# Cavitation dynamics in water at elevated temperatures and in liquid nitrogen at an ultrasonic horn tip

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## Highlights

- Cavitation dynamics in water changes drastically between 20°C and 100°C.
- At 60°C cavitation reaches its peak in extent and in number of structures.
- Cavitation dynamics corresponds well to cavitation erosion.
- Extrapolation of the results from surrogate liquids to cryogenics is questionable.

#### Abstract

Understanding and predicting thermodynamic effects is crucial when the critical point temperature is close to the operating temperature of the fluid, like in cryogenics. Due to the extreme difficulties of experimental investigation, predicting of thermodynamic effects in cavitation often bases on data in liquids other than cryogenics. Most often used surrogate liquids are hot water or certain refrigerants, which are selected by a single fluid property, most commonly by the thermodynamic parameter  $\Sigma$ .

The paper presents a systematic study of the cavitation dynamics in water at  $20^{\circ}$ C,  $40^{\circ}$ C,  $60^{\circ}$ C,  $80^{\circ}$ C and  $100^{\circ}$ C and in addition in liquid nitrogen (LN2). Cavitation dynamics on a 4.8 mm (tip diameter) ultrasonic horn tip, which oscillated at 20 kHz was investigated by high-speed visualization at 300,000 frames per second (fps). Simultaneously acoustic emissions were recorded by a high frequency pressure transducer. Measurements were performed under variation of the acoustic power in a closed, insulated vessel, where pressure could be optionally set.

The main purpose of the presented investigation is to determine whether hot water can act as a surrogate liquid to cryogenics.

The results may implicate the future investigations and development of a new generation of rocket engines, which also feature the possibility of re-ignition while in orbit - understanding and predicting of cavitation behaviour is becoming a crucial part at the (liquid oxygen - LOX and liquid hydrogen - LH2) turbo-pump design.

**Key words:** Ultrasonic cavitation, cavitation dynamics, thermodynamic effects, hot water, liquid nitrogen, thermodynamic parameter.

## **1** Introduction

Cavitation, described as an instability within the bulk liquid, can cause many undesirable effects in hydraulic machinery - from noise, vibrations to critical deterioration of performance and material erosion. Liquid rocket engine systems require high-performance turbopumps to transport LH2 and LOX to be transported from fuel tanks to the combustion chamber, their performance due to cavitation presence can be (and is) an issue, especially considering the possibility of re-ignition of the engine while in orbit. There is a well-known example of space launch failure of Japanese H-II rocket due to the cavitation instabilities in the liquid hydrogen pump [1], which indicates the link issue between the experimental-numerical studies and the actual performance.

In cavitation in cryogenic liquid flows the so-called thermodynamic effects may not be neglected - these are however still not fully understood. Most of the experimental studies with cryogenics were performed in the 1970's by Hord on Venturi profiles [2], hydrofoils [3] and ogives [4]. His experimental data are still considered as the benchmark for validation of numerical models with thermodynamic effects consideration.

To avoid hazardous experiments with LH2 and LOX, researchers often use other liquids, which can act similarly to cryogenics. Cervone et al. [5], [6] conducted experimental observation of cavitation on helical inducer and NACA hydrofoil in water at room temperature and at elevated temperatures, up to 70°C. It et al. [7], [8] observed cavitation on hydrofoil and compared its characteristics between water at room temperatures, 90°C and LN2. Experiments with water at elevated temperatures were conducted by Dular [9], who also investigated the influence of thermodynamic effects on cavitation erosion. First experimental study by direct, non-invasive temperature measurement method on single bubble was performed by Dular&Coutier-Delgosha [10]. Petkovšek&Dular [11], [12] obtained one of the first 2D temperature fields of the cavitating flow in Venturi in water at 100°C. Instead of hot water, Franc et al. [13],[14] used refrigerant R114 and observed cavitation on rotating inducer. Gustavsson et al. [15] studied cavitation and its thermodynamic effects on NACA hydrofoil using fluoroketone. Rare experiments in LN2 were conducted by Yoshida et al. [16],[17] and Kikuta et al. [18] on rotating inducer and by Ohira et al. [19] who performed experimental investigation in convergent-divergent nozzle.

Many researchers avoid experiments at subcooled conditions and try to substitute them with other liquids, yet the question persists - are the gained results reliable or not - can we justify the extrapolation of the results form surrogate fluids to real cryogenics.

This paper deals with experimental investigation of cavitation dynamics in water at elevated temperatures and in LN2. The usage of hot water as a surrogate liquid for thermodynamic effects of cavitating flow is discussed.

