From nucleation to cloud cavitation

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Abstract. This paper shows the dependency of cavitation nuclei and the resulting cavitation, illustrating the lifetime of a bubble from its birth to death. Micro bubbles which are periodically detaching from surface nuclei contribute to the formation of a sheet. After reaching a critical length, which depends on the nucleation rate, the sheet is peeled off by a viscous spreading film. The detached sheet forms a cloud in the shape of a horseshoe with a circulation depending on the sheet length and, consequently, the nucleation rate. Finally, the cloud collapses with an intensity depending on the circulation.

1. Introduction

Cavitation in hydraulic machines is usually accompanied by different negative aspects. Vibration, noise, changes in the machine characteristics and damage of structural elements are just some of the problems that may occur [1]. But there are also useful applications for cavitation, like cleaning surfaces [2], fragmentation of kidney stones [3] or the enhancement of mixing processes [4]. These are only some application examples for both acoustic and hydrodynamic cavitation.

In this paper the focus is on hydrodynamic cavitation. Single bubble cavitation, streak cavitation, sheet cavitation, cloud cavitation and supercavitation are just some of the forms that may occur in a cavitation regime. Regarding the impacts on a hydraulic machine, cloud cavitation can be seen as the worst form. Periodically detaching bubble clusters collapse downstream of a sheet cavity with high intensity, emitting high pressure waves hitting the structure. This causes not only noise and vibration, but can also lead to severe damages of the machine or surrounding structures [1].

This paper deals with the formation mechanisms of cloud cavitation. Like most types of cavitation it consists of three parts, which represent the lifetime of a bubble: (i) birth, (ii) midlife and (iii) death. As the research being conducted at Technische Universität (TU) Darmstadt in recent years indicates, these single phases can be linked to each other [5, 6, 7]. Thus, this paper intends to provide an overview of the most recent findings on the formation of cavitation. It is organized as follows: section 2 introduces the formation of a bubble and gives an overview of the different nucleation theories in a hydraulic system. Section 3 deals with the midlife of the bubble in a sheet cavity and the following transition from sheet to cloud cavitation. Section 4 describes the physical properties of the detaching cloud and its final collapse downstream. The paper closes with a summary and conclusion.
2. Birth of a bubble

It is widely accepted that the origin of cavitation lies within micro bubbles in the liquid. These so-called nuclei act as weak spots, which allow the rupture of liquids under technical relevant pressures [1]. Without such nuclei liquids are able to withstand high tensile stresses, as the experiments conducted by Briggs [8] demonstrate. In cavitation research a distinction is made between free stream nuclei floating within the bulk of the liquid and nuclei attached to surrounding walls or particles within the fluid. The latter ones are usually referred to as surface nuclei [1]. In this article the focus is on surface nuclei, which have been investigated at TU Darmstadt in the last years [7, 9, 10]. For the sake of completeness it has to be mentioned, that other types of nuclei contribute to the formation of cavitation regimes as well.

In the last years several nucleation theories have been developed. Figure 1 provides an overview of these theories. A distinction is made between equilibrium theories and non-equilibrium theories. To serve as cavitation nuclei permanently, both surface nuclei and free stream nuclei have to be stabilized in some way. Dispersed gas bubbles grow or shrink due to diffusion and are consequently unstable. Thus, Fox & Herzfeld [11] proposed the existence of an organic skin that stabilizes the nucleus while Yount et al. [12] developed the theory of surface-active surfactants. This skin impedes diffusion and therefore limits bubble growth and shrinkage, resulting in an equilibrium, cf. figure 1 (a). Harvey [13] proposed the existence of miniature gas bubbles entrapped in hydrophobic surfaces, which are stabilized by the effect of surface tension, cf. figure 1 (b). Since the surface tension acts on the convex liquid-gas-interface, the pressure in the nucleus is lower than the pressure in the liquid. Consequently, the nucleus does not dissolve into the liquid, unless it is strongly undersaturated. Based on Harveys findings Atchley and Prosperetti [14] developed the crevice model, which was later validated by Bremond et al. [15]. Miniature gas bubbles trapped inside a hydrophobic surface grow due to a local pressure drop. This process is called heterogeneous nucleation.

