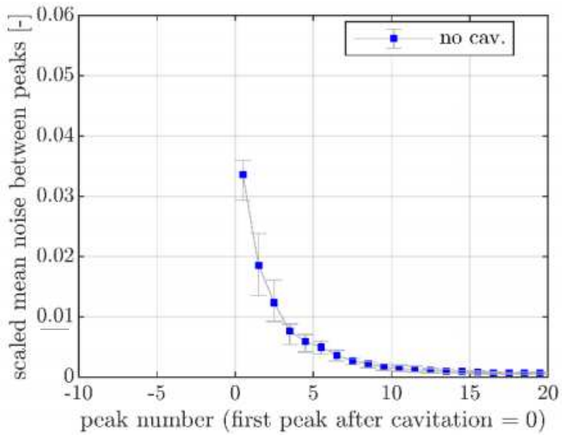
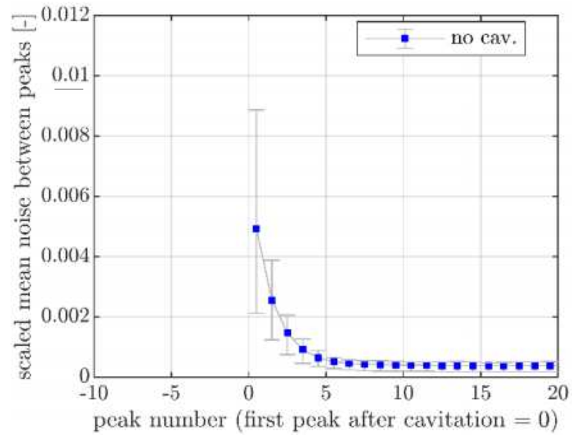
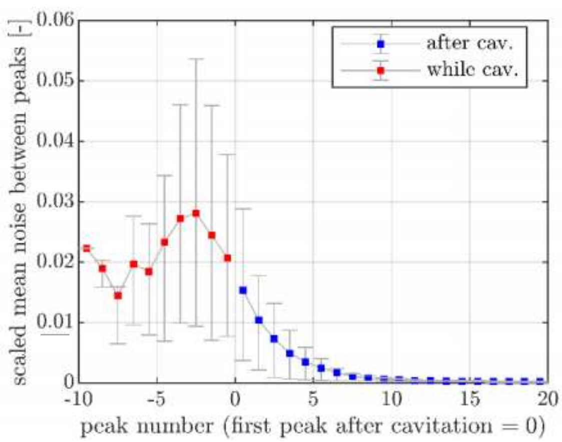
1. H2O testcases are noisier than LN2 testcases.
2. Without cavitation: Exponential decay of noise.
3. While cavitation: Constant amount of noise in H2O and linear decay in LN2.
4. After Cavitation: Comparable behavior to cases without cavitation starting at lower noise



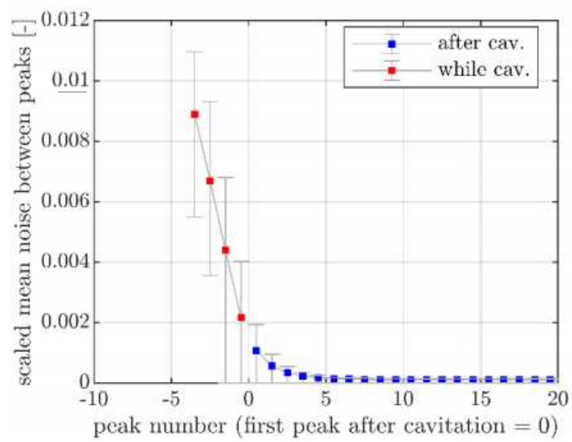
a) H2O, no cavitation



b) LN2, no cavitation



c) H2O, cavitation



d) LN2, cavitation

Figure 3: Averaged amount of normed noise between peaks for **a)** H2O, no cavitation, **b)** LN2, no cavitation, **c)** H2O cavitation, **d)** LN2 cavitation. The traces are cut after 20 peaks without cavitation.

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