In most engineering cases the issues with cavitation in cryogenic liquids is related to the hydrodynamic cavitation - mostly rocket fuel turbopumps. We can justify the use of ultrasonic cavitation instead of hydrodynamic one, due to its very dynamical nature, which resembles the conditions - for example intensively oscillating pressure field. Comparing hydrodynamic cavitation with typical acoustic cavitation reveals distinct behaviour of each type. By acoustic cavitation bubbles repeatedly oscillate in a restricted sonicated volume, while by hydrodynamic cavitation the cavitation structures are advected with the main flow with few oscillations and collapses. When using ultrasonic horn with small diameter tip, sufficient amplitudes are induced causing an attached vapor-gas cavitation "cloud" with oscillation frequency much lower than driving frequency of the horn (usually  $F_0/5 - F_0/4$ ). This type of acoustic cavitation, named as "acoustic supercavitation" [20], can be roughly compared with attached hydrodynamic cavitation and might be used for better understanding of its behaviour [21].

## 2 Experimental set-up

Cavitation phenomena was investigated on a 4.8 mm titanium (Ti) tip of a 20 kHz ultrasonic horn transducer with nominal power of 750W. It was submerged in a closed vessel – pressure chamber, specially designed to operate at cryogenic temperatures (Fig. 1). The vessel also enabled the variation of ambient pressure by which different intensities of cavitation could be achieved. Moreover, the evaporation rate of the liquid could be minimized. As the pressure increases due to constant evaporation a precise regulation valve was mounted to maintain constant pressure conditions. In addition, an automatic safety valve was installed for quick pressure release. Temperature inside the vessel was monitored by a Pt100 probe, mounted below the observation and illumination windows. Cavitation was observed by high-speed visualization at 300,000 fps, using a backlight illumination by high power LED. In addition, the pressure oscillations near the horn tip were simultaneously measured by high frequency pressure transducer. Pressure transducer was mounted in the same level as the observation windows (rotated by 90°) and shifted from the centre of the horn for 50mm.

Measurements were performed in LN2 and in water at 20°C, 40°C, 60°C, 80°C and 100°C. Used fresh tap water contained 7.6 – 7.8 mg/L of dissolved oxygen, with pH 7.4 – 7.5 and conductivity of 440  $\mu$ S/cm at room temperature. In both liquids a set of measurement points were recorded at various absolute ambient pressures (1.2 bar, 2.3 bar, 3.4 bar and 4.5 bar) and at various transducer powers (20%, 25%, 30%, 35%, 40% of maximal power, with amplitudes 130, 165, 200, 235 and 270  $\mu$ m respectively); 20 measurement points in LN2 and 100 measurement points in water. To increase the temperature of the water an external electric heater was used, which was in contact with the bottom surface of the vessel (in experiments with LN2, the heater was removed).



Figure 1: Experimental set-up; scheme (left), image (right).

Cavitation was generated by an ultrasonic homogenizer Cole-Parmer 750W, with a nominal output frequency  $f_0=20,000$  Hz. The original probe made out of titanium alloy is specially designed to ensure its natural frequency of 20 kHz at a room temperature. When the probe is inserted into the LN2, it cools down to approximately -195°C, which causes changes in material properties. The natural frequency of the probe increases, which causes shift of the resonance peak and consequently disables the ultrasonic horn to work properly. Additional problem is partial submergence of the probe - the temperature of the probe varies between the room temperature at one end and -195°C at the other (submerged) end of the probe. The problem was solved by adjusting the length of the probe, by which, one can adjust its natural frequency to compensate the frequency shift due to temperature change.

Visualization was performed by high-speed camera Photron Fastcam SA-Z, which enables recording at 20,000 fps at full resolution ( $1024 \times 1024$  pixels) and up to 2,100,000 fps at reduced resolution. For the present configuration recordings of cavitation with 300,000 fps at relatively high resolution of  $256 \times 128$  pixels were performed. Shutter time was set to 2.5 µs.

A calibrated high frequency charge mode pressure transducer PCB 112A05 with Brüel&Kjaer 2635 charge amplifier was used for acoustic pressure acquisition. The sampling frequency for pressure measurement was 1.2 MHz. Pressure data acquisition and visualization were triggered and synchronized by an external trigger.

Additional attention was given to monitoring the amplitude of the horn. By using high speed visualization of the movement of the tip, we were able to conclude that it remains constant, regardless of the temperature, liquid and variations made to the horn.

