



9. Kavitationsworkshop - BOOKLET -

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Tagungszentrum Kloster Drübeck in Sachsen-Anhalt

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Tests zur Reinigung haufwerksporiger Betonsteine mittels hydrodynamischer Kavitation	4
Jan Groschopp, Frank Rüdiger.....	4
Cavitation and Cavitation Erosion in Oil-Hydraulic Applications.....	5
Sven Osterland, Lutz Müller, Jürgen Weber.....	5
Untersuchung der Jet-Inversion von Laser generierten Kavitationsblasen an gefangenen freien Gas-Oberflächen unter Wasser	6
U. Bauerschäfer, L. Ledig, K. S. Schulz, S. L. Gai.....	6
Single-bubble cavitation-induced pitting on technical alloys.....	7
Jonas Kühlmann ¹ , Christina Lopez de Arcaute y Lozano ² , Stefanie Hanke ² , Sebastian A. Kaiser ¹	7
Detection of cavitation effects at hydraulic pumps	8
Ulrich Heise	8
Hydroelasticity effects on cavitating flows around hydrofoils considering passive flow control methods.....	9
Yuxing Lin, Ebrahim Kadivar, Ould el Moctar, Jens Neugebauer	9
Multi-Scale Euler-Lagrange Simulations of Compressible Cavitating Flows.....	10
Andreas Peters, Udo Lantermann and Ould el Moctar	10
3D-Simulation der Strömung binärer Alkan-Gemische und Bewertung der kavitationsinduzierten lokalen Segregation	11
Philip Schwarz, Romuald Skoda.....	11
3D-Strömungssimulation zur Untersuchung des Einflusses von Luftausgasung auf die Strömungsaggressivität im Spalt einer Sonotrode.....	12
Tobias Gianfelice, Romuald Skoda	12
Stirring effects on multibubble sonoluminescence	13
Atiyeh Aghelmaleki ^{1,2} , Hossein Afarideh ¹ , Carlos Cairós ³ , Rachel Pflieger ⁴ , Robert Mettin ²	13
On acoustic scattering of bubbles and wave localization	14
Rafael Manso Sainz & Robert Mettin	14
Bulk Nanobubble Generation using Laser-heated Gold Nanoparticles	15
¹ Yatha Sharma*, ¹ Claus-Dieter Ohl; ² Juan Manuel Rosselló	15
The laser excitation mechanism for nanobubble generation	16
Jaka Mur, Miha Jelenčič, Uroš Orthaber, Jaka Petelin, Rok Petkovšek	16
Phase transition involved with nanoscale cavitation	17
Mazyar Dawoodian, Bettar el Moctar	17
Influence of the surface roughness on nucleation and global cavitation dynamics.....	18
Grigorios Hatzissawidis, Gerhard J. Ludwig, Peter F. Pelz	18
Water's tensile strength: The significance of oil nanodroplets	19
Matej Kanduc and Marin Sako	19
Thermodynamic effects on nanobubble's collapse-induced erosion	20
M. Ghoohestani, S. Rezaee, E. Kadivar, O. el Moctar	20
Utilization of surfactants as a cavitation erosion control method: an initial experimental study	21
M. Abedini*, C. Lopez de Arcaute y Lozano, S. Hanke	21
A cavitation bubble interacting with a solid surface - what are the mechanisms of cleaning and erosion?.....	22
Fabian Reuter et al.	22
Single cavitation bubble dynamics and erosion in a planar shear flow	23
Dominik Mnich ¹ , Fabian Reuter ¹ , Claus-Dieter Ohl ¹	23
Fluid-Structure Interaction between Single Cavitation Bubble & Elastic Metal Foil	24



Hemant Sagar & Ould el Moctar	24
Controlling cavitation bubble lifetimes on the nanosecond scale: Rayleigh wave induced cavitation	25
Hendrik Reese ¹ , Ulisses Gutiérrez-Hernández ² , Pedro Quinto-Su ² , and Claus-Dieter Ohl ¹	25
Investigation of 3D and viscous effects on single cavitation bubble dynamics	26
Gohar Moloudchiyaneh, Hemant Sagar, Udo Lantermann, Andreas Peters, Ould el Moctar	26
Influence of bubble size, liquid properties and ambient pressure on jet formation of wall attached bubbles	27
C. Lechner ¹ , M. Koch ² , M. Tervo ² , W. Lauterborn ² , R. Mettin ²	27
Laser based submicron/micron-sized bubble seeding for flow tracking	28
Yuzhe Fan ^{1,2} , Saber Izak Ghasemian ^{1,2} , Fabian Reuter ¹ , Claus-Dieter Ohl ^{1,2}	28
Supersonic jetting from anti-phase cavitation bubble pair interaction	29
Alexander Bußmann ^{1,2} , Yuzhe Fan ^{3,4} , Fabian Reuter ³ , Stefan Adami ² , Claus-Dieter Ohl ^{3,4} , Nikolaus Adams ^{1,2}	29
Simulations of bubble surface oscillations and microstreaming	30
Matti Tervo, M. Koch, C. Lechner, R. Mettin	30
Viscous Fingering on Cavitation Bubbles	31
Patricia Pfeiffer ¹ , Hendrik Reese ¹ , Draga Pihler-Puzovic ² , and Claus-Dieter Ohl ¹	31



Tests zur Reinigung haufwerksporiger Betonsteine mittels hydrodynamischer Kavitation

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Haufwerksporige Betonsteine werden auf Flächen mit geringer Verkehrslast verlegt, um die Versickerung von Regenwasser zu ermöglichen. Die Durchlässigkeit dieser Steine nimmt aufgrund von Verunreinigungen mit der Zeit ab und muss durch Reinigung wiederhergestellt werden. Zur Wiederherstellung der Durchflussleistung wird in dieser Arbeit die Reinigung der Steinoberfläche mittels hydrodynamischer Kavitation untersucht.

Die untersuchten Betonsteine haben ein Steinformat von 10 cm x 10 cm bzw. 10 cm x 20 cm. Die Reinigungstests erfolgen unter Verwendung einer Modellverschmutzung mit definierter Zusammensetzung und definierter Herstellungs- und Auftragsprozedur.

Ziel der präsentierten Untersuchungen ist die Ermittlung geeigneter Prozessparameter für die Durchführung der Reinigung. Dazu werden zunächst Methoden zur Bewertung der Reinigungswirkung und der dabei auftretenden Erosion getestet und bewertet. Die variablen Parameter sind der Düsenvordruck $p = \{40 \text{ bar}; 60 \text{ bar}; 80 \text{ bar}\}$, der Düsendurchmesser $d = \{0,6 \text{ mm}; 1,0 \text{ mm}\}$, der dimensionslose Abstand der Düse von der Steinoberfläche $soff/d = \{10; 20; 30\}$ und die Düsengestaltung.

