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Measuring cavitation and its cleaning effect

Bram Verhaagen [a], David Fernández Rivas [a,b,*]

[a] BuBclean, Institutenweg 25, 7521PH Enschede, The Netherlands
[b] Mesoscale Chemical Systems Group, University of Twente, 7500AE Enschede, The Netherlands

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ABSTRACT

The advantages and limitations of techniques for measuring the presence and amount of cavitation, and for quantifying the removal of contaminants, are provided. After reviewing chemical, physical, and biological studies, a universal cause for the cleaning effects of bubbles cannot yet be concluded. An "ideal sensor" with high spatial and temporal resolution is proposed. Such sensor could be used to investigate bubble jetting, shockwaves, streaming, and even chemical effects, by correlating cleaning processes with cavitation effects, generated by hydrodynamics, lasers or ultrasound.

1. Introduction: cleaning with bubbles

Bubbles are well-known for their cleaning potential. As stated by Prosperetti, thousands of papers have been devoted to the subject of bubbles [1]. Bubbles can be generated ultrasonically, by laser, hydrodynamic effects, or other techniques. However, the exact cleaning mechanism induced by bubbles has not yet been elucidated, and the contribution of jets, shockwaves and other phenomena is still under discussion. The aim of this article is to discuss possible methods for identifying the cleaning mechanism. Here we give a non-exhaustive list of the techniques used for measuring the presence and amount of cavitation, and to quantify cleaning, and finally on studies that have correlated the two.

Measurements of the ultrasonic cavitation intensity are used as indicators of the effectiveness of an ultrasonic cleaning system. The intensity is often being related to the speed and thoroughness of cleaning, and the distribution is related to the uniformity of surface cleaning [2]. Section 2 discusses techniques and concepts to evaluate the effects of the violent and short lived emptiness that a collapsing bubble represents.

It is important to define what 'clean' means. 'Clean' can be defined as the absence of contaminants, which can be any undesired substance on an object. Contamination can come from dust, polishing paste, production waste material, bacteria, or even our own cells or hair. It can be said that an object is clean when the amount of contaminant has been reduced to an acceptable or detectable level. The *acceptable* level of contaminants is different for every application, and for some industries and health sectors this has been regulated by ISO norms, e.g. 15883 for medical instruments. The *detectable* level of contamination depends on the measurement technique; and an overview of methods for measuring the cleanliness of a surface is given in Section 3.

A technical challenge in elucidating the cleaning mechanisms is to correlate the cavitation activity to the cleaning performance. Some attempts in this direction are covered in Section 4, and these studies have given some insight into the cleaning mechanisms involved in those situation. However, the ideal sensor or setup is not yet available. An ideal sensor would be able to determine the events of a bubble at relevant time scales, while simultaneously quantifying the cleaning that the bubbles perform, at relevant space and time scales. Our view on this is given in Section 5. Fig. 1 shows the outline of the article.

2. Measuring cavitation

Cavitation is defined as the formation of a void within a liquid, and its subsequent behaviour [3]. Since a void is the absence of fluid, it cannot be detected directly, but there are indirect methods available for measuring cavitation.

The first known attempt to study cavitation bubbles by their erosion potential was by Rayleigh in 1917 [4]. More recent reviews on cavitation, characterisation techniques and physical effects can be found in scientific literature [5–7]. Regarding the chemical

* Corresponding author at: BuBclean, Institutenweg 25, 7521PH Enschede, The Netherlands.

E-mail address: d.fernandezrivas@utwente.nl (D. Fernández Rivas).

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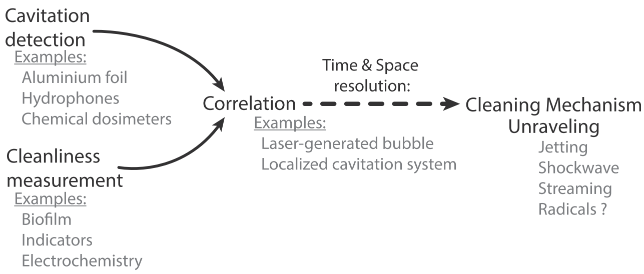

Fig. 1. General structure of the article. We begin with a discussion of the methods available for detecting cavitation bubbles and quantifying cleanliness. This is followed by an overview of previous attempts at correlating the two, in order to unravel the cleaning mechanism of bubbles. An ideal sensor will be required for this aim, which will be discussed at the end of the article.

effects of cavitation, there is equally an extensive body of literature around the generation of free radicals and biological effects [8–12]. Right from the start, researchers highlighted the difficulty in obtaining reproducible results.

A comprehensive review of different techniques to understand the cavitational activity distribution in chemical reactors, divided them in those that register primary effects and secondary effects [13], see Fig. 2. Primary effects include temperature pulse, pressure pulse, generation of free radicals inside the bubble, and micro-circulation in the vicinity of bubble at the collapse instant. Secondary effects involve quantification of chemical or physical effects after the collapse such as oxidation reactions, intensification of mass transfer coefficients, enhanced electrochemical effects, fluorescence, aluminium foil erosion, PIV, etc. Generation of free radicals is considered a primary effect, but measured mostly in chemical reactions after bubble collapse. The experimental information has often been complemented with theoretical modelling.