The crevice model assumes that the liquid is in a concentration equilibrium. This holds true for quiescent liquids, but in hydrodynamic cavitation the liquid is mostly supersaturated due to local low pressure regions. Hence, for nucleation in hydrodynamic cavitation non-equilibrium theories need to be taken into account. The classical nucleation theory, also referred to as homogeneous nucleation, was developed by Jones et al. [16] in 1999 and is usually applied when dealing with hydrodynamic cavitation, cf. figure 1 (c). It describes the bubble formation which is initiated by thermal motion of gas molecules. For this process the tensile strength of the liquids needs to be overcome to form a new phase. It is reasonable to assume that supersaturations of more than 100 are needed in this case [9]. This is far above supersaturations which are to be expected in hydrodynamic cavitation.

In most cases it is argued that diffusion only plays a minor role in cavitation processes, as the typical timescale for diffusion processes is usually much higher than the typical timescale of the cavitation events. This holds true for the bubble collapse. However, even Atchley and Prosperetti [14] stated that for nucleation events diffusion might be important. From that Groß and Pelz developed the theory of diffusion-driven nucleation [9], cf. figure 1 (d). If the local pressure falls below the saturation pressure of the liquid, gas starts diffusing from the now supersaturated liquid into the available nuclei. According to Henrys law [17], the gas concentration within the bulk of the liquid in an equilibrium \( c_S \) depends on the local pressure \( p \) and the Henry-Coefficient \( H \),

\[
c_S = pH. \tag{1}
\]

The supersaturation \( \zeta \) is defined as the relation between the local gas concentration \( c \) and the gas concentration in the initial saturation state \( c_{\infty} \),

\[
\zeta := \frac{c}{c_{\infty}} - 1. \tag{2}
\]
Figure 1. Schematic overview of nuclei and nucleation in liquids. A distinction is made between equilibrium and non-equilibrium theories with respect to the solved gas content [9].

Thus, $\zeta > 0$ can be seen as a necessary condition for diffusion-driven nucleation. When this is fulfilled, gas from the supersaturated liquid is transported through the liquid-gas-interface of the nucleus. This gain of mass leads to the growth of the nucleus. After it reaches a critical size, a bubble detaches and is carried away by the stream. Some of the gas is left behind inside the crevice, and the process starts again. Figure 2 visualizes this cyclic process with periodic bubble detachment.

As Groß and Pelz [9] show, the bubble formation takes much more time than bubble detachment. Consequently, the nucleation frequency $f$ can be written as

$$f = \frac{\dot{m}}{m_B},$$

where $\dot{m}$ is the diffusion mass flux into the nucleus and $m_B$ is the mass of the detaching bubble.
Figure 2. Diffusion-driven nucleation as explained by Groß and Pelz [9]. On the top a NACA0009 hydrofoil from the top view perspective with the flow going from left to the right is shown. On the left side bubbles detach periodically with a nucleation rate of approximately 1000 Hz. The picture below visualizes the nucleation process. A surface nucleus grows due to diffusion of gas from a supersaturated liquid until it reaches a critical size. Then a bubble detaches, leaving behind some of the gas. As Groß and Pelz show, this is a self-exciting process [9].

The bubble travels further downstream where it agglomerates with other bubbles emerging from different nucleation sites. This development of a cavitation sheet layer, which is referred to as midlife of a bubble, is described in the following section.

3. Midlife

There are different forms of cavitation that can be observed in a fluid system. Figure 2 shows the top view of a NACA0009 hydrofoil. A surface nucleus on the left side produces bubbles with a nucleation rate of about 1000 Hz, travelling along with the stream from left to right. This form of cavitation is referred to as streak cavitation. Periodically detaching bubbles from the nucleus line up like on a pearl string, forming a single streak. In typical fluid systems there is not only a single nucleus, but multiple nucleation sites next to each other. This can be a line of roughness, an edge of a hydrofoil, the point of laminar separation, or an artificial roughness. This phenomenon can be observed as sheet cavitation.

Figure 3 (a) pictures the sheet cavitation. A convergent-divergent nozzle with an obstacle is considered. The flow goes from left to the right with the velocity $U_0$ in the smallest cross section
at the position \( x = 0 \). This is where the sheet cavity originates. Detaching bubbles are carried downstream with a velocity which is approximately the flow velocity \( U_0 \), forming a sheet with the length \( a \). Nuclei within the sheet are carried through a region of constant pressure, which grants a stable midlife of a bubble [18]. The front bubble experiences a pressure imposed by the flow causing a bubble collapse in the time \( \tau \). While collapsing it travels a distance \( U_0\tau \). The distance between the first bubble and the next one is \( U_0/f \), with the nucleation rate \( f \) at the nucleation spot. If the travelling distance of the first bubble during its collapse is larger than the distance between the first bubble and the second bubble, the second bubble will collapse further downstream. Thus, the sheet length \( a \) increases. It reaches its maximum length when the travel distance equals the distance between the two bubbles, \( a = \hat{a} = U_0/f \) [18]. This is a simple kinematic condition determining the sheet length.

