Luminescence of water in hydrodynamic cavitation with controlled dissolved gas in microchannel

L. Perrin[a], D. Colombet[a], G. Ledoux[b], F. Ayela[a]

a. LEGI, Université Grenoble Alpes, 38058 Grenoble Cedex 9 – France
b. ILM, Université C. Bernard Lyon 1, 69622 Villeurbanne Cedex – France
E-mail: lionel.perrin@univ-grenoble-alpes.fr

Abstract:

While sonoluminescence is a well known phenomenon in acoustic cavitation (Gaitan et al. 1992), luminescence induced in hydrodynamic cavitation have only been addressed at the macro-scale by Farhat et al. (2010). In this experimental work, hydrodynamic cavitation of water is studied in a micro-channel. The nucleation, growth and collapse of microbubbles in the flow is achieved through a micro-step thanks to a strong pressure change. It is found that such flow can induce an emission of a low light signal (~ 200-1500 photons/s). To study the luminescence and to characterize the intensity of cavitation that is directly correlated to this light emission, an experimental set-up was built with an optical detection system, efficiently isolated from any external light sources (noise ~ 10 photons/s). The influence of the experimental system and data analysis on the quantitative data treatment is discussed. The influence of pressure difference is investigated. As well, the effect of dissolved gas concentration (O_2, Ar, Xe) into deionized water on luminescence intensity is discussed in relation to existing theory (Flannigan & Suslick 2005).

Keywords: Hydrodynamic cavitation, microchannel, luminescence, dissolved gas, ionization

1 Introduction

When a liquid circulates through a pipe and reaches a strongly reduced section area, the liquid accelerates and a sudden decrease of pressure occurred. If the pressure becomes inferior to the saturated vapor pressure of the liquid, instantaneous evaporation occurs and bubbles appears in the liquid. When the pressure returned to a higher value, it induces a violent collapse of the bubbles with high gas temperature and pressure at the end of the bubble lifetime. These extremes conditions generate the ionization of gas presents in the bubbles, production of light and chemical reactions [1]. For the case of water under normal conditions, many different gas can be found in the bubbles such as polyatomic gas (water vapor, O_2, N_2 and CO_2 to a lesser extend) and monoatomic gas like Ar. The composition and the concentration of each gas in the bubble impact strongly the cavitation process and thus the production of light.

In a microchannel, it is very difficult to determine precisely when cavitation will occur due to the different geometrical factors into play. The section area of the flow as well as geometrical configurations like venturi, diaphragm, steps and even micro defects might impact the trigger of cavitation. In this work, a channel with a microstep is used to induce hydrodynamic cavitation of deionized and filtered water. For the first time, an experimental bench allows to measure the luminescence generated by cavitation in a micro-channel. Furthermore, the precision of the measurement allows quantitative comparison regarding the influence of the dissolved gas and pressure drop in the system on the luminescence, thus the strength of cavitation, and are discussed in the next sections.

2 Experimental set-up and signal analysis

2.1 Experimental set-up

A water tank is filled with 3L of deionized water which allows a circulation flow of around 15min for 5bar of pressure difference. In figure 1, a scheme of the experimental bench with detection systems is showed. The liquid goes through a filter of two grids with a mesh size of 40µm and then passes in a microchannel to be finally collected in a bottle. Liquid sample of 150ml is taken at the end of the circulation system when intensity measurement occurred in order to determine the O_2 concentration thanks to an oxymeter.

In order to detect and quantitavely characterize the hydrodynamic cavitation intensity, light emission from collapsing bubbles is measured thanks to a photomultiplier Hamamatsu H10722-210 (PM) with a light range detection of 230-700nm. The signal is then visualized by an oscilloscope (LeCroy 62Xs).

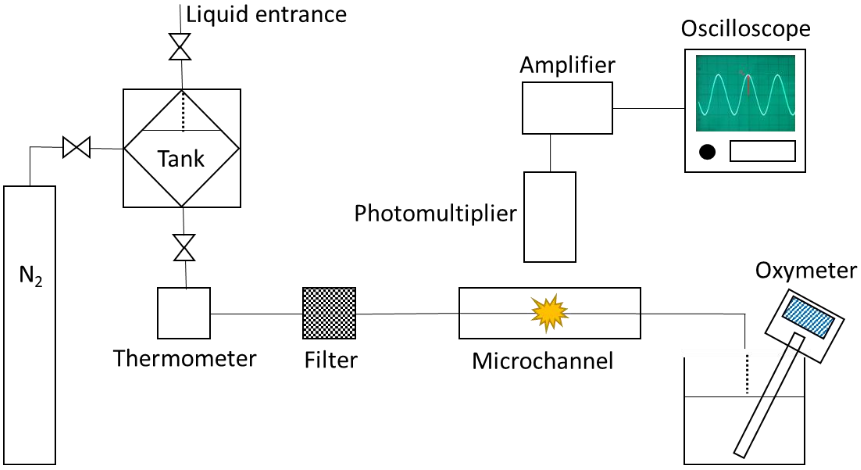

Figure 1: Scheme of the experimental set-up.