Zusätzlich erfolgt ein Vergleich der Reinigungswirkung mit Kavitation zur Hochdruckreinigung in Luft ohne Kavitation.

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Cavitation and Cavitation Erosion in Oil-Hydraulic Applications

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Cavitation and cavitation erosion are the major effects limiting the operational limits of all hydraulic components. At the Chair of Fluid-Mechatronics Systems of TU Dresden an exceptional setup of different experiments was established to investigate cavitation and cavitation erosion in detail. All of these experiments are designed to establish reproducible operating conditions as well as sensory and optical access. The experimental strategy was developed to cover the most erosive and limiting cavitation effects in hydrostatic valves and pumps.

Investigations were performed for different fluids, which are mainly mineral oils, but also water based compounds. All of them are similar concerning the high content of dissolved air. Therefore in hydrostatic applications a differentiation between vapour cavitation and gas cavitation is essential.

With these setups it is possible to review common engineering equations as well as modelling equations of cavitation and cavitation erosion with commercial CFD codes. Further on these investigations can be extended on other fluids as well as to a real hydrostatic pumps with optical access to the cavitation zones.

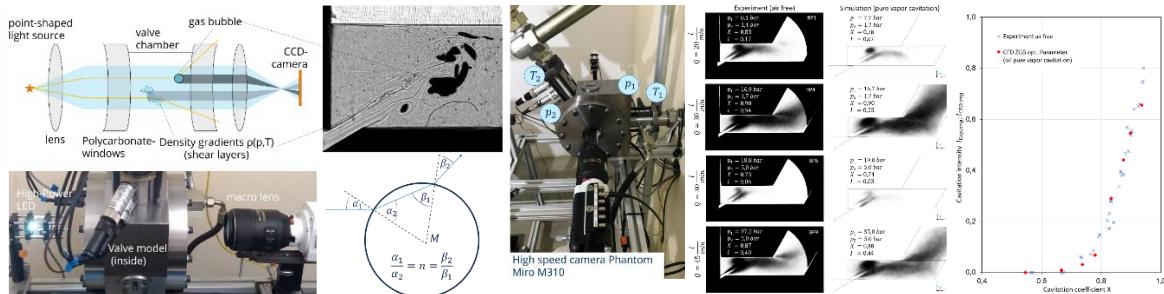


Figure : left - shadowgraphy setup, right - comparison cavitation intensities between air-free experiments and simulation with pure vapor cavitation. [Ost22: 10.1002/ceat.202200465]

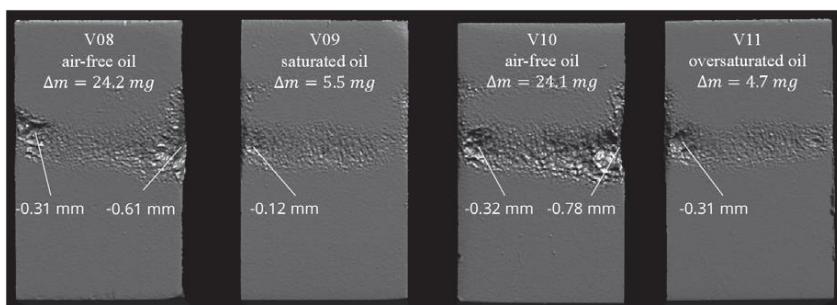


Figure 2: 3D surface scans of the eroded copper samples in the valve model [Ost21: doi: 10.13052/ijfp1439-9776.2234]

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Untersuchung der Jet-Inversion von Laser generierten Kavitationsblasen an gefangenem freiem Gas-Oberflächen unter Wasser

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Die Kavitationserosion in technischen Anlagen und Strömungsmaschinen wird durch Jet-Einwirkungen und Schockwellen verursacht. Bekannt ist, dass Kavitationsblasen die in der Nähe von freien Oberflächen implodieren, eine Jet-Richtung in das Flüssigkeitsvolumen zeigen [1]. Diese Eigenschaft kann für den Schutz der festen Oberflächen genutzt werden. Deshalb wird versucht, dieses Verhalten durch freie stabile Oberflächen unter Wasser, d.h. durch "Gas Entrapping Microstructured Surfaces" (GEMS) nachzubilden [2]. Das Vorbild findet sich in der Natur, wo an Insektenbeinen oder Blattstrukturen besonders stabile und remanente gashaltende Oberflächen gefunden wurden [3]. Als System mit der höchsten Gas-Schichtdicke wurde der Schwimmfarn *Salvinia Molesta* identifiziert [4, 5]. Aus diesem Grund wurden hier erste Kavitations-Versuche mit *Salvinia Molesta* durchgeführt und der Nachweis der Jet-Inversion durch High-Speed-Kameraaufnahmen erbracht. Die Übertragung der physikalischen Eigenschaften dieser biologischen Oberfläche mit einer gefangenen Gasschicht auf technischen Oberflächen ist das Thema vieler Arbeiten [6, 7].

In den aktuellen Untersuchungen werden Lösungsansätze für sich selbststabilisierende und selbstregenerierende Gasfilm haltende Oberflächenstrukturen analysiert. Dabei stehen diese GEMS in engem Zusammenhang mit der hierarchischen Geometrie und deren chemischen Oberflächeneigenschaften.

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Single-bubble cavitation-induced pitting on technical alloys

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Repeated single cavitation bubble experiments were performed primarily on 316L stainless steel, but also on nickel aluminum bronze (NAB) and pure aluminum. The objective of the work is to understand how the results of numerous studies on this topic on soft materials such as aluminum can be transferred to technical alloys. For this purpose, the bubble dynamics were recorded with two high-speed cameras and correlated with surface images taken in-situ between the individual bubbles. These experiments were performed for a range of stand-off distances γ (the ratio of the distance of the surface from the bubble to the maximum radius of the bubble) from 0.3 to 2.15. For all stand-off distances, single pits were the only surface change detected at the beginning of damage formation. The pits occurred on the technical alloys where they also occurred for aluminum. Later phases of the collapse are not axisymmetric but show regions of “stronger” collapse, and the pits occur on the material underneath those regions. Shock-wave emission was detected from the collapse regions that were linked to the damage.