## **3** Results and discussion

## 3.1 Cavitation in water at elevated temperatures

First the comparison in water at different temperatures, different ambient pressures and different ultrasonic horn powers was made. Image analysis was performed in a way, where we followed the overall size of the cavity A and the number of the individual structures N, as is shown in Fig. 2. The contrast of the original image of cavitation was firstly enhanced. The contour of the ultrasonic horn tip was then blended out of the image and finally the number of the remaining objects (N) and their area (A) was extracted.



Figure 2: Image analysis principle.

The general comparison from visualization is shown in Figs. 3 and 4. Figure 3 presents average cavitation characteristic area A for various operating conditions. Each diagram presents a constant ambient pressure, where the individual curves present constant horn power. The characteristic area is determined by extracted area from images. For each operating condition (horn power, water temperature, ambient pressure) a series of 10,000 images was analysed. As expected, the cavitation extent is increasing with increasing horn power from 20% to 40% at all ambient pressures. The influence of ambient pressure can also be observed between the four diagrams - the cavitation extent decreases with increasing pressure.

The most interesting observation is the influence of the temperature on the cavitation extent. It seems, that cavitation extent has its peak at 60°C, then, as the temperature is further increased, the cavitation area decreases. As one can see, cavitation area is the largest at 60°C, by almost all constant pressure diagrams and constant power lines (Fig. 3).



Figure 3: Average characteristic cavitation area for various operating conditions in water.

Observing the average number of individual cavitation structures for each operating condition (Fig. 4), gives even stronger deviations between the different water temperatures. The object number N does not vary much between various horn powers and ambient pressures at different temperatures, except at 60°C. In general, the number of individual cavitation structures N rises from 20°C to 60°C and by higher temperatures (80°C and 100°C) decreases intensively. At 60°C there is a distinctive number peak at all horn powers and all ambient pressures. One can also notice, that the ambient pressure decreases the number of cavitation objects, yet the influence is relatively weak.



Figure 4: Average number of individual cavitation structures for various operating conditions in water.

To understand cavitation behaviour at elevated temperatures, Fig. 5 presents vapor pressure and thermodynamic parameter  $\sum$  for water as functions of the temperature. Vapor pressure rises with the temperature, which allows the liquid to "break down" at lower energy and consequently to form cavitation earlier. This means, that at the same energy input, cavitation forms in larger extent, which can be also seen in Figs. 3 and 6. However, the thermodynamic effect, which can be quantified by thermodynamic parameter  $\sum$  (Eq. (1)), proposed by Brennen [22], delays cavitation growth:

$$\Sigma = \frac{(\rho_v L)^2}{\rho_l^2 c_{p,l} T_\infty \sqrt{\alpha_l}} , \qquad (1)$$

where  $T_{\infty}$  is the test temperature,  $\rho_v$  is the vapor density,  $\rho_l$  is the liquid density, L is the evaporative latent heat,  $c_{pl}$  is the constant pressure specific heat of the liquid and  $\alpha_l$  is the thermal diffusivity of the liquid. For the present experiments, the values of  $\Sigma$  are 4 ms<sup>-3/2</sup>, 30 ms<sup>-3/2</sup>, 175 ms<sup>-3/2</sup>, 796 ms<sup>-3/2</sup>, 2993 ms<sup>-3/2</sup> and 2355 ms<sup>-3/2</sup> for water 20°C, 40°C, 60°C, 80°C, 100°C (Fig. 5) and LN2, respectively. The  $\Sigma$  parameter depends only upon the liquid's temperature, thus various liquids can be compared to each other, regarding the thermal delay. By cavity growth – process driven mainly by the vaporization process, the latent heat is supplied from cavity surrounding, causes a small temperature drop of the liquid which results in a local drop of vapor pressure. Further development of the bubble is now weakened or delayed. With increasing  $\Sigma$  the influence of thermodynamic effects become more intense. Thermodynamic effects become significant at  $\Sigma = 100 \text{ m/s}^{3/2}$  or higher [23].

Observing Fig. 5, one can see that  $\sum$  between 20°C and 60°C increases from 4 m/s<sup>3/2</sup> to 175 m/s<sup>3/2</sup>, while at 100°C reaches 2993 m/s<sup>3/2</sup>. Hattori et al. [23], reported that at  $\sum = 100$  m/s<sup>3/2</sup> the thermodynamic effects become significant, which for water applies between 50°C and 55°C. This could explain why cavitation extent is the largest at 60°C in our case and then decreases at higher temperatures. It seems that the inhibiting influence of thermodynamic effects is stronger than

promoting vapor pressure at temperatures higher than 60°C for cavitation growth. Observing the number of individual cavitation structures (Fig. 4) and connecting these results with the vapor pressure and thermodynamic parameter, while considering the constant number of initial nuclei, gives us the following explanation: at temperatures below 60°C the low vapor pressure and an almost negligible thermodynamic effect are preventing to form large number of cavities. At 60°C the ratio between promoting vapor pressure and relatively low influence of the thermodynamic effect seems to act in favour of large number of cavities. At higher temperatures the thermodynamic effect increases rapidly, which delays the cavitation growth, but promoting of the vapor pressure tends to vaporize the liquid, thus cavities join, which lowers the number of individual cavitation structures.