The intensity of hydrodynamic cavitation is measured optically with the light measurement system. With more intense cavitation due to stronger pressure difference, more light signal is observed on the oscilloscope of the optical system measurement, both in terms of amplitude and number of detected events. Now the optical measurement system has to be characterized with different experimental conditions in order to choose the settings which would give the most precise measurements for this specific experimental bench.

2.2 Signal analysis

The microchannel was efficiently isolated from parasite light coming from external sources. Since the signal of the noise is very low, it is easy to determine optically when cavitation occurred in our experiments. Furthermore, when cavitation is triggered, the signal of luminescence coming from the collapse of the bubbles was surprisingly strong and easy to separate from the noise signal even for simple configuration with only deionized water which has never been observed before at the microscale. It was determined that samples of 10s with a frequency sampling of 250kHz was sufficient in order to have convergence of the numbers of events detected per second (events/s). It has to be noted that each detected event might correspond to one or several photons of different energy and that our system is not able to determine exactly the number of photons that would reach the PM.

In figure 2, a sample of events detected by the PM without flow is represented in a). In b), the number of events per second is compared between the signal without flow and with a non-cavitating flow. Their values are compared over 10s and are shown to be of similar range of less than 10 events/s.

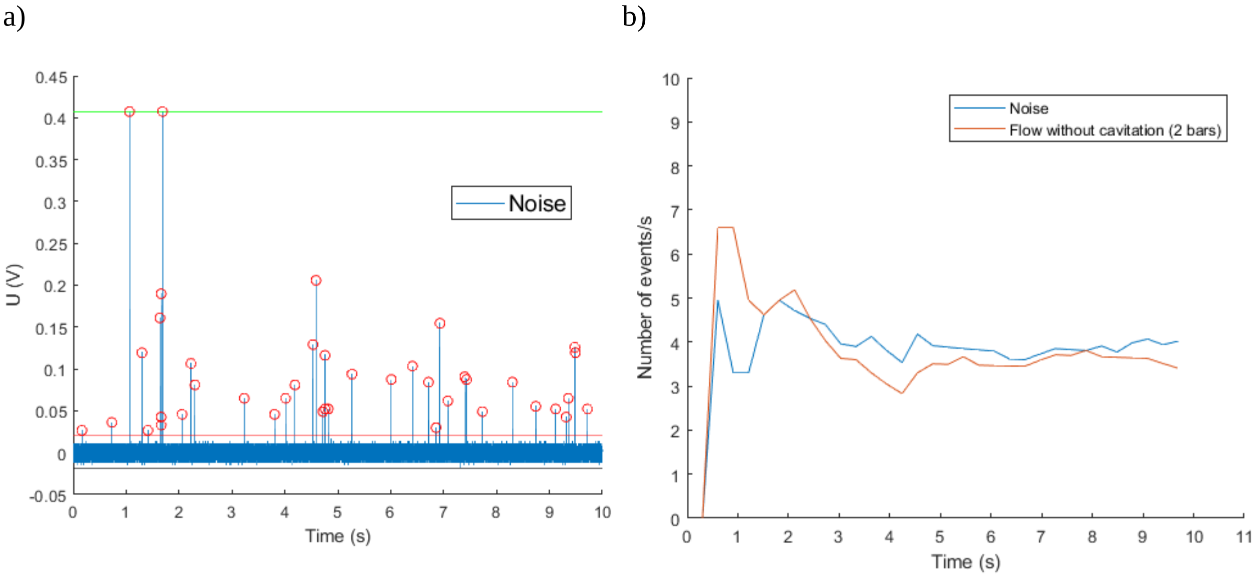

Figure 2: a) Signal detection of noise (without flow) and b) comparison of the number of events/s without flow and with a non-cavitating flow.

The reproducibility of the measurements was tested for different cases. In figure 3, good reproducibility was observed for deionized water with a pressure difference of 5 bar. Results gave around 200 events/s for this specific cavitating flow against less than 10 events/s for the noise.

