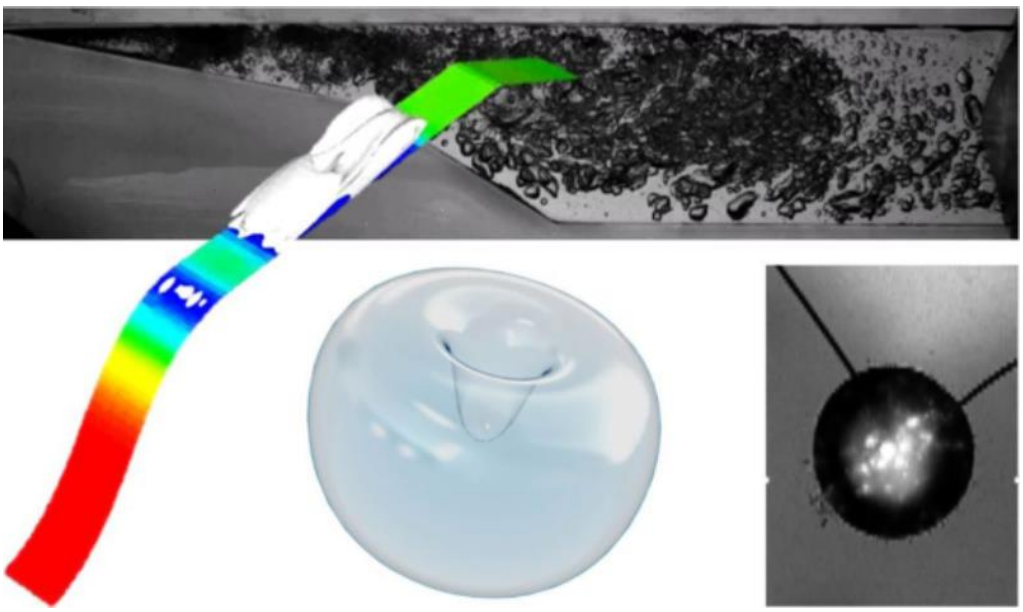
University of Ljubljana
Faculty of Mechanical Engineering

European Research Council

WORKSHOP ON CAVITATION EXPLOITATION



prof. dr. Matevž Dular (editor)

University of Ljubljana

27 – 28 September 2018, Ljubljana Slovenia

Contents:

Schedule

Thursday, September 27th

09:00	Dular	Welcome
09:05	Rivas	Cleaning is a dirty business: tales of microfluidics and ultrasonic cavitation
09:35	Bräutigam	Hydrodynamic-Acoustic-Cavitation – New developments and applications
10:05	Stopar	What makes bacteria resistant to hydrodynamic cavitation treatment?
10:25	COFFEE	
10:55	Ohl	The Dirty Truth of Surface Attached Nanobubbles
11:25	Albanese	Bringing hydrodynamic cavitation powered beer-brewing from the pilot to the industrial scale: challenges and solutions
11:55	Suponnen	Why Kelvin Impulse is a great tool to predict the behaviour of jetting bubbles
12:15	COFFEE	
12:45	Casciola	Vapour bubble nucleation via Fluctuating Hydrodynamics
13:15	Yu	Improvement of FCM Cavitation Model and Prediction for Bubble Cluster Collapse
13:35	Hegedűs	Towards the optimization of dual-frequency driven sonochemistry: a four dimensional parameter scan of a single gas bubble accelerated by GPUs
13:55	LUNCH	
15:15	Lukežič	Apliccation of hydrodynamic cavitation for inactivation of waterborne viruses
15:35	Taubert	Modelling a cavitation cloud employing the van wijngaarden ansatz
15:55	Csoka	Wastewater remediation by hydrodynamic cavitation
16:15	COFFEE	
16:45	Rudolf	Cyanobacteria elimination using hydrodynamic cavitation
17:15	Cravotto	A technology platform based on cavitation to link research labs to industry
17:35	Langone	Hydrodynamic cavitation for wastewater treatments and agro-industrial biogas plants: experimental results

Friday, September 28th

09:00	Quinto	Interaction between laser-induced shocks and bubbles
09:30	Calvisi	Dynamics and modeling of encapsulated microbubbles in biomedicine
10:00	Iben	Influence of cavitation induced pressure loading on cleaning of coking layers in sonotrode tests
10:20	COFFEE	
10:50	Rosselló	Bubble Jets in High-intensity Ultrasound
11:10	Podbevsek	Light based measurements in micro cavitating flow
11:30	Zupančič	Expirience of nanobubble technology usage in fish farming
11:45	Veronik	Wastewater treatment for Wineries
12:00	COFFEE	
12:30	Tzanakis	Application of cavitation bubbles for the production of high quality light metal alloys
13:00	Kadivar	Boundary layer instability control in the unsteady partial cavitation regime using Cavitating- bubble Generators (CGs)
13:20	Prisciandaro	Study of the performance of a hydrodynamic cavitation plant in the treatment of industrial wastewaters at a lab scale
13:40	Žgajnar Gotvajn	Hydrodynamic cavitation in combination with the advanced oxidation processes for water treatment – selected implications
14:00	LUNCH	
15:00	Ledig	Sensing Cavitation in Hydraulic Machines and Devices by Acoustic Emissions
15:20	Manmi	Numerical Investigation of Acoustic Cavitation as a Novel Method of Dental Plaque Removal
15:40	Meneguzzo	CAVIBEER: advancing a new technological standard in beer brewing powered by hydrodynamic cavitation

Foreword

There is a large gap between the understanding of the mechanisms that contribute to the effects of cavitation and its application. Although engineers are already commercializing devices that employ cavitation, we are still not able to answer the fundamental question: How exactly do cavitation bubbles clean surfaces, deactivate different microorganisms, degrade organic compounds and help synthetize chemical substances?

The idea to organize a workshop on the topic coincides with the start of the ERC project: An investigation of the mechanisms at the interaction between cavitation bubbles and contaminants: CABUM".

The workshop is dedicated to sharing and exchanging recent advances and experiences in experimental and numerical techniques dealing with cavitation exploitation. It represents a great and unique opportunity for all guests as well as organizers to present their on-going activities, exchange ideas, share their thoughts on current and newly acquired knowledge. During the two days of the workshop, invited scientists from academia, private companies and government laboratories who are currently active in the exploitation of cavitation will present and discuss their work regarding relevant subjects. Given lectures and presentations are expected to stimulate an open technical discussion among present leading researches in the field and organisers to share their knowledge and experience (successes and failures) as freely as possible.

Our final and overall objective is to understand and determine the fundamental physics of the interaction of cavitation bubbles with different contaminants. To address this issue, the CABUM project will investigate the physical background of cavitation from physical, biological and engineering perspective.

Understanding the fundamental physical background of cavitation in interaction with different contaminants, will have a ground-breaking implication in various scientific fields (i. e. engineering, chemistry and biology) and will, in the future, enable the exploitation of cavitation in water treatment processes.

Ljubljana, September 27th and 28th 2018

CABUM team (Matevž Dular, Mojca Zupanc, Tadej Stepišnik Perdih, Martin Petkovšek, Žiga Pandur, Jure Zevnik)

Ljubljana, 27 – 28 September 2018

Invited talks

David Fernandez Rivas

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Cleaning is dirty business: tales of microfluidics and ultrasonic cavitation

Ultrasonic cavitation can be seen as a green process intensification technology since it focuses acoustic energy to produce mechanical forces and chemical reactions [1].

These effects can be used for applications such as cleaning objects, water treatment and nanochemistry. However, reproducibility of cavitation processes is poor. Even when the ultrasonic equipment, glassware, chemicals and experimentalist person, are not changed, there is no guarantee of small error bars of an expected result. This is because creating bubbles with ultrasound closely resembles a stochastic process influenced by physical-chemical factors difficult to control at once. Due to this lack of reproducibility and low energy efficiency, industrial applications are scarce.

In this talk, some technical hurdles in scaling up sonochemical reactors to industrial size will be presented. I will share experiences in scaling-up a microfluidic sonochemical reactor that reached 10 times higher efficiencies with improved reproducibility [2]. This microreactor has already been used to remove contaminants with bubbles generated with sub-millimetric spatial control [3]. With the same approach we have obtained a significant improvement in reproducibility, as determined with radical dosimetry [4]. Our efforts in scaling up these ultrasonic cleaning and sonochemical processes have given us a better understanding of the cleaning process [5], how to control it for practical uses and compare different alternatives [6].

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Hydrodynamic-Acoustic-Cavitation: New developments and applications

Cavitation is known to induce and/or enhance different biological, physical or chemical processes [1]. For industrial applications, cavitation can be initiated either by acoustic effects (ultrasound) or through the utilization of hydrodynamic phenomena [2,3]. Both techniques have advantages and disadvantages, concerning scale-up, energy efficiency, collapse temperature, and bubble density [4-7]. Therefore, a combination of both techniques in one reactor system (hydrodynamic- acoustic-cavitation, HAC) was introduced, taking advantage of the benefits of the single generation methods (high bubble density and high collapse intensity) and avoiding the corresponding drawbacks [4,8-10].

In the presentation, the technique of hydrodynamic-acoustic-cavitation will be introduced and the influence of different parameters like the orifice design (α, β0, δ), reactor design (geometry, distance between the orifice and sonotrode) and ultrasound system (frequency, amplitude, pulsed mode) will be discussed. Moreover, the use of hydrodynamic-acoustic-cavitation in various processes (biogas production, biodiesel synthesis, wastewater treatment) at different scales (lab, industrial) will be shown.