**Figure 5:** Water vapor pressure and thermodynamic parameter  $\Sigma$ .

Images on the left side in Fig. 6 present the average cavitation extent, the diagrams on the right show the cavitation size evolution in time. Presented cases were chosen for water at temperatures of 20°C, 40°C, 60°C, 80°C and 100°C, at ambient pressure of 1.2 bar and at horn power of 35%.

Observing cavitation dynamics in Fig. 6, one can see, that cavitation oscillates at certain frequency, much lower than driving frequency of the horn - this was first reported by Žnidarčič et. al [20], [21] in water at ambient temperatures. While the driving frequency of the horn is 20,000 Hz, the frequency of the cavitation oscillation varies between 4700 Hz at 20°C, 4000 Hz at 40°C, 3850 Hz at 60°C, 2850 at 80°C and 2500 Hz at 100°C. Cavitation dynamics seems to be very complex and no explanation is provided yet to fully explain the constantly decreasing main cavitation forming frequency. Probably the speed of sound in water also plays an important role in the process - it increases from 1481 m/s at 20°C to 1543 m/s at 100°C.

From Fig. 6 one can also notice, that growth-collapse cycles do not have constant size amplitudes, but also oscillate, the cavitation forms for a few cycles with larger extent and then oscillates a few cycles with smaller extent. These extent oscillations are driven at an even lower frequencies, below 500 Hz. They are indistinctive and seem to be random and complex.



Figure 6: Average cavitation extent for period of 30 ms (left) and time developed cavitation extent (right) for water between 20°C and 100°C.

## 3.2 Discussion on the thermodynamic effect

The relationship between the two values, A/N, gives us a parameter, which is proportional to the size of an individual (circular) cavity ( $R = \sqrt{\frac{A}{N \cdot \pi}}$ ). A mean value of R for each investigated operating point was calculated, which is shown in diagrams in Fig. 7. The dots in the diagrams represent the experiments done in water and the stars (the measurements at  $\Sigma = 2355 \text{ m/s}^{3/2}$ ) the ones in LN2.

Regardless the power of the transducer, the relationship between the characteristic radius of the circular cross-section of the cavity R and the thermodynamic parameter  $\Sigma$ , the R firstly falls with the increasing  $\Sigma$ . Then, it rises significantly at  $\Sigma = 2355 \text{ m/s}^{3/2}$ , which in fact corresponds to the only experiments done in LN2 (denoted by stars in the diagrams). Further on, at  $\Sigma = 2993 \text{ m/s}^{3/2}$  (again in water, at 100°C) it drops significantly.

Obviously, the results, which were performed in LN2 stand out - if one would observe only the results from tests in water, the trend would be a generally decreasing one, with a slight increase at the very highest  $\Sigma$ . This raises a concern that the thermodynamic parameter  $\Sigma$  cannot be extrapolated over different liquids. This conclusion also coalesces with our previous investigations [9], [24] and offers some new insights into the physics of cavitation and cavitation erosion. In [9] we reported on cavitation damage in water at elevated temperatures. We showed that the maximum damage occurs at about 60°C, at  $\Sigma = 175 \text{ m/s}^{3/2}$ , the damage was smaller at lower and higher temperatures ( $\Sigma$  value). This corresponds well to the results obtained in the present work (at  $\Sigma = 175 \text{ m/s}^{3/2}$ ) - trend of the overall size A (Fig. 3), characteristic size of the structures R (Fig. 7) and the number of the cavitation structures N (Fig. 4).

In [24], we extended the work to cavitation erosion in liquid nitrogen, where significantly less damage was observed in LN2 than in water at approximately the same  $\Sigma$  value. In the present work we see that the characteristic size R of the structure differs significantly between the two cases (in LN2 the size is much larger).

From this we can conclude that the smaller the structure, the more aggressive is the cavitation going to be. Fine correlation can also be made between the number of structures N (Fig. 3) and the cavitation erosion [9].



Figure 7: The characteristic size of the cavity R as a function of thermodynamic parameter  $\Sigma$ , horn power P and operating pressure p.