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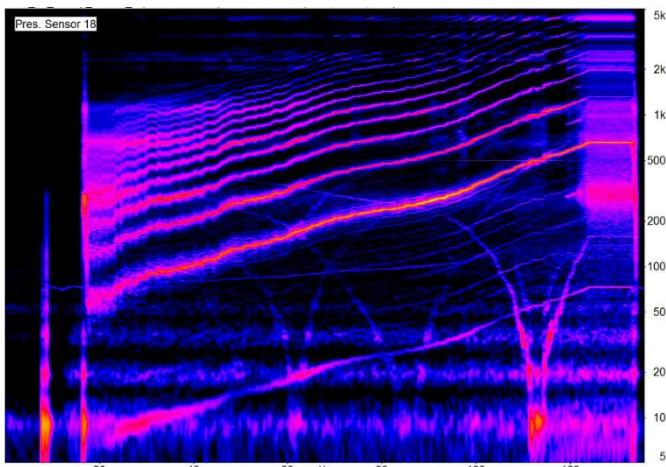
Detection of cavitation effects at hydraulic pumps

Ulrich Heise

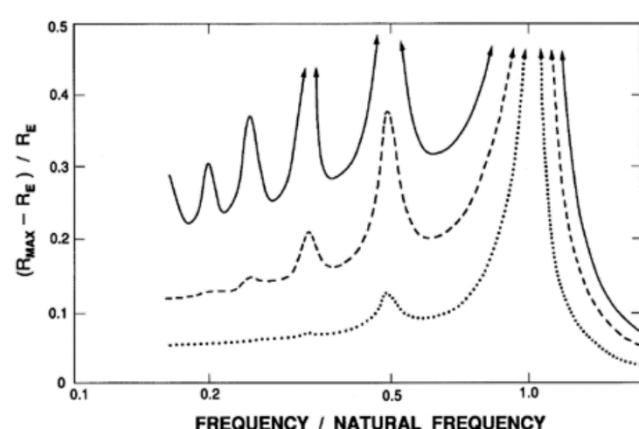
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Cavitation noise is created by the implosion of cavitation bubbles. The implosion of cavitation bubbles creates short pressure impulses which can be detected by fluid borne noise sensors. If no additional excitation pressure amplitude exists, the cavitating noise is random.

If additional driving pressure pulsation amplitudes are existing, an interaction of the imploding cavitation bubbles and the driving pressure pulsation can be measured. In the frequency spectra, subharmonics can easily detect. This information can be taken to detect critical working areas and compare different states of optimization.



Pressure pulsation spectra of a hydraulic motor. Abscisse is time related [s], Ordinate is the frequency axis (log scaling Hz) and colour is indicating the dynamic pressure amplitude.



Frequency response spectra of a bubble with three different excitations (Brennen (1995)).

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Hydroelasticity effects on cavitating flows around hydrofoils considering passive flow control methods

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We studied experimentally hydroelasticity effects on cavitation dynamics around a rigid and flexible hydrofoil made in stainless steel and polyvinyl chloride (PVC), respectively. In addition, we investigated the effect of passive cavitation control method on the structural vibrations of the flexible hydrofoil. We performed the experiments in our low-pressure cavitation tunnel. The cavitation-induced structural vibrations of the hydrofoil were measured using the digital image correlation (DIC) method. Further on, the dynamics of the cavitating flows was analysed using high-speed cameras. The hydrofoil's angle of attack was adjusted to 6 deg and the Reynolds number was about 0.6 million. Results showed that the passive cavitation control increased the cavity shedding frequency, and decreased the cavity length on the hydrofoil. Furthermore, the high-pressure pulsations due to the collapse of the large scale cloud cavity, along with the corresponding structural response of flexible hydrofoil were successfully mitigated.

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Multi-Scale Euler-Lagrange Simulations of Compressible Cavitating Flows

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Hydrodynamic cavitation occurs in flows around hydrofoils such as propellers. Among the different types of cavitation are sheet, cloud, and tip vortex cavitation. Cavitation is one of the major sources of underwater noise, which negatively affects the underwater living conditions of many marine animals by causing, e.g., acoustic interference or stress. Erosion of propellers leads to additional repair and maintenance times and generates additional costs for ship owners. The prediction of cavitation-induced noise and erosion from model tests is only qualitative and afflicted with scale effects. Seizing on these ideas, numerical approaches to predict cavitation, which model the behaviour of large vapour volumes as well as single cavitation bubbles are required. Numerical methods to simulate cavitating flows are mostly characterized by the approach to model the vapour phase. While homogeneous mixture approaches consider both the liquid and the vapour phase as continua, Euler-Lagrange methods assume only the liquid phase to be continuous and the vapour phase to be an accumulation of spherical Lagrangian bubbles. To benefit from the efficiency of the homogeneous mixture method and still gain insight into details of single bubble behaviour using a Euler-Lagrange method, we implemented a multi-scale Euler-Lagrange method, which captures large vapour volumes on the Eulerian grid, while small vapour volumes are treated as spherical Lagrangian bubbles. For each Lagrangian bubble, equations for its motion and dynamics are solved. Vapour volumes are transformed between the Eulerian and Lagrangian framework. In this work, we simulate the compressible cavitating flow around a propeller using the multi-scale Euler-Lagrange approach. Information from the dynamics of single cavitation bubbles, specifically, related to their collapses, enables a more accurate prediction of cavitation erosion and noise generation than Eulerian-based approaches for the vapour phase.

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3D-Simulation der Strömung binärer Alkan-Gemische und Bewertung der kavitationsinduzierten lokalen Segregation