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The Dirty Truth of Surface Attached Nanobubbles

Surface attached nanobubbles have not only been a challenge to understand their diffusional stability but even more they challenged the experimentalist to prove their existence reliably. Only a multimodal optical-atomic force microscopy approach provided data to measure size and content of these soft objects. I will try to convince you that hydrophobic attraction and pinning is sufficient for the understanding of all reliable experimental data.

Lorenzo Albanese

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Bringing hydrodynamic cavitation powered beer-brewing from the pilot to the industrial scale: challenges and solutions

Many innovative technologies fail in the face of challenges related to their transition from the laboratory or pilot scale to the industrial one. Such challenges are particularly severe in the field of food processing due to issues such as reliability and safety of the equipment, synchronization and automation of processes, and safety of the consumer products.

A novel technology and related method for beer-brewing, based upon controlled hydrodynamic cavitation, was first developed and tested at the pilot scale of 250 L, then brought to the industrial scale of 12 hL and complemented with all the necessary devices such as an advanced liquid-solid separation unit, a cleaning-in-place system, and an electronic control panel managing the mashing and hopping stages of the brewing process.

The industrial-grade system, under the name of CAVIBEER, first underwent an intensive optimization phase aimed at minimizing vibrations and noise, then was successfully tested to check the functionality of the processes chain, as well as the repeatability of the results achieved at the pilot scale, the reproducibility of any beer recipe, and the comparative performances with respect to conventional devices.

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Vapor bubble nucleation via Fluctuating Hydrodynaics

Vapor bubbles form in liquids by two main mechanisms: boiling, by increasing the temperature over the boiling threshold, and cavitation, by reducing the pressure below the vapor pressure threshold. The liquid can be held in these metastable states (overheating and tensile conditions, respectively) for a long time without forming bubbles. Bubble nucleation is indeed an activated process, requiring a significant amount of energy to overcome the free energy barrier and bring the liquid from the metastable conditions to the thermodynamically stable state where vapor is observed. Nowadays molecular dynamics is the unique tool to investigate such thermally activated processes. However, its computational cost limits its application to small systems (less than few tenth of nanometers) and to very short times, preventing the study of hydrodynamic interactions.

In this work a continuum diffuse interface model of the two-phase fluid has been embedded with thermal fluctuations in the context of the so-called Fluctuating Hydrodynamics (FH), enabling the description of the liquid-vapour transition in extended systems and the evaluation of bubble nucleation rates in different metastable conditions by means of numerical simulations. Such an approach is expected to have a huge impact on the understanding of the nucleation dynamics since, by reducing the computational cost by orders of magnitude, it allows the unique possibility of investigating systems of realistic dimensions on macroscopic time scales. Depending on available time, the extension of the approach to heterogeneous nucleation processes of special interest for cavitation in macroscopic application will be illustrated.

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Cyanobacteria elimination using hydrodynamic cavitation

Cyanobacteria belong among the oldest organisms on Earth, creating oxygen in the atmosphere and thereby suitable conditions for evolution of life. However, they also produce toxins, which are harmful to people and animals, causing allergies, skin irritations, bronchitis, but also liver tumors. Climate changes (increasing temperatures of shallow waters) and eutrophication of water from polluted streams and washed down fertilizers enhance cyanobacteria blooming in many lakes not only in region of central Europe. While remedies in form of chemical additives, which prevent cyanobacteria growth are known, their use is connected with side effects. Physical methods (ultrasonic radiation, mechanical removing) are very difficult to be applied on large volumes of water.

Present contribution is about application of hydrodynamic cavitation (HC) on disintegration of cyanobacteria. The research focuses on using HC in real situations (ponds, currents) rather than on laboratory utilization. Several devices were applied to induce cavitation and eliminate cyanobacteria with different success, namely: Venturi tube, orifice, rotating cavitation device and cavitation jet. Experiences with these devices in form of hydraulic characteristics and impact on cyanobacteria will be summarized in the contribution.

Acknowledgement:

Czech Science Foundation is gratefully acknowledged for support of this research under project No 16-18316S „Principles and mechanisms causing microorganism elimination by hydrodynamic cavitation “.

Pedro Quinto

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Interaction between laser-induced shocks and bubbles

In this work we study the interaction between laser induced bubbles and shock waves in liquid. A spatial light modulator is used to simultaneously focus laser pulses at multiple spots or into an arbitrary shape. We observe that the shocks that reflect from the bubbles can nucleate microscopic bubble clouds. In particular we explore the geometries of multiple focused spots at the vertices of a regular polygon and a ring-shaped pulse. Finally, we study the effect of multiple laser induced shocks on static bubbles.

Michael Calvisi

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Dynamics and modeling of encapsulated microbubbles in biomedicine

Encapsulated microbubbles (EMBs) have been widely used for decades as contrast agents in ultrasound sonography. More recently, EMBs are emerging as powerful tools for noninvasive biomedical therapies ranging from drug/gene delivery to tumor destruction.

EMBs consist of a gas core surrounded by a stabilizing shell made of protein, polymer, or lipid. Due to their small size and fast time scales, it is difficult to study EMBs directly through experimental means; therefore, it is necessary to develop accurate theoretical and computational models.

A primary goal of such models is to understand the effect of the incident ultrasound on the radial and shape dynamics of microbubbles, which are essential to their functionality. For example, the nonlinear radial response of EMBs can give rise to subharmonic and ultraharmonic frequencies that improve blood-tissue contrast in ultrasound imaging. Nonspherical shape instabilities can be an effective mechanism for inciting rupture of the EMB shell and the release of drugs to a target site. When oscillating near a tissue interface, EMBs can develop high-speed microjets that can be exploited to increase cell permeability and drug uptake, or destroy tumors.

In this talk, both spherical and nonspherical models of EMBs will be reviewed and the results of numerical simulations presented. It will be shown that the shell and ultrasound properties strongly influence the EMB dynamics. This leads to the prospect of optimizing the shell properties and ultrasound protocols to control the EMB response based on the intended application, e.g., diagnosis vs. therapy.

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Application of cavitation bubbles for the production of high quality light metal alloys

Ultrasonic melt processing (USP) offers sustainable, economical and pollution-free solutions to melt treatment of conventional and advanced metallic alloys, resulting significant improvement of quality and properties of the end cast product. USP uses intense ultrasonic fields to generate cavitation bubbles and recirculation acoustic streaming patterns where concomitantly affect nucleation, porosity and growth of crystals during solidification of metallic alloys. However, fundamental understanding of cavitation and acoustic streaming underlying this promising and potentially revolutionary materials processing technology is still very vaguely understood. Additionally, it is commonly admitted that experimental study of cavitation on liquid melts is difficult due to high temperatures, opaqueness and chemical activity of the melts. Thus, more insight into the phenomena governing cavitation development and acoustic streaming is required for both fundamental understanding of the process and to provide predictive simulations on relevant applications

To this end our group undertook an extensive research program during the last 5 years to investigate the mechanisms of USP in molten metals. The most recent techniques using highly sophisticated experimental methods were applied to low temperature transparent liquids and liquid aluminium, including acoustic pressure measurements, high-speed camera observations, advanced synchrotron radiography and particle image velocimetry. Results showed that i) Water shares the closest cavitation behaviour with liquid aluminium and can therefore be used as its physical analogue in cavitation studies; ii) Maximum predicted acoustic pressures of 10–15 MPa in liquid aluminium domain could be responsible for deagglomerating particle clusters, aiding primary phase fragmentation and intermetallic breakage promoting grain refinement; iii) Fragmentation of primary phases and intermetalics due to bubble collapse is revealed not to be an instantaneous process but rather a fatigue-type process leading to brittle fracture; iv) USP facilitates sonocapilarity in liquid metals thus reducing porosity by instantaneous filling of pre-existing flaws in metal matrix during solidification; v) Cavitating bubbles in liquid aluminium can sustain for long periods of time promoting stable cavitation with kinetics associated with rectified diffusion; vi) Cavitation intensity quickly dissipates inside the cavitation zone and attenuates in the melt by in the order of 1.45 per metre; vii) Cavitation zone in liquid metals resembles in geometrical and dynamic features that in water; viii) Flow speed and direction of acoustic streaming depends on the amplitude of the sonotrode. An unexpected upward flow pattern at low input acoustic power (50% corresponding to 8.5 µm p-p) may facilitate USP.

These results contribute to the understanding of USP and development of numerical models that can accurately predict cavitation development and acoustic streaming within liquid melts while facilitating further the formulation of guidelines and reproducible protocols for controlling USP at the industrial scale.

Presentations

Giancarlo Cravotto, Veronika Gunjević, Francesco Mariatti, Emanuela Calcio Gaudino

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A technology platform based on cavitation to link lab research to industry

The new generation of chemists have grown up with the awareness of their important role in the environment preservation with smarter and greener chemical processes with lower carbon foodprint. In contrast to previous generations of chemists mainly involved in reducing pollutants but reluctant to design new protocols, in the last two decades new enabling technologies opened the doors to environmental friendly processes with a benign impact to human life and the planet. In this context, acoustic and hydrodynamic cavitation could find relevant applications from lab to industrial scale [1]. Despite convincing scientific evidence to support it, the scale-up and further industrialization of new processes is generally troublesome, while industrial set-up requires long periods of study and optimization, even in the most promising of cases. The main reason for this is the large gap that exists between research laboratories and industrial plants.

In order to help bridge the gap between academy and large-scale production, we established in our department a "Green Technologies Development Platform", made up of a series of multifunctional laboratories that are equipped with non-conventional pilot reactors developed in direct collaboration with partner companies which brings together research, R&D and production expertise. The reproduction of laboratory, gram-scale data in pilot, kilogram-scale reactors was a challenging project. This strategy enabled the principle heat and mass transfer data to be obtained and a potential industrial plant to be designed. In this context our team that includes organic chemists, experts in catalysis and chemical process engineers, followed multifaceted strategies based on cavitation to design highly efficient green chemical processes well suited for the industrialization. As representative examples: *i*) advanced oxidation processes (AOPs) to destroy resistant organic pollutants [2,3] and the detoxification of asbestos fibres [4,5]; *ii*) the preparation of new highly efficient nano-catalysts [6,7]; *iii*) a green process intensification of critical synthetic processes with kinetic bottlenecks [8,9] *iv*) the biofuels production in flow reactors [10,11].