#### 3.3 Cavitation in water vs. cavitation in LN<sub>2</sub>

Finally, a detailed comparison between the observation of cavitation in water at 20°C, 100°C and in LN2 was made. Since, there is no general consensus on a dimensionless number, which would describe the cavitation condition at an ultrasonic horn (one approach was recently proposed by Dular & Petkovsek 2018 [24]), only the simple pressure difference expression (p-p<sub>v</sub>) was used to compare cavitation at different working conditions.

Figure 8 presents a sequence of images of typical cavitation on an ultrasonic tip horn submerged into water at 20°C (upper image), 100°C (middle image) and LN2 (lower image). For the present comparison a horn power of 30%, and ambient pressure of 1.2 bar was chosen.

The image sequences in Fig. 8 starts at time t (marked in diagrams in Fig. 9). Figure 8 reveals that cavitation in LN2 is much more chaotic and structural undefined as it is in water. As one can see, cavitation in water both at 20°C and at 100°C is compact, attached to the tip of the horn and more or less kept together in a mushroom like form. On the other hand, cavitation in LN2 easily falls apart, detaches from the tip of the horn and forms complex structures. Due to chaotic formation of cavitation bubbles in an area further away from the tip of the horn, the so called cushioning effect influence on bubble collapses emerges - this results in less aggressive cavitation and consequently less erosive cavitation [24].

Pressure signals which are complementary to the images (Fig. 8) are presented in Fig. 9. One can see, that the driving frequency of the horn (20 kHz) dominates pressure signal. In water at 20°C, also pressure peaks after cloud collapses can be noticed (34  $\mu$ s delays marked on upper diagram in Fig. 9). 34  $\mu$ s delay corresponds precisely to time that the shock wave needs to travel between the center of the horn and pressure transducer (considering the distance and the sonic velocity). These peaks cannot be noticed at temperature of 100°C or in LN2, most probably due to asymmetrical and consequently less violent collapse. Comparing a single growth-collapse cycle for the three cases, one immediately notice the difference in their duration. An average duration of one cavitation growth-collapse cycle seems to be similar between two cases in water (20°C and 100°C), while in LN2 the cycle it is about 25% shorter. Speed of sound in LN2 - 1056 m/s is much lower in comparison with water at 20°C - 1482 m/s and 100°C - 1543 m/s. This shows different nature of cavitation dynamics in various liquids and indicates again, that it is very difficult to extrapolate results from tests in water to the cryogenic liquids.



**Figure 8:** Example of cavitation in H2O  $- 20^{\circ}$ C (upper image), H2O  $- 100^{\circ}$ C (middle image) and LN2 (lower image).



**Figure 9:** Time evolution of cavitation area and pressure distribution for  $H2O - 20^{\circ}C$  (upper image),  $H2O - 100^{\circ}C$  (middle image) and LN2 (lower image).

## **4** Conclusions

A series of experiments was conducted to deepen the understanding of cavitation dynamics in thermosensible liquids. Cavitation was induced by ultrasonic horn, where the so called acoustic supercavitation was achieved. With rising temperature of water from 20°C to 100°C, we achieved

gradually rising thermodynamic parameter  $\sum$  from 4 m/s<sup>3/2</sup> (T = 20°C) to about 3000 m/s<sup>3/2</sup> (T = 100°C), while thermodynamic parameter for LN2 was 2355 m/s<sup>3/2</sup>.

The results show, that cavitation dynamics in water changes drastically between 20°C and 100°C. At 60°C a notable cavitation extent peak and an even stronger peak in the number of individual cavitation structures were observed. The explanation based on the thermodynamic effect and vapor pressure influence on cavity growth was proposed.

Comparing cavitation behaviour between water and LN2 raises the question whether hot water can act like a surrogate to cryogenic liquids. It can be observed, that different liquids behave differently even though they have similar thermodynamic parameter  $\sum$ . Comparing cavitation dynamics between water and LN2 reveals their diverse nature of behaviour.

Results from observing cavitation dynamics in the presented paper correlates well with cavitation erosion tests from Dular&Petkovšek [24] and Dular [9], where the most aggressive cavitation appears at water temperatures of about 60°C. This can now be explained by the increase of the number of individual cavitation structures, which results in a higher number of cavitation collapses that stress the surface material.

Furthermore, the present paper might also explain our previous work on cavitation assisted removal of pharmaceuticals [25], [26]. There also, we observed that the removal rate is the highest at approximately 60°C, which means that the cavitation dynamics have also an extremely important effect on different water treatment processes by cavitation.

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