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In [1,2] haben wir ein mathematisches Modell zur 1D-Strömungssimulation binärer Alkan-Mischungen an einzelnen sphärischen Blasen in unendlich ausgedehnten Flüssigkeiten vorgestellt. Durch unterschiedliche Flüchtigkeiten erfolgte ein unterschiedlicher Massetransfer und damit eine lokale Segregation beider Alkane in der die Blase umgebenden Flüssigkeit. Durch Vergleich mit einem „Bulk-Fluid“-Modell konnte z.B. beim Blasenwachstum in überhitzter Flüssigkeit ein erheblicher Einfluss der Segregation auf die Blasenwachstumsrate gezeigt werden. Dieser Ansatz wurde auf Basis eines blasendynamischen Kavitationsmodells [3] in einen 3D-Finite-Volumenlöser übernommen [4] und an kaviterenden Stoß- und Verdünnungswellenproblemen sowie an der Wolkenkavitation an einem Hydroprofil erprobt. Dabei wurde eine homogene Dispergierung zahlreicher Einzelblasen in jeder CFD-Zelle angenommen (homogener Mischungsansatz). Neben diesem homogenen Mischungsansatz werden im Vergleich zum 1D-Einzelblasenmodell gelöste sowie ungelöste Luft sowie Spezies-Interdiffusion vernachlässigt. Es wird ein thermodynamisches Gleichgewicht angenommen. Am Beispiel eines Hochdruck-Kraftstoffeinspritzinjektors wird eine n-Heptan/n-Dodekan- und eine n-Heptan/n-Oktan-Mischung untersucht. In der Dampfphase sammelt sich i.W. der jeweilige Leichtsieder der Alkan-Mischung an, was eine Anreicherung des jeweiligen Schwersieders in der umgebenden Flüssigkeit und somit eine lokale Segregation bewirkt. Aufgrund der größeren Spreizung der Flüchtigkeiten von n-Heptan und n-Dodekan ist dieser Effekt für die n-Heptan/n-Dodekan-Mischung stärker ausgeprägt als für die n-Heptan/n-Oktan-Mischung. Im Vergleich zur sphärischen Einzelblase [2] ist die lokale Segregation im 3D-Gebiet dennoch erheblich geringer ausgeprägt. Die Konzentrationsgrenzschicht an der Einzelblasen ist dünn und kann mit dem homogenen Mischungsansatz nicht aufgelöst werden, so dass als Ursache eine Verschmierung der lokalen Segregation in jeder 3D-Rechenzelle vermutet wird. In weiteren Arbeiten soll daher der lokale Stofftransport an Einzelblasen in die 3D-Simulation eingebettet werden, z.B. mit einer Euler-Lagrange-Methode.

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3D-Strömungssimulation zur Untersuchung des Einflusses von Luftausgasung auf die Strömungsaggressivität im Spalt einer Sonotrode

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In Vorarbeiten [1,2] wurde die Kavitationsdynamik in Form von Subharmonischen und deren aggressive Wirkung im Spalt von Sonotroden, die mit der indirekten Methode betriebenen werden, untersucht. Bei großen Spalten konnte die mittels an der Gegenprobe durchgeföhrten zeitlich hochaufgelösten Druckmessungen bewertete Strömungsaggressivität mit der 3D-Simulation sehr gut reproduziert werden. Bei kleinen Spalten zeigten die Messungen eine Abnahme der Aggressivität, die in der Simulation nicht reproduziert wurde. Wir sehen die Vernachlässigung von thermischen Effekten sowie von gelöster und ungelöster Luft als mögliche Ursache für die Abweichung, wobei zweiteres im Fokus dieser aktuellen Untersuchung ist. Es wird ein Luftpulster vermutet, das am schwingenden Sonotrodenkopf anhaftet und mit verringertem Abstand zur stationären Gegenprobe die Strömungsaggressivität dämpft. Es werden 3D CFD-Simulationen mit einem kompressiblen Finite-Volumen-Strömungslöser mit Verwendung eines barotropen, homogenen Flüssigkeits-Dampf-Gleichgewichtsmodells und Vernachlässigung viskoser Effekte durchgeführt. Die Luftausgasungsmodellierung basiert auf dem Ansatz von [3], der zuvor an Durchlichtbildern stromabwärts einer kavitierenden Blende [4] kalibriert und validiert wurde [5] und hier erstmals an einer Sonotrode angewendet wird. Die Simulationsergebnisse werden mit experimentellen Daten für Inkubationszeit- und Abtragsrate, Erosionsprofilen und Druckmessdaten verglichen.

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Stirring effects on multibubble sonoluminescence

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Light emissions from cavitating liquids serve as a diagnostic tool for chemical activity, bubble collapse conditions, or excited species. Here we demonstrate the influence of mechanical stirring on sonoluminescence (SL) and sono-chemiluminescence (SCL) emissions emerging under presence of dissolved sodium salts and luminol in different sonicated liquids. In the systems investigated, driven in the 20-40 kHz range, stirring can change the spatial distribution of blue/white broadband SL emissions and the orange/yellow sodium D-line, as well as their relative intensities. In many cases, an amplification of sodium emission is observed under stirring, but striking exceptions appear as well. SCL emission from luminol is mainly quenched by the mechanical agitation. The liquids under study comprise water, ethylene glycol, and phosphoric acid, all with dissolved argon or krypton. From the stirring-induced changes in sonoluminescence and high-speed video recordings, we make conjectures on the effects of rapid bulk liquid flow on bubble dynamics and bubble interaction. One effect seems to be a bubble separation or de-clustering, possibly by a separative impact of the stirring flow on populations of smaller and larger bubbles, respectively. As a consequence, large bubbles with extremely bright sonoluminescence flashes appear in phosphoric acid under stirring.

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On acoustic scattering of bubbles and wave localization

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The propagation of sound waves in scattering media is investigated theoretically and numerically. We start from the reported phenomenon of wave localization in a bubbly liquid, i.e. the trapping of sound waves between resonant scatterers of random position. From a spherical geometry of the scattering domain and a sound source in the center, we proceed via variations of the geometry to variations of the scatterers' resonances, the randomization of their locations, and addition of passive scatterers. The focus lies on the robustness of the localization effect to investigate its relevance in realistic systems.

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Bulk Nanobubble Generation using Laser-heated Gold Nanoparticles

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In the past decades, there has been a surge in claims supporting the existence of stable nano-sized gaseous domains in bulk liquids. However, they remain controversial due to the lack of objective evidence confirming their gaseous nature. The majority of studies rely on laser scattering techniques such as Dynamic Light Scattering (DLS) and Nanoparticle Tracking Analysis (NTA) for measuring the size distribution and number density of nanobubbles. However, these techniques are limited in their ability to differentiate between gaseous nanobubbles and other light-scattering entities such as nanoparticles or nanodroplets. This limitation raises concerns about the reliability of these techniques in detecting nanobubbles.

Rosselló and Ohl (2021, 2023) have proposed a new method for generating and detecting nanobubbles using collimated pulsed-laser illumination followed by a tension wave-induced expansion. This approach provides an unambiguous way to confirm the gaseous nature of nanobubbles. There is currently no good understanding of how the bubbles are generated, and how to stabilize them. The hypothesis of heating of contamination in the liquid is tested by adding well-controlled concentrations of light-absorbing nanoscale particles and counting the increased nanobubbles. The laser energy is related to the number of nanobubbles generated. Interestingly, the rarefaction wave amplitude has very little effect on the number of detected bubbles. Additionally, we report on the effect of the size of nanoparticles on the resulting nanobubble size.