Over the last few years, we have been involved in science-based partnerships, with leading chemical and pharmaceutical companies, in order to promote "radical technological innovation" projects based on cavitation and move toward process sustainability. In spite of the understandable difficulty that industries face in crossing the abyss created by technological novelty, the availability of *ad hoc* tailored cavitational reactors and the possibility of intellectual property, are a real driving force for new investment and academic collaboration. A challenging, but promising, future lies in wait for innovation in cavitational chemistry.

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Hydrodynamic cavitation in combination with the advanced oxidation processes for water treatment-selected implications

For water and wastewater treatment, hydrodynamic cavitation (HC) can be used in combination with conventional advanced oxidation processes (AOPs) [1,2]. The latter include applied combinations of strong oxidants, namely ozone (O_3) and hydrogen peroxide (H_2O_2) and/or photo-oxidants (UV photolysis), as well as other processes resulting in formation of hydroxyl radicals [3]. Previous and recent research [1,2,4–7] show that application of HC in combination with (photo-)chemical AOPs can yield better overall performance of the systems (increased degradation of the target pollutants, lower energy consumption per order of removed pollutant etc.).

The objectives of this research were to assess the effects of hybrid hydrodynamic cavitation on advanced oxidation processes based on ozone (O_3), hydrogen peroxide (H_2O_2) and UV light for the treatment of selected natural organic matter (humic acid) and synthetic organic matter (methylene blue, metaldehyde, diatrizoic acid, iohexol). The experimental set-up was as a semi-batch scale-up system with the reaction volumes of 50–83 L. The changes in the removal efficiency of the target poluttants and specific energy consumption to achieve the same order of target pollutant removal were set as the control parameters. The reaction times up to 20 minutes were considered preferential with the assessment of these up to 60 min. Ozonation alone and the combinations of H_2O_2/O_3, H_2O_2/UV and O_3/UV AOPs were applied. Hybrid hydrodinamic cavitation was added to the process. The experimental set-up was designed as a semi-batch scale-up system and utilized the reaction volumes of 50–83 L. Various geometry of HC generators was also tested (nozzle with single opening and orifice plates with 4, 8 and 18 openings).

Based on the results obtained, the application of the hybrid HC, under the applied experimental conditions [6,7], was able to improve the efficiency of treatment by ozone, H_2O_2/O_3 and H_2O_2/UV advanced oxidation processes. Further, conditions of low number of passes through the system (3–12) were sufficient to exploit the beneficial effects of hybrid hydrodynamic cavitation and the reaction times up to 20 minutes were proven to be sufficient. The application of hybrid hydrodynamic cavitation could be in some cases at least as energy efficient as the O_3, H_2O_2 and UV based AOPs alone. These results were most evident when the ratios between the dosages of the applied oxidants or UV light and concentrations of the target pollutants in the samples were relatively low. Special attention needs to be paid to the formation of the by-products of the advanced oxidation processes.

This presentation deals with implications that combined (hybrid) HC + AOP based on O_3, H_2O_2 and UV has on performance of the system and abovementioned pollutants removal efficiencies.

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Towards the optimization of dual-frequency driven sonochemistry: a four-dimensional parameter scan of a single gas bubble accelerated by GPUs

One of the main success stories of modern chemistry is the use of high frequency and high intensity ultrasound on a liquid domain to increase the chemical yield of various reactions. This phenomenon is called sonochemistry in which the key phenomenon is acoustic cavitation and the collapse of the emerging bubbles. According to many experimental observation, the chemical yield can be further increased by the use of two different frequencies during the irradiation. Due to the large involved parameter space, however, even in case of a single spherical bubble, a clear theoretical understanding of such a synergetic effect is still missing in the literature [1].

Our strategy is to employ a bottom-top approach; that is, investigate a model as simple as possible but perform a large dimensional and fine parameter scan. Later, the model complexity can be gradually increased until a suitable explanation for the synergy of dual-frequency driving is found. As an initial step, the main aim of the present this study is to present numerical simulations obtained by solving the Keller—Miksis equation well known in sonochemistry that is a simple second order ordinary differential equation describing the dynamics of a single spherical gas bubble [2].

The investigated four dimensional parameters space involves the amplitudes of the dual-frequency driving and varied between 0 and 2 bar; and the corresponding frequencies and spanned in the range 0.1 and 10, and normalized by the linear undamped eigenfrequency of the system. Even with a moderate resolution of 100 values of each parameters applied here (the effect of phase angle is neglected and the equilibrium bubble size is), one hundred million transient initial value problems have to be solved. The initial condition is the equilibrium state of the unexcited system at each parameter combination. In order to obtain results within reasonable time, the high computational capacities of professional GPUs were exploited (2 Nvidia Tesla K20m). The overall computations took approximately one week. The integration algorithm was the adaptive Runge–Kutta–Cash–Karp method.

After the initial transient (1024 number of collapses), 64 additional collapses were simulated and their properties saved (maximum and minimum bubble radii, collapse times and maximum bubble wall velocities). A collapse is defined as the evolution of the bubble radius from a local maximum to a subsequent local minimum. The above quantities provide a good flexibility to describe the strength of a bubble collapse mandatory for efficient application. The data of the 64 number of collapses allows to make a coarse statistical investigation as well. In addition, the total time of the 64 collapses were also recorded, which makes it possible to determine the number of the strong collapses (a suitable threshold is required) in a unit time. In the present paper, we focus only in the examination of the relative maximum bubble radius as a measure of the collapse strength used also by many researchers [3, 4].

The building block of the investigation is the production of bi-parametric contour plots of the relative maximum bubble radii in the plane of the relative frequencies at fixed pressure amplitudes. Out of the plots, only one is presented in the left hand side of Fig. 1 at and at. It is clear that high maximum bubble radius can be achieved only at low frequencies (red-yellow domain). This low frequency region is known as the giant response region. During the evaluation of all the diagrams, no synergetic effect has been found. The only possible optimization strategy (in terms of the collapse strength) is the distribution of power between the ultrasonic transducers. If they are equal, the energy efficiency can be increased approximately by a factor two.

Another important factor in sonochemistry is the number of the strong collapses in a unit time. As an example, in the right hand side of Fig. 1., the number of the strong collapses are plotted as a function of the excitation frequencies at fixed pressure amplitudes. Strong collapse here means that the relative maximum bubble radius is greater than two, which is a common threshold in the literature [5]. It is clear that very frequent strong collapses can be achieved near the resonance frequencies (read stripes near). The detailed investigation of such collapse frequencies revealed that in case of nearly equal pressure amplitudes (optimal for energy efficiency), the number of the strong collapses dropped by a factor of two (compared to a single frequency driving) due to the canceling effect of the combined driving pressure signal. The main consequence is that the evolution of the maximum bubble radius cannot explain the high increase (sometimes 300% [5]) of the efficacy of sonochemistry compared to single-frequency driving. These results put the main outcome of some previous studies [3, 4] into question. Consequently, other explanation(s) need to be found and investigated in more details. Some possible candidates: other measures for the strength of the collapse and/or the number of strong collapses in a unit time may show different trends; dual frequency may stabilize the spherical shape of the bubbles; or the efficiency increase may occur inherently due to the collective dynamics of bubbles in a cluster.

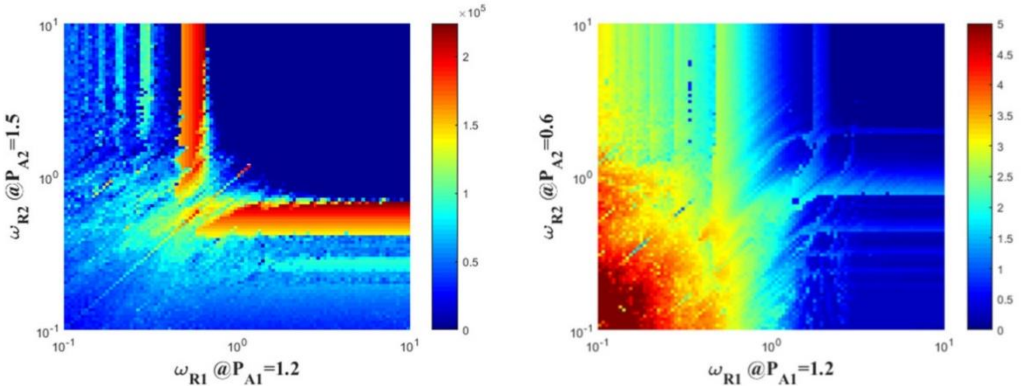

Figure 1: Left panel: Maximum bubble radii as a function of the relative frequencies and at pressure amplitudes. Right panel: The number of the strong collapses as a function of the relative frequencies and pressure amplitudes.

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Influence of cavitation induced pressure loading on cleaning of coking layers in sonotrode tests

In injection nozzles of diesel engines, coked diesel layers could exist at certain operating conditions. These coked layers lead to improper function of the system. Cavitation, which usually occurs in nozzles and often is responsible for unwanted erosion of material, is also known to have a beneficial effect while it is capable of cleaning the coking layer on the nozzles surface. Since it is not known which mechanisms exactly leads to a removal of this coking layer, the knowledge of the relation between cavitation induced pressure loading and the removal of the coking layer is important to identify in which operation conditions and which nozzle design removal happens and when it won't appear.