![Schematic view of sheet cavitation (a) and cloud cavitation (b)](image)

**Figure 3.** Schematic view of sheet cavitation (a) and cloud cavitation (b) [18].

As the experiments by Pelz et al. [19] show, viscous effects only play a minor role for the dynamics of sheet growth, as only the bubble dynamics is damped by viscous stresses. Yet, they do play an important role when it comes to the transition from sheet to cloud cavitation. As soon as the sheet growth comes to an end, a thin viscous film begins to form. This so called re-entrant jet originates at the tip of the sheet and moves upstream across the curved surface. It starts with the initial length \( \xi(t = 0) = 0 \) and the initial speed \( \xi(t = 0) = U_0 \), cf. figure 3 (a) [18].

There are two possible situations that may appear. If the maximum length of the viscous film is much smaller than the length of the sheet, \( \xi \ll \hat{a} \), the sheet appears to be stationary. Only small bubbly vortices are peeled off at the tip of the sheet, gaining a circulation \( \Gamma \approx 2U_0\xi \). This situation is referred to as sheet cavitation [18]. If the re-entrant jet reaches the point of origin, \( \xi = \hat{a} \), the sheet is peeled of completely. It forms a cloud with a circulation \( \Gamma \approx 2U_0\hat{a} \), which
will most likely form a horseshoe vortex, cf. figure 3 (b) [18]. This horseshoe was first observed by Kato [20]. Only the horseshoe and the related torus shaped cloud satisfy the Helmholtz vortex theorem. This process acts periodically with the cloud detachment as a trigger. With the bubbly vortices detaching from the sheet, the final phase in the life of a bubble begins as it is described in the following section.

4. Death
After the sheet detaches from the point of origin it forms horseshoe shaped cloud, cf. figure 4 (a). The picture shows the top view of a detaching cloud in the experimental setup used by Buttenbender and Pelz [21]. The formation of a cloud is a consequence of vortex shedding [22]. According to the Helmholtz vortex theorem a vortex filament can not end inside the fluid but must be either closed or end at infinity. This suggests a torus model as pictured in figure 4 (b). The radius $R_T$ denotes the major radius, while $R_{Cl}$ is the minor radius of the torus.

Figure 4. Cloud cavitation (a) and the corresponding torus model (b). After detaching from the point of origin, the sheet layer forms a cloud in the shape of a horseshoe [21].

The torus has three different time scales. The first one is the typical time of a bubble inside the cloud $t_B$, which is given by its natural frequency [23]. The typical time of the cloud $t_{Cl}$ is the time a perturbation needs to travel from the outer boundary of the cloud to its center. The interaction parameter $\beta_0 \propto (t_{Cl}/t_B)^2$ as introduced by Wang [24] describes the interaction between the bubble and the cloud. If $\beta_0$ is small, $\beta_0 < 1$, the natural frequency of the cloud is close to the natural frequency of individual bubbles. For $\beta_0 > 1$ the cloud effects are dominant, resulting in a natural frequency of the cloud which is much lower than the natural frequency of individual bubbles [24]. The excitation time of a dynamic or kinematic excitation is denoted as $t_e$. In this case the focus lies on kinematic excitation given by the circulation, cf. section 3. In the following, the circulation is related to the critical circulation $\Gamma_{crit}$ at which an unstable growth of the cloud occurs, $\Gamma/\Gamma_{crit}$ [21].

The influence of circulation on the collapse intensity of the cloud can be investigated in two different ways. The first one is the evaluation of the farfield pressure $p_A$. It describes the acoustic load at a given distance $R_a$ and occurs at the time of maximum cloud radius acceleration, $\ddot{R}_{Cl}$. Figure 5 (a) pictures the farfield pressure for different circulations and interactions. As Buttenbender and Pelz [21] show, the maximum farfield pressure, and consequently the collapse intensity, is strongly enhanced when the related excitation time $t_{E}/t_B$ is sufficiently large.