Exhaustive reviews on cavitation detection and measurement methods for high power ultrasonic fields have discussed their application in health care, sonochemistry and industrial ultrasonics [14,15]. The standardisation attempts of cavitation have been compared to that of standardising fire: its occurrence can be visualised and it can be controlled for practical uses, but only the

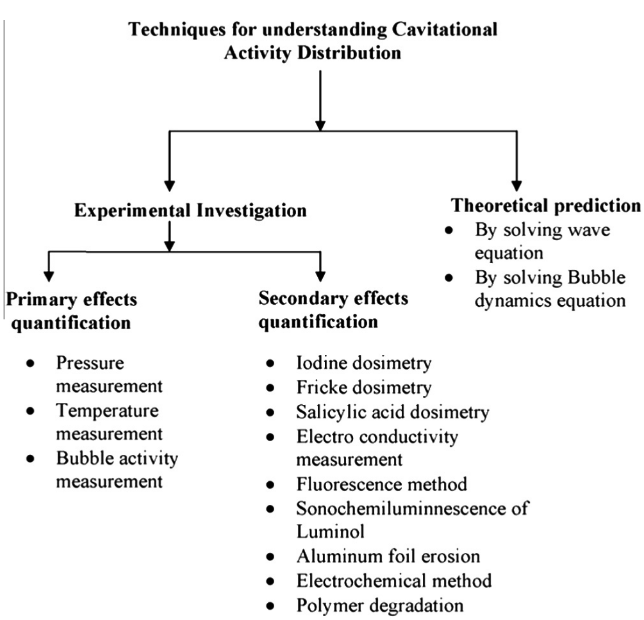

Fig. 2. Classification of different types of cavitation mapping techniques. The experimental techniques are divided into primary and secondary effects. Taken from [13].

time- and space-averaged phenomena of the flame (light emission, produced heat, oxidisation, etc.) can be standardised. The same is true for cavitation.

2.1. Basic tests for detecting cavitation

Aluminium foils placed inside ultrasonic baths or close to ultrasonic horns are among the most basic tests to determine cavitation activity. A thin foil is eroded within minutes, and erosion patterns may be found corresponding to cavitation hot spots resulting in cleaning action concentrated in horizontal stripes (at pressure antinode regions). Bubbles can grow on the foil surface, translate and cluster. Streams of bubbles originate from certain regions on the surface and end in a bubble cloud "smoker" (or "streamers"), which has a strong erosive power [16].

It has been reported how streamers (multibubble structures) in standing waves are organised in planes parallel to the water surface. This resulted in cleaning action concentrated in horizontal stripes on the aluminium foil or painted glass surface [16]. This test is suitable for comparing the performance of an ultrasonic bath over time and obtaining a rough estimation of high pressure zones (hot spots), however the results are very sensitive to the placement of the foil, liquid temperature, dissolved gas and other variables. Ideally, this test would be standardised using materials with well-defined specifications, since the rigidity of the wall will affect the attraction of a bubble towards the boundary [17]. Automated analysis (e.g. image analysis or sample weighing) is another possible improvement [2].

The foil test is specified in the IEC/TR 60886 Technical Report, although it was concluded that there was no method suitable for standardisation. An alternative version of the foil test involves the erosion of pieces of lead under ultrasound exposure, or painted glass surfaces [2]. Another standard test uses carbon-coated ceramic rings, where the amount of removed carbon over time gives a measure of the mechanical cleaning activity inside an ultrasonic bath.

The distance from the bubble, or cluster of bubbles, to a wall as collapse occurs is defined as $\gamma = r/R_{max}$, where r is the distance from the wall and R_{max} the maximum radius attained by the bubble. This stand-off distance has a strong influence on the type of erosion effects. Fig. 3 shows how the laser-generated bubble collapses on aluminium foil leads to different erosion patterns for different values of γ [18]. The presence of defects in the surface, which can serve as nucleation sites, or simply pinning bubbles, have been observed to be accelerators of cleaning and erosion effects [19–21].

SonoCheck™ is a vial with a solution that changes colour within a few minutes due to ultrasound exposure, and can therefore be used as ultrasonic activity indicator. Its main ingredients are chloroform, buffer solution, and a pH-sensitive dye; its working principle appears to be based on ultrasound degradation of chloroform. Since the chloroform concentration is reduced by cavitation [22], the pH of the solution changes and therefore the colour of the vial solution changes. The SonoCheck™ also allows for monitoring the performance of an ultrasonic bath over time, but not to compare baths due to the underlying processes that depend on several factors, including ultrasound frequency and sample positioning.

2.2. Acoustic detection of cavitation

The onset of cavitation is characterised by an increase in the first subharmonic of the ultrasonic driving frequency. The origin of this phenomena lies in the onset of instabilities of large bubbles before they start to collapse [23]. Monitoring the subharmonic frequency component can therefore give an indication of the onset of