Series of tests both in direct and indirect cavitation approaches were performed on sonotrode facility with specimens with coke layers in order to determine the cleaning behavior. Cavitation intensity was varied by sonotrode amplitude, liquid temperature and gap height.

Artificial coking layers were created using procedure of Diesel aging and temperature treatment on specimens surface, fig. 1. Aluminum, copper and stainless steel specimens were tested.

Figure 1: Specimens with cocking layers before and after cavitation exposure.

After preliminary tests indirect cavitation approach was chosen as more flexible in terms of cavitation intensity variation. Determining the location of the removed coking layer after specified time steps by digitalized image processing of tested specimens.

Comparison of the local load spectra derived from the CFD simulation with the surface locations of removed coking layer derived from image processing of tested specimens in order to find a correlation between the load spectra and the cleaning behavior was provided.

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Boundary layer instability control in the unsteady partial cavitation regime using Cavitationg bubble Generators (CGs)

In this article, we propose a passive boundary layer control method to control boundary layer instability in the unsteady partial cavitation regime on the suction side of the CAV2003 benchmark hydrofoil. This method may be used in many engineering applications such as propeller and rudder in marine technology, turbine and pump impeller in turbomachinery. First, we used a hybrid URANS model for turbulence and Schnerr-Sauer mass transfer model to simulate the unsteady partial cavitating flow and validated it based on experimental data. We used the compressive volume of fluid (VOF) method to track the cavity interface. We employed two-phase flow solver of the OpenFOAM package, intephaseChangeFoam. Second, we studied the effect of passive control method on vortex structure on the suction side of the hydrofoil and in wake region. We showed that this control method may influence the boundary layer structure on the hydrofoil surface and also near the trailing edge. Using this method, the pressure distribution and the fluctuating part of the velocity field on the hydrofoil surface were modified. This method stabilized the boundary layer and delay its separation. Therefore, the local boundary layer on the hydrofoil surface was altered, and the turbulent velocity fluctuation was reduced significantly, confirming that the vortex structures on the suction side and the wake region of the hydrofoil were changed remarkably.

Passive cavitation control

We adapted this idea of the passive control from vortex generators (VGs) which are common in boundary layer control around airfoils in aerospace engineering applications. Because of their small size and high performance, the VGs are one of the effective methods to control flow separation on airfoils, Gad-el-Hak [21]. Using vortex generators, the freestream flow with high fluid momentum can be transferred into the vicinity of the wall surface of the hydrofoil with low energy fluid. The created vortices bring the fluid with higher kinematic energy to withstand a pressure rise before the separation phenomenon occurs. This method may be used in hydrodynamic applications to delay or suppress the boundary layer instabilities and flow separation on the suction side of hydrofoils under non-cavitating and cavitating conditions. In this work we used a wedge-type called cavitating-bubble generator (CG) located on the suction side of the hydrofoil where it is expected that the boundary layer becomes instable. The view of the same shape of wedge-type CGs located in four different positions on the suction side of hydrofoil was shown in Fig. 1. Our investigations on the height of the CGs show that it should be small enough so that it does not have a significant effect on the hydrodynamic performance of the hydrofoil. First, we estimated the location of inception point on the suction side of the hydrofoil without CGs. Second, we inserted a CG at different locations of the boundary layer in front and behind the inception point on the suction side of hydrofoil near the leading edge. This leads to find a proper location of CG with regard to the reduction of the highest amplitude corresponding to the cavitation shedding.

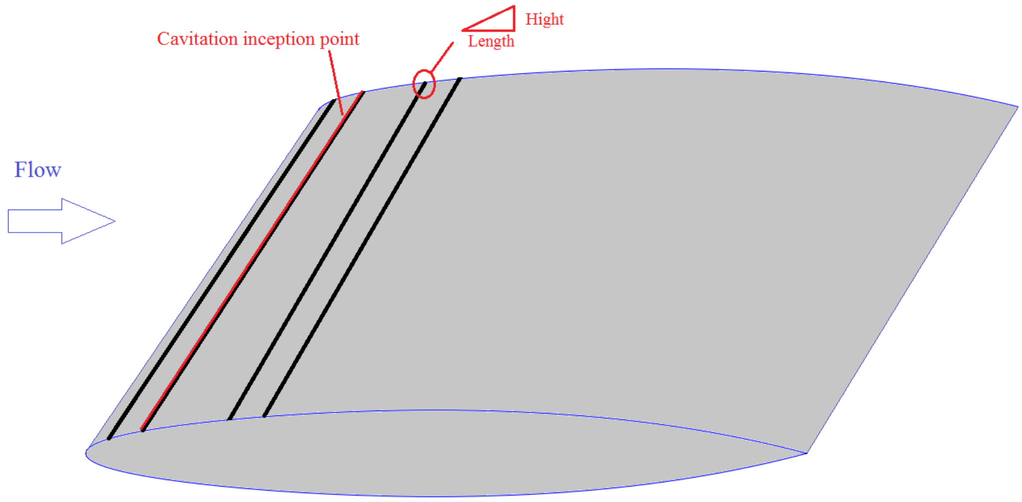

Figure 1: Viev of four wedge-type CGs located in four different positions on the suction side of hydrofoil, (black line). Position inception point without CGs, (red line).

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Hydrodynamic cavitation for wastewater treatments and agro-industrial biogas plants: experimental results

In the last years, hydrodynamic cavitation (HC) was increasingly used for a variety of applications in the field of wastewater treatment, ranging from biological applications (i.e. cells disruption) to chemical reactions such as oxidation of organic, bio-refractory and toxic pollutants in aqueous effluents. HC is induced in fluids by subjecting them to velocity variations due to the presence of constrictions in the flow, such as orifice plate, venturi or throttling valve. This process involves the formation, growth, implosion and subsequent collapse of micro-bubbles, occurring in extremely small intervals of time and releasing large magnitudes of energy over a very small location. Up to now, different reactor configurations and different schemes have been proposed and studied. In this paper, experimental results of our research group have been given for a modified swirling jet-induced reactor described in [1-3] and for a stator and rotor assembly described [4], aiming at showing different promising applications of the HC technology in wastewater treatment plants (WWTPs) and in agro-industrial biogas plants.

Two different HC schemes have been studied by our research group. The first one consists of a closed loop circuit designed to treat 50.0 L of material from a feed tank, then taking it into a flow channel internally accommodating the HC reactor and then discharging the treated fluid back to the main tank by means of a Mohno pump (3.0 kWel), allowing several recirculation passes through the cavitation zone (Figure 1, A1). The HC reactor is a modified swirling jet reactor (Ecowirl, Officine Parisi, Italy), previously described in [1-3], in which cavitation is generated by using a multiple-hole orifice plate able to generate multi-dimensional vortices which impact on a collision plate. A frustum-conical pre-swirling chamber (2) is preceded by another chamber (1) where injection slots are located (conical concentric holes), through which the flow enters and a core-vacuum vortex can be generated, and is followed by a double cone chamber (3) where a collision plate is present in order to fast recover the pressure, increasing the cavitation intensity (Figure 1, A2). For this configuration the effect of several parameters on the HC efficiency have been analyzed, such as inlet operating pressure, temperature and pH of the liquid to be treated in the feed tank, geometry of the pre-swirling and the double-cone chambers. The second HC system consists of an open loop circuit, where the effluent is treated only once, in an operational setup called “one shot treatment", with the advantage of any recirculation (Figure 1, B1). The HC reactor is a stator and rotor assembly (BioBANG®, Three-ES – Italy, 20 – 40 kWel). The rotor was a solid cylinder attached to a gear assembly which is connected to a variable frequency drive (VFD). This VFD controlls the speed of rotation of the rotor and thus the energy input provided to the system and the cavitation intensity as well described in literature [5] (Figure 1, B2). For this configuration the effect increasing electrical power, and thus increasing speed of rotation on the HC efficiency have been analyzed.

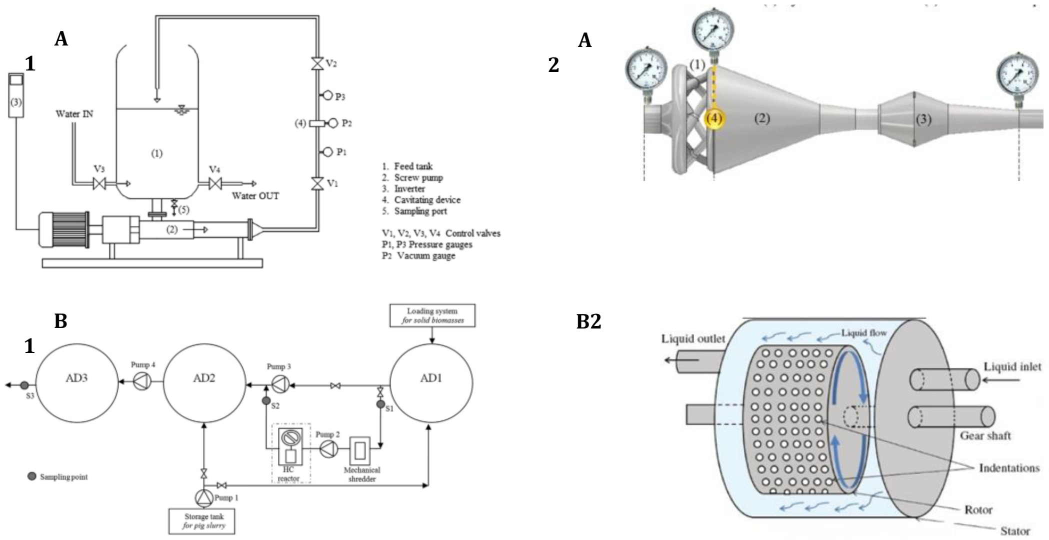

Figure 1: Schematic representations of the closed (A1) and open (B1) loop circuits, and schematic representations of the modified swirling jet HC reactor (A2) and the stator-rotor assemblu (B2).