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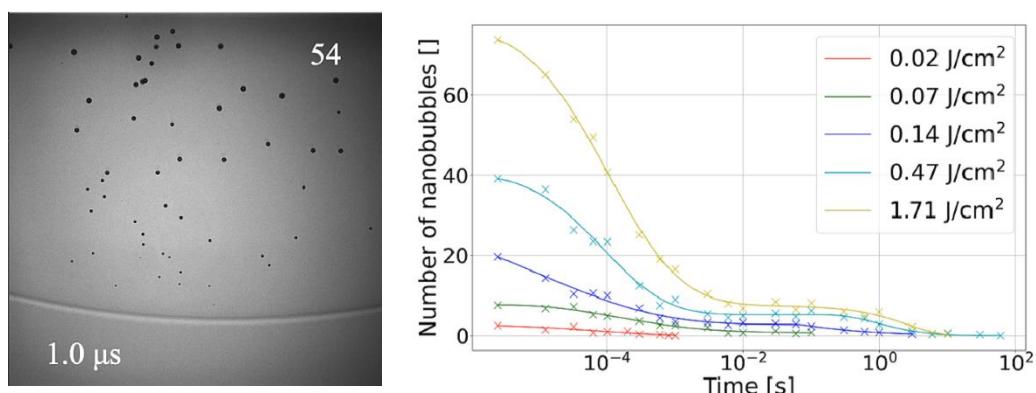
The laser excitation mechanism for nanobubble generation

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Nanobubbles have found increasing use in various applications, though the physical background of their formation and interactions remains largely unresearched as studies primarily focus on the benefits of nanobubbles rather than the governing principles. Recently, Rossello et al. published papers describing a method for production and observation of nanobubbles, which is based on similar principles as secondary cavitation phenomenon observed beforehand in the works of other groups. Nanobubbles were generated by laser light at intensities below threshold for laser-induced breakdown and subsequently expanded by a rarefaction wave to facilitate their observation and analysis.

In this work, the principles of laser-induced nanobubble formation in pure water and in water with added gold nanoparticles are studied and presented. Firstly, probability of nanobubble formation as a function of water sample purity was examined, while for solutions with added nanoparticles the number of excited nanobubbles was compared with the expected average number of nanoparticles within the excitation volume. Secondly, the relation between laser fluence at different wavelengths and the number of generated nanobubbles was investigated. Thirdly, measurements of nanobubble lifetime were conducted. Even in pure water samples, the measured long lifetimes were indicating a contradiction to the Epstein-Plesset equation-based prediction of free bubble dissolution. Accumulated evidence suggests that the presence of physical impurities is a prerequisite for nanobubble formation. Results with controlled concentration and type of impurities, namely gold nanoparticles, are also presented. In conclusion, a lack of impurities results in the absence of nanobubbles, while with the presence of impurities, either naturally occurring in water samples or added artificially, the nanobubble lifetimes do not correspond to the predictions of free bubble dissolution.



Left: Nanobubbles in pure water expanding behind the tension wave passing downwards. Right: Number of detected nanobubbles in pure water as a function of time delay after their excitation.

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Phase transition involved with nanoscale cavitation

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Molecular Dynamics (MD) simulations are performed to study the dynamics of single nanobubble nucleation and collapsing, where the phase transition occurs. The existence of nanoscale particles, as an embedded nucleus, facilitates the liquid–vapor phase transition. Understanding the exact mechanism of this phenomenon is important from the fundamental point of view, since it can reveal interesting phenomena relevant to phase change and heat transfer at the nanoscale in general. Furthermore, the effects of nuclei size, liquid properties, and bulk temperature on the cavitation dynamic and phase transition are discussed in detail.

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Influence of the surface roughness on nucleation and global cavitation dynamics

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The global dynamics of developed cavitation about a NACA0015 hydrofoil for several surface finishes, i.e., roughness up to 50 μm , were investigated. Experiments were conducted for several cavitation numbers at a constant Reynolds number covering three cavitation regimes, (I) shockwave-driven and (II) re-entrant flow-driven cloud cavitation as well as (III) sheet cavitation. High-speed recordings of the cavitation appearance with simultaneous transient pressure measurements were conducted at the cavitation tunnel at the Technische Universität Darmstadt. The surface roughness has three influences: 1. nucleation dynamics, 2. the critical cavitation number σ_c defining the transition from re-entrant flow-driven cavitation to sheet cavitation, 3. the shedding frequency for re-entrant flow-driven cloud cavitation due to dissipation.

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Water's tensile strength: The significance of oil nanodroplets

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The tensile strength of liquids refers to their ability to resist tensile forces attempting to pull them apart, a trait linked to their metastable states. In the case of water, the tensile strength defies theoretical expectations. While the theoretical value is around 140 MPa, experiments consistently find much lower values, revolving around 30 MPa. The enigma of this divergence has persisted for quite some time. While explanations encompass factors such as heterogeneous cavitation and cavitation stemming from pre-existing nanobubbles residing within wall grooves, it remains unclear whether these are always responsible for the reduced tensile strength, even in the most controlled experiments with purified water and hydrophilic walls. In our theoretical analysis, supported by molecular dynamic simulations, we show that even a tiny hydrocarbon nanodroplet compromises the intrinsically high tensile strength of water, driving it down to the order of tens of MPa, as typically observed. This underscores that minor traces of impurities, invariably present even in highly purified water, prevent them from achieving its theoretical value.

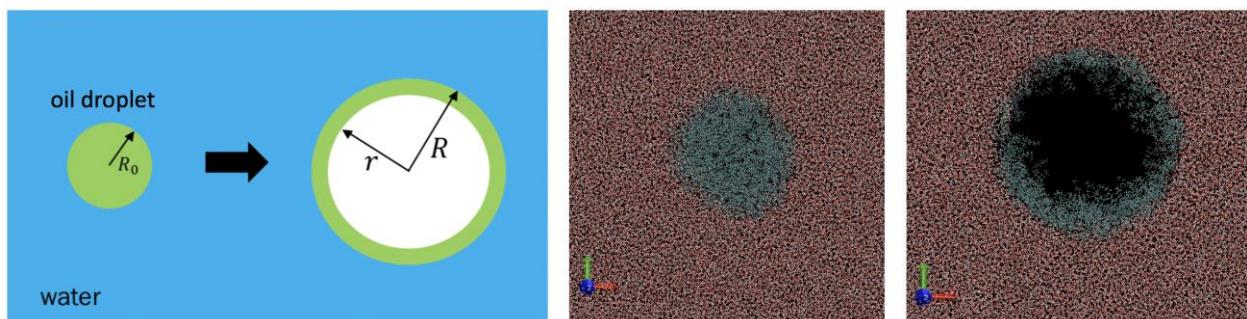


Figure 1: A tiny oil droplet within a bulk of water triggers cavitation, resulting in a substantial drop in the water's tensile strength.