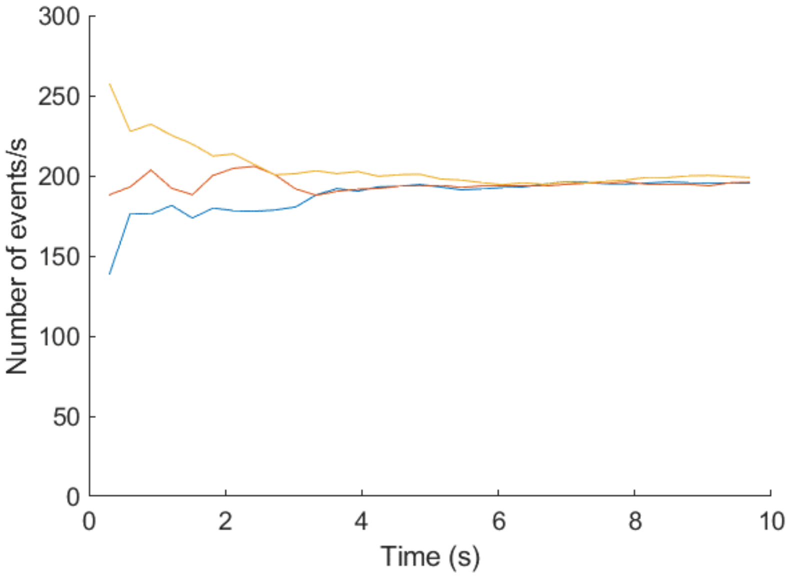

Figure 3: Reproducibility measurements for deionized water and DP=5bar.

3 Experimental results

3.1 Influence of concentration of dissolved gas

The concentration of all the dissolved gas could not be determined. Although, the concentration of dissolved O_2 is measured precisely at the end of the flow thanks to an oxymeter. With first approximation, we assumed that the concentration of all the other dissolved gas are proportional to the concentration of O_2 that is measured.

The luminescence of the cavitation of deionized water with different O_2 concentrations were measured and compared in figure 5. The pressure difference is 5 bars for all the experiments. The light signal (events/s) is more important when the concentration of O_2 (and other dissolved gas like N_2 and Ar) decreased. A plateau is observed when approaching 100% of O2. To explain this behavior, a higher concentration of these gas slows down the collapse of the bubble and decreases the amount of energy released during the collapse, inducing less ionization. The higher concentration of molecules potentially ionized cannot compensate this behavior and less photons are emitted.

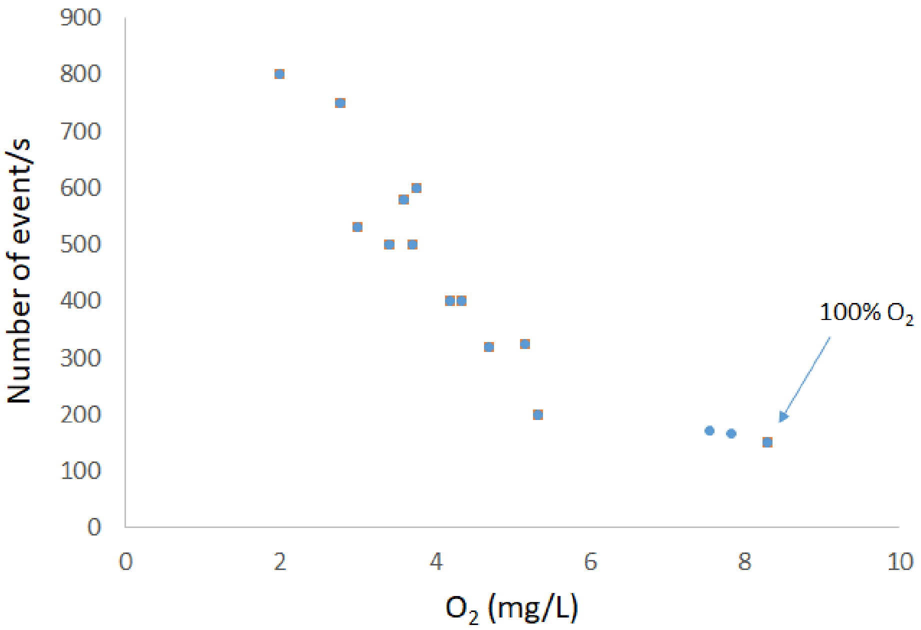

Figure 5: Number of events detected per second with different O_2 concentrations for DP=5bars.

3.2 Influence of the nature of the dissolved gas

In figure 6, the influence of Xenon and Argon on the luminescence signal in comparison to a solution with the same concentration of O_2 is shown. The concentrations of Argon and Xenon gas were increased in water but their values as well as the concentration of other naturally dissolved gas in water are not known in our experiments. Although, the concentration of O_2 is controlled and about the same for each experiments. As a first approximation, we can assume that the concentration of the other naturally dissolved gas like N_2 and CO_2 are similar for the different tests and would not impact the comparison between the different curves. A high concentration (although not controlled) of noble gas increases considerably the signal of luminescence for identical experimental conditions. Indeed, Xenon is known to increase the signal of luminescence induced by cavitation [2], [3] and [4] due to its low ionization potential.