Results

Concerning applications in WWTPs, the swirling jet-induced cavitation reactor in a closed loop circuit has been successful applied at lab scale in order to allow the degradation of a waste dye aqueous solution (Rhodamine B, RhB) [2]. An extent of degradation (ED) of 15% had been achieved using Ecowirl reactor with an inlet pressure of 2.0 bar and at 20.0 ± 1.0 °C and pH of 4.0, after 260 passes through the HC system, which corresponded to 169 min (162 kJ L-1). Increasing inlet pressures (from 2.0 to 4.0) super cavitation occurred, with a decrease in ED. Further, the decolourization was most efficient for the combination of HC and chemical oxidation with NaOCl, as compared to chemical oxidation and hydrodynamic cavitation alone. The highest degradation rate of the dye was observed at pH 2-4, due to the prevalence in the acid conditions of RhB in the cationic form that is easier to degrade. The swirling jet-induced cavitation reactor in a closed loop circuit has been applied as pretreatment of activated sludge, too. Chemical and respirometric tests proved the effectiveness of the HC reactor on sludge solubilisation and aerobic biodegradability [3]. The best results in terms of sludge solubilisation were achieved after 2 h of HC treatment, treating a 50.0 gTS L-1 sludge using a three heads Ecowirl system, at 35.0 °C and 4.0 bar (3276 kJ kg TS-1). Authors observed an increase in sludge disintegration degree by increasing the inlet pressure from 2 to 4 bar, due to an increase of flow velocity of the treated liquid. Further, the authors showed the higher the temperature, the more efficient HC was. Moreover, respirometric results obtained in the study showed that for specific supplied energy lower than 3000 kJ kg TS-1 sludge solubilisation was related to floc disintegration while cell lysis occurred for higher specific supplied energy.

Concerning agro-industrial biogas plants both the swirling jet-induced cavitation reactor in a closed loop circuit and the rotor-stator assembly in an open loop circuit have been applied. The anaerobic biodegradability of cattle manure improved by using the modified swirling jet-induced cavitation as pre-treatment [1]. The degree of disintegration increased by 5.8, 8.9, and 15.8% after the HC treatment at 6.0, 7.0, and 8.0 bars, respectively. However, the HC treatment at 7.0 bars had better results in terms of methane production (2000 kJ kgTS-1). This result has been attributed by authors to the possible formation of toxic and refractory compounds at higher inlet pressures, which could inhibit the methanization process. Interestingly, total Kjeldahl nitrogen content was found to decrease with increasing inlet pressures, as the pH and the turbulent mixing favored the ammonia stripping processes.

The rotor-stator assembly has been applied with a specific energy input of 470 kJ kgTS-1 in a full scale agricultural biogas plant, with molasses and corn meal as a supplementary energy source [4]. The HC pretreatment maximized the specific methane production of about 10%, allowing the biogas plant to get out of the fluctuating markets of supplementary energy sources and to reduce the methane emissions. In both applications, HC treatment decreased the viscosity of the treated biomass, reducing the energy demand for pumping and mixing. Thus, in biogas plants, a positive energy balance can be obtained looking at both the improved biogas production and improved operational practices after the implementation of the HC pre-treatment.

Conclusion

The HC technology has been proved to be a promising application in different stages of a WWTP, such as in the wastewater handling units (water line) as pre-treatment of the activated sludge recycled to the denitrification process, and as tertiary treatment for toxic dyes removal and in the sludge handling units (sludge line) as pre-treatment of excess sludge before anaerobic digestion. When applied as pre-treatment of sludge, both in the water and in the sludge line, HC always allow a sludge reduction. Further, the implementation of HC as pretreatment of agricultural biomasses was successful applied to improve the biogas production and the rheological characteristics of anaerobic sludges. However, HC implementation has to be properly designed, depending on the aim, reactor configuration, and energy requirement.

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Sensing Cavitation in Hydraulic Machines and Devices by Acoustic Emissions

Cavitation Detection by Acoustic Emissions

In many cases cavitation detection is important to support the validation of constructive machine design layouts as well as the monitoring of machines under actual conditions.

In this respect a non-invasive detection tool using broadband acoustic emissions (AE) is a promising approach to get information out of turbid fluids (e.g. lubricants, oils and waste water etc.) but avoiding the risk of sensor erosion. In addition, using high frequency signals compared to airborne noise give the chance for proper discrimination of signal sources, which is a further advantage of this method in technical applications.

In order to get high frequency signals a sensor is mounted closed to the cavitation source but outside at the surface of the housing. Thus, shock waves originating from the implosion of cavitating bubble fields inside produce broadband acoustic emissions which are transmitted through the housing wall and are captured by the sensor.

Spectral signal analysis methods together with synchronous machine data give raise to the hope to provide deep insights to the dynamics of cavitation process within mountings, nozzles or rotating pump propellers. The method makes necessary broadband sensors and I/O boards with high signal bandwidth and dynamics.

For applying this method the necessary hardware and software requirements were tested in a laboratory pump circuit generating cavitation at a convergent-divergent nozzle at definite conditions.

Cavitation Diagnosis in Hydro and Turbomachines

In order to demonstrate the performance of this method we have first focused on cavitation fields produced by power ultrasound devices. A piezo sensor was mounted at the so called sonotrode. The latter is working as a wave guide to the high frequency signals. The captured broadband spectra signals (over six decades) have highly stochastic amounts in the range of MHz. This signal identified as cavitation noise are properly well similar to signal spectra recorded from a cavitating convergent-divergent nozzle. In this way a validation of the AE method for the determination of cavitation was reached.

Pumps are cavitating when exceeding a specific operation value called NPSH value. Investigations were done mounting an acoustic senor at the housing of the pump. Acoustic emissions from the pump were recorded operating below and above the NPSH value. The signal analysis shows a distinctly extinction of the high frequency amounts suggesting that the signal path from the cavitating bubble to the exterior sensor is interrupted. The reason for this is the cavitating bubble fields dragged by the rotating propeller blades which are damping the transfer of the signal. Compared to the established NPSH value determination the acoustic method shows a much better sensitivity. This could be a great advantage when testing pumps in order to validate fluid-dynamics computations or proving machine quality.

Similar effects and cavitation dynamics could be determined when evaluating measuring data from turbines and turbomachines. Cavitating bubble fields which adhere at the rotating propeller blades and are dragged on by the rotating fluid stream. Again, they are the reason for changing the transmission of the acoustic signals to the sensor. The relative change of the acoustic wave amplitudes in respect to the frequency bandwidth is shown to be measuring quantity in order to prove existence and observing the extension of cavitating zones in fluid machinery.

In all cases shown it is demonstrated how the application (i.e. based on the proper interpretation of the physical process) of established mathematic tools and algorithms could raise the informative value of experimental results. Furthermore such algorithms open the way in order to develop methods for real time monitoring of fluid machinery and devices presuming powerful hardware and software exists. The latter is no longer unreachable looking at the advances of FPGA microcontrollers and high-speed electronics in nowadays.

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Application of hydrodynamics cavitation for inactivaction of waterborne viruses

Water for human consumption, or for human related activities (i.e., irrigation or hydroponics plant cultivation), should preferably be free from microbiological hazards. Modern molecular technologies are increasingly relating human and plant viruses to waterborne disease outbreaks and crop losses, respectively. The USA EPA states that a proper water disinfection method should reduce the viral load in 4 logs, while new European legislation is in preparation. Most commonly used methods for water disinfection are chlorination, raising temperatures and ultraviolet irradiation. However, each procedure has some drawbacks; chlorination can, for example, cause formation of mutagenic by-products, while some methods, on the other hand, are not very cost-effective or even ineffective under some conditions. Therefore, the purpose of our research is to implement novel, clean and efficient methods as hydrodynamic cavitation for inactivation of waterborne viruses. The use of hydrodynamic cavitation shows high potential for industrial designs because it can be incorporated into a continuous flow process and can be easily scaled-up allowing for a cost-effective water disinfection system [1].

We investigated the effect of hydrodynamic cavitation on MS2 bacteriophage [1], a virus that infects *Escherichia coli* and is an indicator of fecal contamination. The survival of MS2 bacteriophage in the environment and removal by commonly used water treatment processes resembles that of food and waterborne human enteric viruses (for example the enterovirus, hepatitis A, and rotaviruses), therefore it is widely used as a surrogate for waterborne viruses. To establish a proof of principle we used two different cavitation reactors, of 3 ml and 1 L volumes, respectively. Tap water was spiked with bacteriophage MS2 at high (10exp8,8 pfu/ml) and low (10exp2,7 pfu/ml) concentrations, followed by exposure to a number of cavitation cycles. The effect of hydrodynamic cavitation on the viral viability was assessed with the double layer agar assay. Proper controls were used to ensure the effect on viral infectivity was due only to cavitation. 1000 cavitation cycles (cca 1 hour of exposure), reduced in more than 4 logs the infectivity of MS2 spiked at high concentrations in both the low scale and medium scale reactors. Low MS2 concentrations were completely inactivated after 416 and 208 cavitation cycles in the medium and low scale reactors, respectively. We have also collected some preliminary results on the use of hydrodynamic cavitation for reduction of the presence of Rotavirus in a water sample. We have observed a 75% reduction of Rotavirus on genomic level (detection with reverse transcription quantitative PCR), which does not necessarily correlate with virus infectivity, but anyway shows the undoubtful effect of cavitation on Rotavirus [2].