Another approach for the evaluation of the collapse intensity is the investigation of the minimum bubble radius or, equally, the maximum compression. As figure 5 (b) shows, the
circulation enhances the compression independent of the interaction. The compression increases with proximity to the center of the cloud [21]. It has to be noted that, considering the toroidal geometry of the cloud, the center is in contact with a surrounding wall. As the result, the damage potential is strongly increased by the influence of circulation. Further details can be found in the work of Buttenbender and Pelz [21].

![Graph](image)

**Figure 5.** Maximum farfield pressure (a) and maximum bubble compression (b) for different circulations and interactions [21].

5. Conclusion
Cavitation consists of the three phases of lifetime of a bubble: (i) birth, (ii) midlife and (iii) death. This paper highlights the link between the single phases. Due to diffusion-driven nucleation surface nuclei periodically detach free bubbles with a given frequency $f$. These bubbles form a cluster, which can be observed as a streak or sheet attached to a single line of roughness, the edge of a hydrofoil or an artificial obstacle. The sheet length increases as long as the nucleation frequency is higher than the collapse time of a bubble at the tip of the sheet. Consequently, the sheet length depends on the nucleation rate, $a = a(f)$. When the sheet growth comes to an end, a re-entrant jet forms and peels off the sheet, which then forms a cloud in the shape of a horseshoe. This cloud gains a circulation $\Gamma$ depending on the length of the sheet, $\Gamma = \Gamma(a(f))$. Finally, the cloud collapses downstream, with the collapse strength being enhanced by the circulation of the cloud.

This paper provides a new understanding of the formation of cloud cavitation. It highlights the dependency of the single mechanisms, working together like a Matryoshka doll. Based on the presented findings other forms of cavitation can be investigated from a new perception.

References

[1] Brennen C E 1995 *Cavitation and Bubble Dynamics* (Oxford University Press)
[2] Verhaagen B and Fernandez Rivas D 2015 *Ultrasonics Sonochemistry* 29 619–628
[3] Brennen C E 2015 *Interface Focus* 5
[4] Spiridonov E K 2015 *Procedia Engineering* 129 446–450
[5] Buttenbender J 2012 *Über die Dynamik von Kavitationswolken* (Shaker Verlag)
[6] Keil T 2014 *Theoretische und experimentelle Untersuchungen der Schicht- und Wolkenkavitation* (Shaker Verlag)
[7] Groß T F 2018 Diffusionsgetriebene Keimbildung an Porenkeimen in kavitierenden Strömungen (Shaker Verlag)
[8] Briggs L J 1950 J. Appl. Phys. 21 721–722
[9] Groß T F and Pelz P F 2017 Journal of Fluid Mechanics 830 138–164 ISSN 0022-1120
[10] Groß T F, Bauer J, Ludwig G, Rivas D F and Pelz P F 2017 Experiments in Fluids 59 1–10 ISSN 0723-4864
[11] Fox F E and Herzfeld K F 1954 J. Acoust. Soc. Am. 26 984–989
[12] Yount D E, Gillary E W and Hoffman D C 1984 J. Acoust. Soc. Am. 76 1511–1521
[13] Harvey E N, Barnes D K, McElroy W D, Whiteley A H, Pease D C and Cooper K W 1944 J. Cell. Physiol. 24 1–22
[14] Atchley A A and Prosperetti A 1989 J. Acoust. Soc. Am. 86 1065–1084
[15] Bremond N, Arora M, Ohi C D and Lohse D 2005 J. Phys.: Condens. Matter 17
[16] Jones S F, Evans G M and Galvin K P 1999 Adv. Colloid Interface Sci. 80 27–50
[17] Henry W 1803 Philos. Trans. R. Soc. London 93 29–274 ISSN 0261-0523
[18] Pelz P F, Keil T and Groß T F 2017 J. Fluid Mech. 817 439–454
[19] Pelz P F, Keil T and Ludwig G 2014 Advanced Experimental and Numerical Techniques for Cavitation Erosion Prediction (Springer Netherlands) chap 9
[20] Kato H e a 2002 JSME International Journal 45 655–660
[21] Buttenbender J and Pelz P F 2012 Proceedings of CAV 2012: 8th International Symposium on Cavitation (Singapore)
[22] Brennen C 2005 Fundamentals of Multiphase Flows (Cambridge University Press)
[23] Plesset M S and Prosperetti A 1977 Ann. Rev. Fluid. Mech. 9 145–185
[24] Wang Y C 1996 Shock Waves in Bubbly Cavitating Flows (PhD thesis. Cal. Inst. of Tech.)