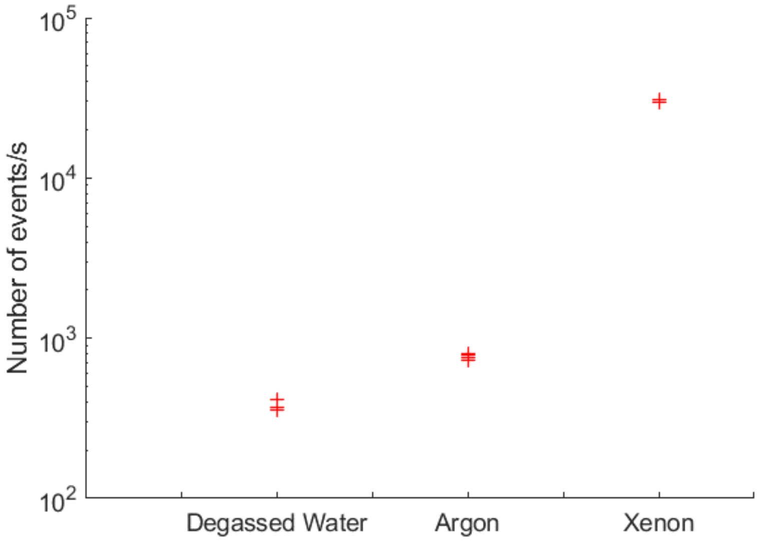

Figure 6: Number of events detected per second for different gas composition with a pressure difference DP=5bar and a concentration of around 5mg.L^{-1} of O_2.

3.3 Influence of pressure for different O_2 concentrations

Measurements were done on deionized water under different pressure drop. It was observed that under DP=4.7 bar, no hydrodynamic cavitation occurred. Starting 4.7 bar, metastable cavitation was observed and stable cavitation appeared at 5 bar which was measured with continuous light detection of our optical measurement. Pressure drop of 0 to 12 bar were tested and are represented in figure 5 for three different concentrations of dissolved O_2 (8.7, 4.2 and 3.7mg.L^{-1}). The maximum of 12 bar for the pressure difference is due to our pressurized bottle limitation. It was observed that using a higher pressure difference increased the intensity of the luminescence induced by cavitation as observed by Farhat et al. [2] for cavitation of water on a hydrofoil at the macroscale or Podbevsek et al. [5] with the chemiluminescence of luminol in water solution in a microchannel.

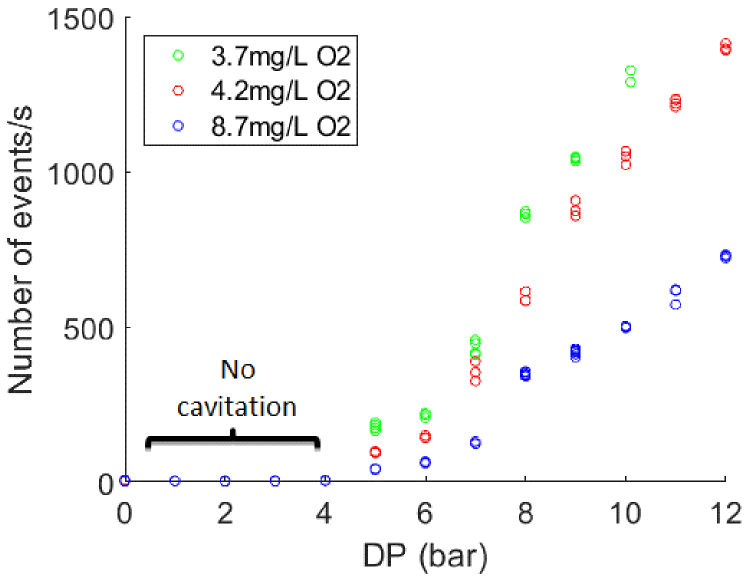

Figure 5: Number of event/s of three different concentrations of O_2 as a function of the pressure difference DP.

Conclusion

Hydrodynamic cavitation of water was generated in a micro-channel thanks to a sudden change of geometry inducing an important drop of pressure in the liquid. The violent collapse of the bubbles which occurs in the continuity of the flow has the potential to ionize the gas that are dissolved in the liquid. A new experimental bench was developed with an optical measurement system able to quantify the light emitted by the cavitation of deionized water for the first time in a microchannel, moreover with an important precision. Results show that decreasing the concentration of dissolved gas like O_2 would lead to an increase of the luminescence signal because these gas would slow down the collapse of the bubbles and decrease the level of energy released by the collapse that is necessary to ionize the dissolved gas. However, an increase of the concentration of noble gas (Ar and Xe) with lower potential of ionization increased considerably the measured luminescence. Further experiments would be needed in order to reach and control the concentration of all the dissolved gas in the liquid as well as different geometry conditions regarding the micro-channel.

References

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