These results confirm hydrodynamic cavitation as a valuable, clean and efficient tool for waterborne virus disinfection. In the frame of a recently awarded ERC consolidator grant CABUM (project leader Prof Matevz Dular), we are going to explore deeper the cavitation mechanisms of viral inactivation. Various methods will be used to characterize the effect of cavitation on selected viruses. Infectivity will be assessed by double layer agar assay (for bacterial viruses), mechanical inoculation on appropriate test plants (for plant viruses) or by immunofluorescence staining of host cells after infection and tissue culture infective dose assays (for enteric viruses). Furthermore, additional methods will be applied to seek for more detailed information on which viral feature has been affected. Electron micrographs will help us to evaluate effects on the overall virion integrity and structure. Molecular biology methods as real time qPCR and droplet digital PCR will be used for viral genomes quantification, while long range classic reverse transcription PCR and Nanopore sequencing for qualitative assessment of the integrity of longer genomic patches and for assessment of average viral genome size, respectively.

We aim to expand the technology exploiting hydrodynamic cavitation to other human and plant viruses. This will open doors for designing higher scale cavitation devices to be tested at industrial level such as wastewater treatment plants.

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Numerical Investigation of Acoustic Cavitation as a Novel Method of Dental Plaque Removal

Dental plaque is difficult to remove from areas of the mouth with limited access such as between teeth, or from biomaterial surfaces such as dental implants. Pathogenic bacteria remain attached at the microscopic level which require removal to prevent further disease. Cavitation occurs in the cooling water flowing over dental ultrasonic scalers which are used by dental professionals to mechanically remove hardened dental plaque calculus. They have a thin tip which vibrates ultrasonically at 25-30 kHz during the cleaning process. Jet formation and shock wave emission during cavitation bubble collapse can be exploited as non-touch tool for cleaning dental implants and teeth.

However, there is currently not enough cavitation occurring around the scaler tips to remove dental plaque, and the aim of our research is to maximize this cavitation to enable the instrument to be used in a novel non-contact mode. This would allow more effective cleaning with cavitation without causing damage to structures in the mouth from contacting the vibrating tip to teeth or implants. Two aspects of the dental ultrasonic scaler require consideration to maximize the cavitation. Firstly, the vibrations and acoustic pressure amplitude around the tip need to be optimized to increase the cavitation, and secondly the interactions between cavitation bubbles, and between bubbles and a wall need to be investigated to find the optimum power of the cavitation bubble clouds for cleaning.

The coupled acoustic-structural algorithm of the ABAQUS software is adopted to simulate the vibration of the ultrasonic scaler tip. The acoustic pressure disturbed by the oscillation of the scaler in the fluid medium is solved by the acoustic finite element method. The scaler's response is solved by the explicit finite element method. The pressure in the fluid field and displacement of the scaler are calculated. When the absolute pressure is below the cavitation limit, the fluid zone is regarded as undergoing cavitation. We can observe that the cavitation region mainly occurs at the bend and free tip of the scaler.

The dynamics of microbubble(s) near a rigid wall was numerically modelled based on mass and momentum conservations coupled with the non-linear equation of states (Tait equation and Van Der Waal). Therefore, the viscosity and compressibility effects and non-linear shockwave propagation is considered. The open-source OPENFOAM package was used which is based on the FVM and VOF methods. To save CPU time and increase accuracy the spherical mesh was used. The bubble radius history was validated with the Gilmore equation for bubble oscillation in an infinite liquid for the relatively small and large Reynolds number and the shockwave propagation was validated with experimental data. Further work will be done by considering two bubbles near a rigid wall in different scenarios to investigate the bubble-bubble and bubble-wall interactions.

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CAVIBEER: advancing a new technological standard in beer brewing powered by hydrodynamic cavitation

Controlled hydrodynamic cavitation (HC) technologies are arising as new standards in a growing number of industrial applications, often synergically with conventional processes. Water remediation, extraction of bioproducts, waste and biomass processing, creation of ultra-stable nanoemulsions, represent few of the fields benefitting from HC technologies.

In the field of production and processing of beverages and other liquid foods, sometimes HC-based technologies can completely replace conventional ones with distinct advantages. For example, HC processes alone can achieve food-grade sterilization, pasteurization and homogenization, as well as enhance the extraction of valuable bound bioactive compounds.

In the case of beer-brewing, HC processes make long-established production stages such as grain milling and wort boiling unnecessary at all, by means of stand-alone, highly scalable mashing and hopping devices, such as patented and developed on the industrial scale under the name of CAVIBEER. Dramatic reduction of saccharification temperature, acceleration and increase of starch extraction efficiency, significant time and energy savings, increased content of valuable prenylflavonoids and beer's shelf life, reduction of gluten concentration up to the gluten-free threshold, are among the most important advantages, while retaining safety, reliability, scalability, virtually universal application to any brewing recipe, and beer quality.

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Light based measurments in micro cavitating flow

Microchannels are often used to explore fundamentals in fluid dynamics [1]–[3]. For steady state problems like cavitating flow, fluorescent microscopy, with the addition of temperature sensitive nano probes into the observed fluid, can be used to determine the temperature at a chosen point, averaged over the integration time. Coupled with a confocal microscope setup, we are able to produce two and three-dimensional temperature maps of the flow in the microchannel by the use of ratiometric intensity measurements [4]. The nanometric scale of the probes assures fast thermalization of the probes and below certain concentrations does not modify the properties of the studied liquid. Since the probes are not present in the vapor phase, the relative intensity map also corresponds to the average void fraction in the flow. These nanoprobes are composed of a gold core and a polysiloxane shell containing fluorescent dyes (FITC, RBITC) [5]. Organic dyes were chosen due to their compatibility with the shell and primarily for the fast luminescence lifetime, which is essential due to the rapid flow in the microchannel and the consequent short dwell time of an individual nanoprobe in the excitation volume. The temperature information in each measured point is obtained from the temperature sensitive spectrum of the dye. The shell protects the dye from the environment and allows for the functionalization of the surface to prevent agglomeration, while the gold core mitigates photo bleaching. The technic allowed us to observe temperature gradients in microfluidic two-phase flow and observe the thermal effect associated with phase transition. Typically, a region of decreased temperature is observed downstream the orifice in the liquid-vapor stream, attributed to the cooling of the liquid due to the latent heat of the phase change. However, small changes in the diaphragm geometry can induce recirculating vortices, where the vapor bubbles condensate and induce a high temperature region [4].

A different technique recently developed, allows us to quantify OH radical production in hydrodynamic cavitation. Radical formation has been frequently observed with cavitation and is believed to be linked with the extreme conditions in the bubble implosion. The well-known chemiluminescent reaction of luminol with radical species has been used with ultrasonic cavitation [6]–[9], while for hydrodynamic cavitation only one previous application was found by the authors [10]. Due to the different bubble dynamics between ultrasonic and hydrodynamic cavitation [11], there were concerns whether there will be significant radical production also for hydrodynamic cavitation [12]. Using an aqueous solution of luminol and the same microfluidic devices as before, the chemiluminescent pathway was used to quantify OH radical production, by a photon counting technique [13]. By placing the photomultiplier tube (PMT) on top of the microfluidic channel, as close as possible to the cavitation active area and using a simple microphone to coordinate when cavitation was occurring, we could observe the well correlated relationship between the cavitation noise and the chemiluminescent signal from the OH/luminol reaction. The PMT detects individual photons being produced and by logging the arrival time, the photon yield could be obtained. As the solid detection angle was known and the efficiencies (PMT, quantum yield) estimates in place, we could therefore estimate the actual radical production rate at specific flow conditions. A linear relationship was observed between the flow rate and photon production rate for several microfluidic devices. Considering the relative simplicity of the technique and the ability to quantify radical production, it is a viable option for optimizing radical yield in hydrodynamic flows (biological or chemical wastewater treatment).

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Study of the performance of a hydrodynamic cavitation plant for the treatment of industrial wastewaters at a lab scale

In the present work, the results of degradation experiments carried out by using hydrodynamic cavitation on synthetic liquid wastes contaminated by tetramethyl ammonium hydroxide (TMAH) and dyes (methyl orange) are presented. The core of the experimental apparatus is a Venturi tube having a diameter of 12 mm and a convergent of 2 mm.

As for TMAH $(CH_3)_4NOH$ liquid waste, it is an organic compound used for the production of semiconductors by the microelectronic industry; the experiments were performed using synthetic solutions with an initial TMAH concentration of 2 g/L.

Moreover, the degradation of dyes (*e.g.* methyl orange, $C_{14}H_{14}N_3NaO_3S$) has been investigated by using two different experimental devices, a Venturi tube and an orifice plate. The effect of some parameters such as inlet pressure, pH of solution and hydrogen peroxide concentration as a function of time were studied to define the best configuration and the optimal experimental conditions for dye decolorization.

Figure 1: Pictures of the Venturi tube and orifice plate devices used for the experiments.

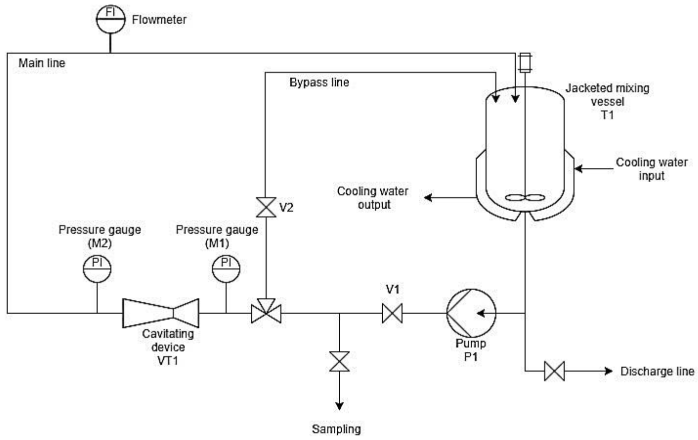

Figure 2: Layout of the experimental apparatus used for the hydrodynamic cavitation tests.