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Thermodynamic effects on nanobubble's collapse-induced erosion

M. Ghohestani, S. Rezaee, E. Kadivar, O. el Moctar

We studied the thermodynamic effects of the nanobubble's collapse-induced erosion occurring at different ambient temperatures using molecular dynamics simulation. We analyzed the dynamics of a single nanobubble collapsing near an aluminum solid boundary immersed in water at temperatures ranging from 10 to 60 °C. We used a momentum mirror protocol to investigate the nanobubble's collapse-induced shock wave as the associated nanojet formed and moved toward the solid boundary. Results showed that the nanojet was formed during the collapse process after the collision of the nanobubble with the shock wave. On the aluminum surface, the erosion at lower ambient temperatures was greater than at higher ambient temperatures.

Reference:

Ghohestani, M., Rezaee, S., Kadivar, E., el Moctar, O. Thermodynamic effects on nanobubble's collapse-induced erosion using molecular dynamic simulation. *Physics of Fluids* 35, 073319 (2023)

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Utilization of surfactants as a cavitation erosion control method: an initial experimental study

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Cavitation erosion damage can be controlled by proper material selection, changes in component design, and modification of fluid. The latter one, as a straightforward option, could offer a method to reduce erosion damage in the circulated systems. Adding surfactants to water can alter the generation, coalescence, and collapse of cavitating bubbles as they reduce the water surface tension. This may, therefore, introduce surfactants as an economical and effective potential solution for reducing cavitation-induced mechanical damage. Here, we study the effect of sodium dodecyl sulfate (SDS) addition into distilled water on the cavitation erosion damage of CuZn38Pb3 brass and 316L stainless steel. Ultrasonic cavitation erosion tests were performed for various testing times up to 5 h in distilled water with and without SDS addition. The surface of samples after various sonication intervals were investigated by scanning electron microscope and confocal light microscope. The results showed a decrease of more than 30% in the erosion accumulative weight loss of the samples after 5 h sonication by adding SDS.

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A cavitation bubble interacting with a solid surface - what are the mechanisms of cleaning and erosion?

Fabian Reuter et al.

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The interaction between cavitation and solid surfaces is of great interest for various technical applications. Specifically, there is a strong focus on preventing cavitation erosion, and achieving effective ultrasonic cleaning. While cavitation typically occurs in complex cloud formations, the use of laser-generated single cavitation bubbles provides an excellent method to study the fundamental aspects of cavitation-surface interactions. Through single bubble experiments, we have observed different jetting regimes, self-focusing shockwaves, and the influence of asymmetries in the surrounding environment (e.g., background flows or non-planar surfaces) on bubble collapse. By employing high-speed imaging and time-resolved techniques, we can establish a connection between bubble dynamics and their impact on the surface. These findings enable us to address important questions such as how a bubble should collapse to achieve surface cleaning without causing material damage.

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Single cavitation bubble dynamics and erosion in a planar shear flow

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We study the dynamics and erosion of a single cavitation bubble nucleated in a shear flow inside a narrow gap formed by two parallel flat plates. High-speed recordings show rich and distinct bubble dynamics and the material damage from multiple bubble collapses next to an aluminium sample is measured using confocal profilometry. A moderate shear flow velocity of 18 m/s already deforms the bubble in a peculiar way and breaks the axial symmetry. The altered jetting behaviour can change the bubble-wall interaction drastically. In particular, the violent collapse in contact with the surface can be avoided by weakening or completely suppressing the formation of a directed jet flow toward the surface.

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Fluid-Structure Interaction between Single Cavitation Bubble & Elastic Metal Foil

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Cavitation and its effects have been extensively investigated over decades. This includes, the bubble near the solid boundary (Philipp & Lauterborn 1998, Sagar & el Moctar 2020), between parallel or oblique plates (Zeng 2022, Sagar & el Moctar 2023), and near object e.g. sphere (Goh et al., 2016), cylinder (Koch et al. 2023). However, in real life, cavitation occurs often near non-rigid/elastic boundaries (e.g., propellers, tissues, coating, and membranes). Therefore, the aim of this study is to investigate the interaction between laser-induced cavitation bubbles and elastic thin metal foil by measuring the bubble dynamics and the structural response. We generated single cavitation bubbles in the distilled water and the bubble dynamics was captured using a highspeed camera with the back illumination shadowgraphy method. The thin aluminum foil was attached to the sample holder to upside down. Displacement of the thin metal foil by a millimeter-sized single cavitation bubble was captured by using an optical displacement sensor having a high-speed photodetector equipped with the linear photosensor from the target surface. We observed that, the intensive pulling displacement of foil occurs during the bubble's collapse phase. The second pushing of the foil was observed during its second rebound and the pulling during the second collapse. The correlation of the foil displacement and cavitation bubble fundamentally clarified various phases of the motion and dynamics.

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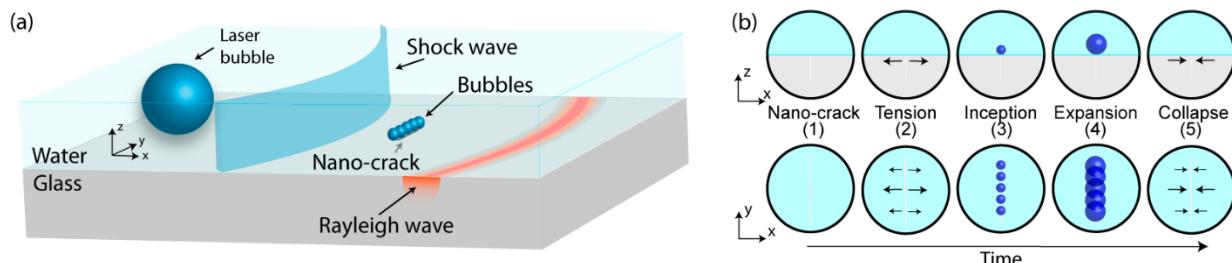
Controlling cavitation bubble lifetimes on the nanosecond scale: Rayleigh wave induced cavitation

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The maximum size and lifetime of an acoustically nucleated cavitation bubble is inversely proportional to the driving frequency and has achieved a limit of about 10 MHz. Smaller cavitation bubbles that are critical to microscopic applications require shorter lifetimes which correspond to higher oscillation frequencies. Here we demonstrate that acoustic cavitation in the 100 MHz range and beyond can be achieved through wave propagation in a solid rather than in a liquid. The cavitation bubble is nucleated at a nano-sized fracture on a glass substrate and its expansion is driven by a leaky Rayleigh wave, while the inertial collapse is induced by a trailing shock wave. As both waves travel at different velocities, the time interval between these two events is a function of the distance to the source. In this way, we experimentally demonstrate control of the lifetime of the bubbles in a range between 6 and 80 ns, corresponding to oscillation frequencies between 13 and 166 MHz. Our results agree with finite volume fluid-structure interaction simulations.