Results

The hydrodynamic cavitation experiments of TMAH were performed in according to a full factorial plan with two factors and two levels (2). In these tests, the factors were solution pH values (3.5 and 7) and reaction time (5 and 30 min). The aim of experiments was to mainly define the effect of pH on TMAH degradation.

Results obtained at lab scale were used for process simulation and permitted to scale up the process to a pilot scale application, as indicated in Fig. 3.

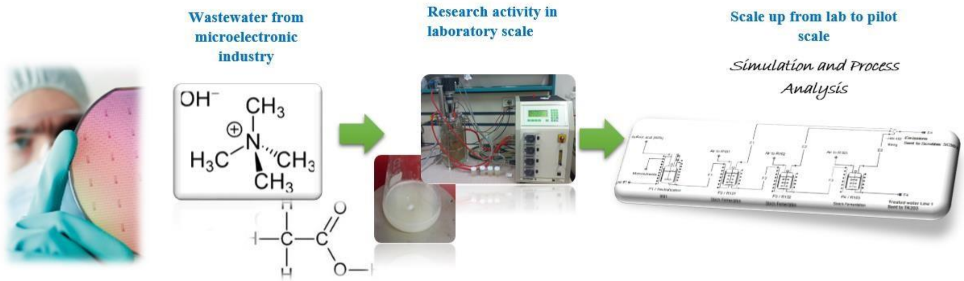

Figure. 3: From lab scale experiments to pilot plant.

As for dye degradation, the addition of hydrogen peroxide increased the effect of the decolourization and allowed a good colour removal (about 60%) under the tested conditions, as shown in Fig. 4.

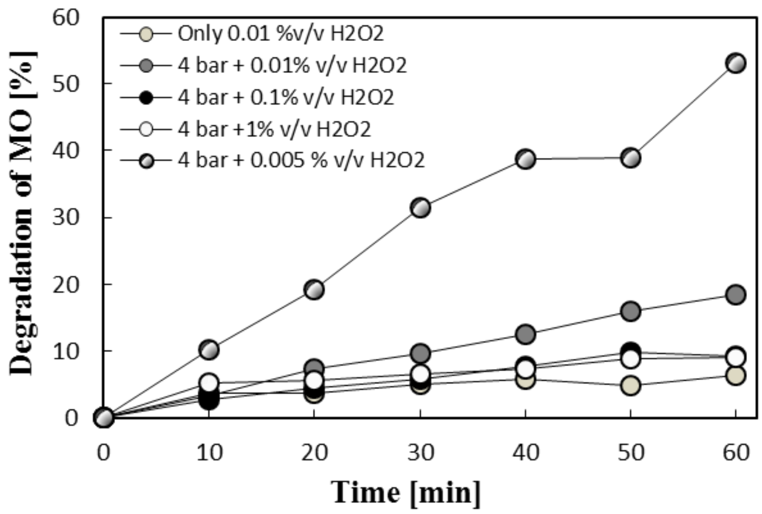

Figure 4: Degradation of methyl orange with time for different concentration of hydrogen peroxide; pH = 2 and MO initial concentration = 5 ppm.

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Bubble Jets in High-intensity Ultrasound

Bubble jetting is a complex non-linear two-phase phenomenon frequently observed in bubbly flows and cavitating systems, characterized by an aspherical collapse of a gas cavity forming a toroidal bubble with a central hollow cone emerging from one of its sides. In spite of the diversity of possible scenarios where bubble jets can be found, they always occur when one or many bubbles collapse (from an expanded state) within a pressure gradient. This gradient can be caused by local flow conditions, e.g. due to the presence of a close boundary like a wall, a free surface or another bubble, the gravitational field, a shockwave or the action of a standing acoustic field in the liquid.

In this work we present a detailed experimental study on bubble jets far from any solid wall, produced when a laser induced gas cavity is generated in an aqueous solution of phosphoric acid while applying a strong ultrasound field. Then, jetting is caused by the time varying acoustic field gradient. This particular type of bubble jets allows a high degree of control on its oscillatory dynamics, achievable by changing critical experimental parameters as the laser pulse energy, the driving signal frequency (and its phase), the acoustic pressure amplitude and also the gradient in the bubble inception location. This phenomenon has not been extensively discussed in the current literature and is relevant for acoustic cavitation in bulk liquid from a fundamental point of view. Furthermore, it could be extremely useful for many industrial applications, especially in the field of sonochemistry. It offers the potential of controlling chemical reactions that take place when some liquid/vapour mass is injected into the bubble nucleus by the jet while the gas is heated due to the cavity compression.

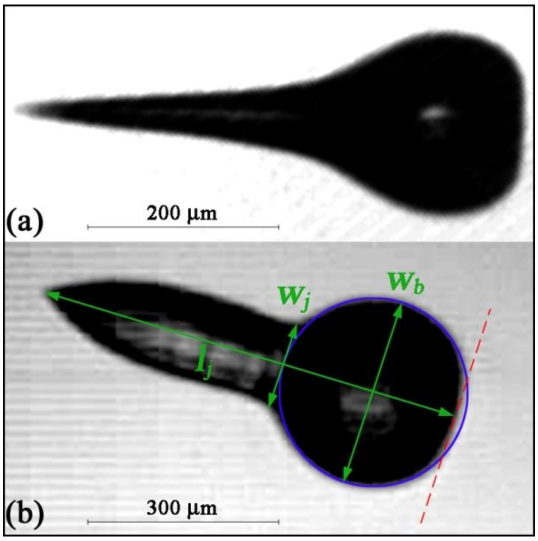

Figure 1: Photographs of typical acoustically induced jets (AIJ). (a) The jets are produced at the final stage of the bubble collapse. At an early stage of the bubble re-expansion phase the usual "nose" shape can be observed. (b) Dimensional parameters used to characterize the bubble jets. The bubble jets are composed by a spherical cavity with a flatten end (actually a toroidal shape bubble) next to a spike shaped tube. The jet length (l_j) was measured from the tip to the dashed red line. The jet width (w_j) was measured where the perimeter of the spherical cavity of diameter w_b crosses the jet axis.

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Cavitation bubble dynamics in flow milli-channels

Sonochemistry in small channels requires active cavitation bubbles in confined environments. Here we investigate the dynamics and chemical activity of sonicated aqueous solutions in milli-channels and look for correlations. The indicative chemical reactions like sono-chemiluminescence (luminol) rely on OH radical formation. Parameter variations include channel dimension, ultrasonic frequency and power, and the liquid flow speed. Final aim is a better understanding and optimization of milli-channel flow reactors for chemical process intensification by non-classical means.

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What makes bacterial resistant to hydrodynamic cavitation treatment?

Hydrodynamic cavitation is a modern technique for the inactivation of bacteria in water distribution systems. The efficiency, however, can be inadequate if one is not careful about biological, chemical and engineered constraints. In particular, the double viscoelastic nature of bacterial cells, embedded in self-constructed biofilm structures, can be an unsurmountable obstacle for an efficient treatment. Bacterial cell is a viscoelastic system that damps externally imposed oscillations induced by implosion of hydrodynamically generated bubbles, thereby reducing significantly the efficiency of hydrodynamic cavitation. We have shown that with fine-tuning of cavitation (i.e. supercavitation, new rotating hydrodynamic cavitation generation systems) a major improvement in inactivation of planktonic bacteria is possible to achieve. The treatment, however, is completely inefficient for biofilm removal. Biofilms are viscoelastic supra-structures composed of microbial extracellular polymeric components, which glue cells to each other and to the surface making them highly resilient to physico-chemical treatment. We are currently developing a new hydrodynamic treatment scheme in for water distribution system to disperse mature biofilms from the surface and subsequently mechanically treat the released cells by hydrodynamic cavitation.

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Why kelvin impulse is a great tool for predicting the behaviour of jetting bubbles

In order to properly exploit cavitation in the wide plethora of modern applications benefiting from it, we must gain a proper understanding how cavitation bubbles behave at an individual level and how they can be controlled and tuned on-demand. Kelvin impulse is a concept that, as initially suggested by Benjamin and Ellis [1], is useful for describing the collapse of cavitation bubbles that deform under the effect of external perturbations. It was later extensively investigated by Blake, Gibson and their collaborators [2, 3], who demonstrated that the direction of bubble migration and jetting was well predicted by the final kelvin impulse, i.e., kelvin impulse at the bubble's final collapse point.

What is the kelvin impulse? It can be viewed as the 'force' exerted upon the bubble by an external perturbation, such as the Bjerknes force exerted by a neighboring boundary. It is the linear momentum acquired by the liquid during the growth and the collapse of the bubble – and this quantity correctly equals to zero for a perfectly spherically collapsing bubble. Blake [3] computed the kelvin impulse in such case by modelling the collapsing cavity by a point source and the effect of a rigid boundary by an image source (note that using a sink or a source yields the same kelvin impulse at the bubble collapse).

How about other configurations? Blake and his collaborators investigated the combined effects of the rigid surface beneath the collapsing bubble and with buoyancy, searching for the "null-kelvin impulse" regime where no migration and jetting occurred due to the cancelling effects of the two individual sources of kelvin impulse. They also computed the kelvin impulse for a bubble collapsing near a free surface, near a two-fluid interface, near a flexible surface and at an axisymmetric stagnation point flow.

This concept may initially seem awfully simplistic to apply in real engineering problems. How can we translate this tool into more complex configurations? As a first-order approximation, any smooth pressure field can be described by a uniform pressure gradient, such as the one induced by gravity. This idea allows for the non-dimensionalisation of the kelvin impulse, as described by Supponen et al. [4]. When multiple different sources act on the bubble at the same time, the equivalent uniform pressure gradients computed through this dimensionless version of the kelvin impulse (vector-parameter) are summed, allowing for an estimate of the direction and strength of the ensuing bubble jets. We have quantitatively verified that the bubble migration follows the kelvin impulse for our setup, which uses laser-induced bubbles and has multiple sources of bubble deformation. Its dominant source of deformation is gravity, but as we lower it aboard parabolic flights and produce particularly large bubbles, the presence of the bubble-generating parabolic mirror also contributes to jetting. By carefully measuring the displacement by combining high-speed imaging with simultaneous pressure signals from two hydrophones, we have been able to confirm that the jetting and the bubble displacement indeed follow well the prediction provided by the kelvin impulse for a wide range of bubble deformations. The recent findings by Tagawa and Peters [5], who studied jetting bubbles in corner geometries formed by two flat boundaries, turn out to also be well approximated by the dimensionless kelvin impulse, although they provided a more elaborate model to predict the jet direction using multiple image sources instead of just two.

Other more complex scenarios are sources involving time-dependent pressure gradients yielding bubble-jets, such as shock waves or acoustic radiation forces. Gas or vapour bubbles subject to shock waves have been shown to produce jets along the shock propagation [6, 7]. Gerold et al. [8] found that focused ultrasound could be used to produce and orient jets along its propagation direction. In a recent review paper, Blake et al. [9] found that the angles of a jetting bubble simultaneously deformed by an ultrasound field (Bjerknes force) and a neighbouring rigid boundary (secondary Bjerknes force) were well described by the kelvin impulse. However, the magnitude of the jetting is more troublesome to define for time-dependent pressure gradients as it is sensitive to the phase of the bubble's lifetime at which the shock wave acts upon it, as shown by Sankin et al [10]. It would be interesting to find an adequate approximation for the kelvin impulse at the collapse point accounting for the time dependence.

Through idealised experiments using highly spherical laser-induced bubbles deformed by various sources (hydrostatic pressure gradient, rigid and free boundary), we have found that the bubble displacement, jet speed, jet impact timing, and the bubble volume at jet impact scale as power laws of the dimensionless version of the kelvin impulse for a wide range of bubble deformations. Similarly, the pressure of the shock waves produced at the collapse of bubbles or varying sphericity levels is well predicted by a function of this quantity. In addition, the energy redistributed into shock waves, luminescence and rebounds at the bubble collapse varies in a rather orderly fashion with the dimensionless kelvin impulse for various sources of deformation. All of these findings consolidate the utility of kelvin impulse in describing the jetting of bubbles subject to different sources of deformation simultaneously. This provides another bridging step from idealised single bubble dynamics towards more realistic scenarios involving bubble clouds, pressure fluctuations, and complex geometries, among others.

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Modelling a cavitation cloud employing the Van Wijngaarden ansatz

The present work analyses the dynamics of a cavitation cloud in a compressible flow, focusing on the cloud collapse. This investigation improves the understanding of the behaviour of cavitation clouds yielding deeper insights into the physics of the interaction between cavitation bubbles and its surroundings. Recent experiments [1-3] highlight that a common cloud geometry for cavitation clouds is a horseshoe. With the Helmholtz vortex theorem in mind the horseshoe is artificially completed to be a generic torus shaped cloud. Following van Wijngaarden, the mixture of cavitation bubbles and liquid inside the cloud is treated as a continuous medium i.e. a homogenous model with the share of vapour $\alpha\alpha$ and the single bubble radius RR. Hence, the bubble radii are a function of the radial position inside the cloud only, $RR = RR(rr, tt)$. The flow outside the cloud is modelled by a potential flow. The excitation of the cloud is carried out dynamically by applying a pressure history at infinity or kinematically by imposing a circulation. With the Gilmore equation the resulting system of partial differential equations is a parabolic system. This is due to the compressibility of the flow, which is taken into account. Previous investigations [4] considered an incompressible flow, resulting in a hyperbolic system.

The resulting pressure coefficient CC_{pp} and the bubble radii RR inside the cloud are highlighted and analysed. They vary in time tt and position rr and depend on the pressure excitation of the cloud $CC_{PP\infty}$, the Mach number $MMMM$, the Reynolds number $RRRR$ and the Weber number $WWRR$.

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Irrigation water for Golf courses & Waste water treatment for Wineries

Irrigation water for Golf courses

For golf course operators, proper ornamental pond and irrigation pond maintenance is an important aspect of grounds maintenance. Although ponds and lakes may not be as important to the golfer as the turfgrass, a pond that is not properly maintained can leave a negative impression.

Westlake Golf Club 10.000 m3 irrigation pond receives 1.800 m3 water daily from the local sewage treatment plant causing several problems in March 2017: Unpleasant odors, Grey murky water, high level of bacteria**.**

The presence of Faecal Coliforms in the irrigation reservoir is an indicator that water have been contaminated by pathogens, desease producing bacteria or viruses, which can cause a potential health risk or humans, animals and plants exposed to this water.

Based in the assesment of the site and water analysis data, our team of experts recommended 60 days treatment of the pond with Ultra Fine Bubble Generator.

Due to the high level of dissolved oxygen and the presence of nanobubbles in the irrigation water, the course soils became increasingly aerobic and following observations were made:

- Germination of rye-gras after 3 days (instead of 7 days)
- First cutting of grass after 7 days (instead of 15-21 days)
- New green setup finished after 7 weeks (instead after 15 weeks)
- Extremely robust and thick consistency
- No yellow spots or root rot observed
- No fertilizers used

Waste water treatment for Wineries

Tulbagh Winery’s 3000m3 waste water treatment pond causing significant community impact. Strong unbearable odors permeate community around the site due to years of dumping post production, untreated solids and liquids into pond. Water analysis revealed following starting water quality levels: COD: 3.180 mg/L, pH: 4. 120 days treatment of the pond with Ultra Fine Bubble Generator was executed. Results after treatment: COD: 322 mg/L , ph: 7,4, Odor disappeared after 5 days, Sediment layer removed.

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Expirience of nanobubble technology usage in fish farming

From October 2017 to January 2018 Waboost (Geateh, Fabulas) and Fisheries Research institute, Slovenia conducted Pilot test operation in the Fish farm Obrh, Slovenia with the nanobubble technology aeration (Ultra fine bubble). The aims of the test were observing the reduction of the occurrence of algae in the pools farm which causes the problems for regular farm operation (clogging, costs for the removal..) and observing the improvement of the intake of oxygen with the purpose to reduce the stress the fish and prevent a potential fish dying in a lack of oxygen time (mostly in the summer). In addition to the above objectives, also the observation (and measurement) of the following parameters have been carried out:

- Increase the production and health of fish;
- Fish mortality reduction;
- Concentration of pathogenic organisms reduction
- Water quality improvement in the outflow.

On the basis of the carried-out observations and measurements at the expiry time of the test partners finding that, there is a noticeable difference in turbidity of the water before and after the completion of the test. Partners also concluded that in the period of implementation of the test the growth of green filamentous algae was declining (weakened). Due to the autumn-winter period of the test with high water levels, it's difficult to credit this algae growth decline only to the usage of nanobubble technology. Algae growth has been weak for about a month after the end of the test.

On the basis of the analysis of the data collected during the implementation of the test, despite the relatively high saturation of the inlet water with O2 during the experiment and high values of the concentrations of O2 inflow and the relative low retention time of the bubbles in the pools, it was still possible to conclude the constant increase of the O2 concentration in the pools during the operation. The concentrations were increased up to 0.5 mg O2/l.

Partners also find that, the health status of the fish at the time of the implementation of the test improve. The health status of the fish Danube salmon (Hucho hucho) which represent the majority of production of the farm, improved and remain good even after the end of the test. Partners assumes that nanobubble operation had positive effect on the health of the fish because all the different species and ages of fish were in good shape the whole test duration. Indications of a possible reduction in fish mortality and an increase in production of fish was not possible to confirm due to the short duration of the test and because of visual methods of monitoring usage and because the absence of control data.

On the basis of carried out test it can be concluded that the concentration of the coliform bacteria between the test did not decrease. It can be also concluded that the concentration of the measured chemical parameters during the test did not increase or significantly decrease.

Partners were unified on the mostly positive results of the test. Due to the positive results and the fact that the test was held in a relatively inconvenient time of year (higher flow rates, more oxygen in the water) partners were unified to continue the test in the time of the lower water levels and higher temperatures, or even with the possible addition of pure oxygen and the introduction of a different methodology for monitoring and proving the parameters from this experiment.

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Improvment of FCM cavitation model and prediction for bubble cluster collapse

The dynamic characteristics of a single bubble collapse have been widely studied by CFD simulation. However, it is difficult to investigate collapse of the vapor-bubble cloud by considering the interaction between bubbles. In this study, we aim to establish a reasonable cavitation model representing the dynamic characteristics of bubble cluster, which is critical to the accuracy of the simulation results.

Considering the bubble cluster as monodisperse system, it is necessary to introduce two assumptions in order to establish the mass transition law explicitly, including spherical collapse for each bubble and collapse order from outer to inner for cluster. Unreasonable characteristics time during collapse process of previous models was remedied by adopting the analytical solution of R-P equation.

Referring to the case of 125 bubbles collapse beside a rigid wall by Schmidt, we investigated three different meshes to show grid independence. We found that the new model we built can provide a more accurate collapse period than that of the previous one, and high pressure pulse appeared when the last period of cloud collapsed. We proposed a new sub-grid cavitation model, which can quickly and effectively predict the collapse duration and pressure pulse.