Inertial cavitation process. (a) A schematic of the sample is shown. The Rayleigh and shock waves are drawn. The Rayleigh wave travels faster in the elastic solid than the shock wave in the liquid and thus arrives first at the position of the nano-crack. (b) Close-up at the nano-crack position: (1) unperturbed nano-crack, (2) tension induced by the Rayleigh wave, (3) cavitation inception due to the tensile pressure, (4) bubble expansion due to on-going tensile pressure, (5) bubble collapse induced by the arrival of the shock wave.

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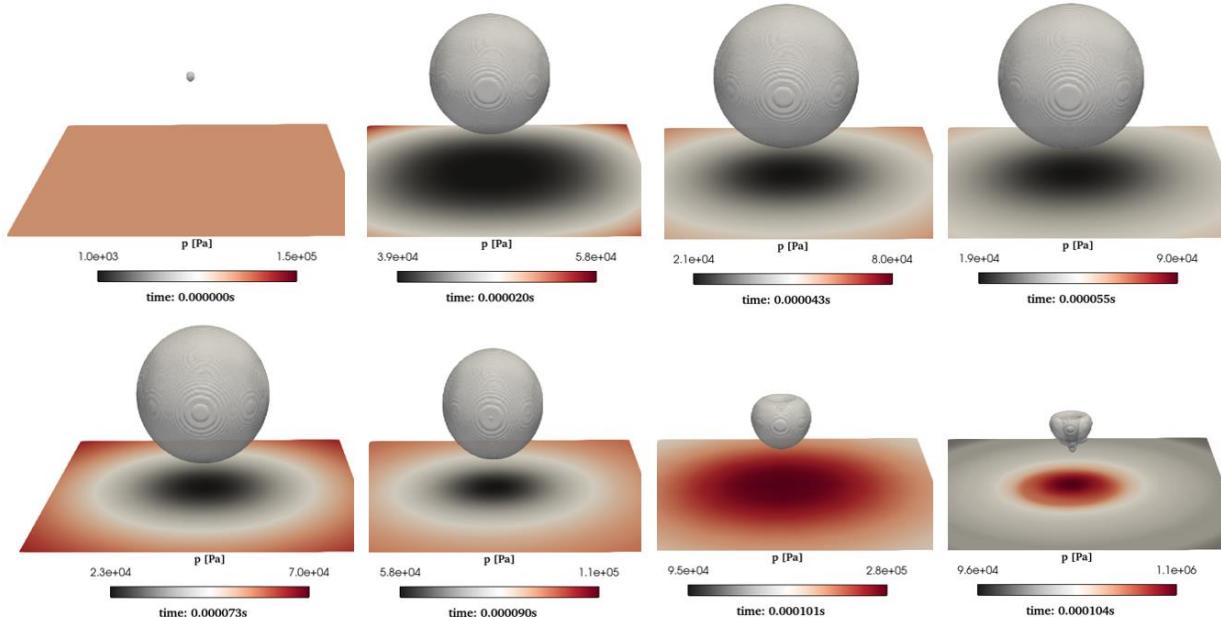
Investigation of 3D and viscous effects on single cavitation bubble dynamics

Gohar Moloudichiyaneh, Hemant Sagar, Udo Lantermann, Andreas Peters, Ould el Moctar

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The required spatial and temporal resolution to simulate the dynamics of single cavitation bubbles based on field methods (e.g., Finite-Volume Method) requires high computational effort. Therefore, two-dimensional computations are often performed by assuming rotational symmetry. Furthermore, the flow is usually assumed to be laminar. Here, we investigate three-dimensional as well as viscous effects on the single bubble dynamics near a solid boundary. Moreover, we investigated the iteration and discretization errors and quantified them based on a procedure for the estimation of numerical errors.

For this purpose, we performed systematic 2D and 3D simulations of the bubble dynamics near a solid boundary with different spatial and temporal resolutions. Furthermore, we quantified the viscous effects on the bubble dynamics.



Computed bubble dynamics near solid boundary at a relative wall distance (D/R_{max}) of 1.4.

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Influence of bubble size, liquid properties and ambient pressure on jet formation of wall attached bubbles

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The formation of very fast, thin jets resulting from liquid self-impact during bubble collapse is known to occur in several settings (e.g. bubbles close to an elastic boundary, bubble pairs, bubbles close to a curved boundary, bubbles on top of a cylindrical rod, etc.). It has been shown recently, that fast jet formation also happens in the simple case of an initially hemi-spherical bubble expanding and collapsing right at a flat solid boundary in a low-viscosity liquid [1,2,3,4]. Here, the phenomenon has its roots in the viscous boundary layer, that forms during the rapid expansion of the bubble. The boundary layer causes a slight deformation of the hemi-spherical bubble shape around maximum extension, which, due to flow focusing, leads to a cylindrically converging annular liquid inflow during collapse.

Since fast jet formation is related to the viscous boundary layer, it is of interest to vary the parameters that determine the thickness of the boundary layer and quantify their influence on the jet formation process. We present results from numerical simulations with the finite volume and volume of fluid method, modeling the dynamics of single (laser-generated) cavitation bubbles in axial symmetry [5].

Bubble size, the viscosity of the liquid and the ambient pressure are varied. Configurations with high values of a bubble Weber number, $Web = p^\infty \mathcal{R}eqmax/\sigma$ are considered, where p^∞ denotes the ambient pressure, $\mathcal{R}eqmax$ the maximum bubble radius and σ the surface tension coefficient.

Results can be labeled with respect to an inverse bubble Reynolds number $1/Reb = (\nu l / \mathcal{R}eqmax) (\rho^\infty / p^\infty)^{1/2}$, with νl , p^∞ denoting the kinematic viscosity and the density of the liquid [6]. Fast jet formation is found for $1/Reb \lesssim 0.0033$, including e.g. millimeter sized bubbles in water but also in 50 cSt silicone oil.

For decreasing values of $1/Reb$ the moment of self-impact of the annular inflow happens later and later in the bubble evolution. For $1/Reb \gtrsim 0.0033$ the mechanism of jet formation changes. First a jet forms by involution of the upper bubble wall after a high curvature spherical cap has collapsed. For higher values of $1/Reb$ a broad "standard" micro-jet forms. The jet speed decreases monotonically with increasing values of $1/Reb$, however, jets still can impact onto the solid with a speed of several hundred meter per second. No jet formation is found for $1/Reb = 6.25 \times 10^{-2}$ corresponding, e.g., to the case of a millimeter sized bubble in PAO40.

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Laser based submicron/micron-sized bubble seeding for flow tracking

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Submicron-sized and micron-sized bubble, showing high echogenicity with such a small size under the excitation of the ultrasound with central frequencies commonly adopted by medical imaging, could be idea for flow tracking, especially when large scale flow motions are of interest. However, the resolution of the ultrasound imaging is relatively low, and, due to its millimeter-sized elevation plane focus, the 3D effect of the flow motions cannot be ignored. Besides, due to its buoyancy nature, the seeding of submicron/micron-sized bubbles could be problematic in many scenarios, which further stops its application to general flow tracking. Here, we present a laser-based submicron/micron-sized bubble seeding method for flow tracking. A collimated pulse laser beam is shaped into a light sheet, and used for randomly seeding bubbles in 2D space temporally/spatially controllable. The method offers a real time bubble seeding during the flow tracking, and shrink the elevation plane focus during the ultrasound imaging into micrometer scale. Taking advantage of super-resolution ultrasound localization microscopy, which is based on localization and tracking of individual bubbles, the resolution of ultrasound imaging is further reduced to $O(10)\mu\text{m}$, while detecting flow in $O(10)\text{mm}$ scale with a $O(10)\text{kHz}$ frame rate.

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Supersonic jetting from anti-phase cavitation bubble pair interaction

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Cavitation bubbles generate jets in different contexts where the environment plays a crucial role. Near elastic and rigid boundaries, cavitation bubbles generate jets up to supersonic speed compared to the bubble content. We demonstrate that such ultra-fast jets also occur in bubble pair interactions, where two bubbles of the same volume are created in anti-phase at a proper initial distance. Compared to a single cavitation bubble, the supersonic jet does not atomize while penetrating the second bubble. We provide detailed insight into the mechanisms that lead to the formation of such jets by high-resolution numerical simulation and high-speed imaging at two million frames per second using laser induced bubbles in water. We show that a singularity on the axis of symmetry induces the ultra-fast jet, which forms by the collapse of an elongated neck that evolves during the expansion of the second bubble. Furthermore, we explain the narrow parameter range of the ultra-fast jets by comparing the experiments and simulations.

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Simulations of bubble surface oscillations and microstreaming

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Non-spherical bubble oscillations require a careful analysis of surface modes that affect the stability of the bubble and the surrounding liquid flow. For instance, microstreaming and corresponding shear forces can be generated near the bubble. Here we employ a Volume-of-Fluid method to simulate surface-tension-driven bubble oscillations. Although the method is more expensive than the frequently used Boundary-Integral-Method, it has some advantages and allows for a straightforward capture of bubble break-up. VoF requires careful meshing and tuning of parameters, but can result in accurate simulations of surface mode oscillations and the subsequent microstreaming of both acoustically driven and laser-generated bubbles.

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Viscous Fingering on Cavitation Bubbles

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Expanding bubbles in a thin liquid gap may show an interfacial instability. A cavitation bubble is initiated by an optical breakdown in a thin liquid gap between two glass plates. During its expansion, an instability occurs at the liquid-gas interface. In contrast to the highly branched fingers in ridged-walled Hele-Shaw cells [1], the observed fingers are short and subby (Fig. 1(a)). To reveal the nature of the instability, its dynamics has been studied.

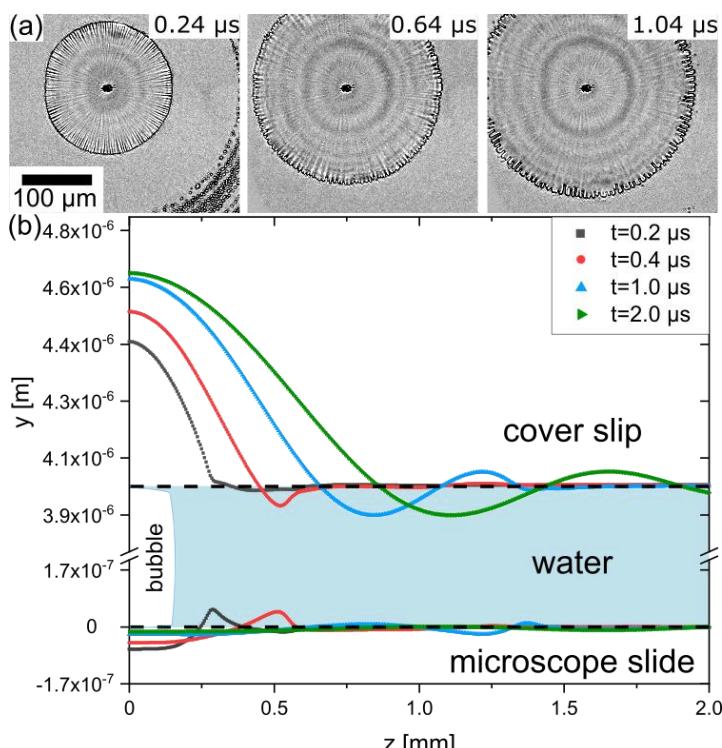


Figure 1: (a) Evolution of an expanding cavitation bubble in a thin liquid gap. (b) Numerical simulation of the gap deformation caused by the cavitation bubble at different instants in time.

As the cavitation bubble experiences a high internal pressure, it expands rapidly, i.e., with several hundred meters per second. The high internal pressure enables the bubble to deform the glass walls [2]. Numerical simulations reveal that the glass plates are pushed apart from each other, forming a wedge-shaped gap (Fig. 1(b)). The viscous fingers occurring in this configuration are analogous to those in a Hele-Shaw cell with an elastic boundary for geometric reasons.

A linear stability analysis is performed to compare the growth rate of the fingers from the experiment with the theoretical one, which differ by a factor of two. Hence, it can be assumed that the observed instability is indeed a Saffmann-Taylor instability.

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