7. Workshop

Komplexe Aspekte der Kavitation:

Grenzflächen, Chemie und Erosion

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Organisation:

Prof. Dr. Claus-Dieter Ohl

Otto-von-Guericke-Universität Magdeburg
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Kavitation in der Hydraulik

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Kavitation tritt in hydraulischen Komponenten wie Ventilen und Pumpen auf und ist häufig nicht oder nur durch eine Begrenzung der Leistungsdichte vermeidbar.

Auf Grund der hohen Luftlöslichkeit von Mineralöl spielt neben der Dampfkavitation (Phasenübergang flüssig/gasförmig) auch die Gaskavitation(Lösungsprozess Luft/Druckflüssigkeit) eine wichtige Rolle. Dampfkavitation ist verantwortlich für Bauteilschädigung durch Erosion und Lärmentwicklung, wohingegen Gaskavitation zu Befüllungsverlusten in Pumpen, Ölalterung und zu einer Absenkung der Systemsteifigkeit führt, welche zu negativen Auswirkungen auf Steuerung und Regelung hydraulischer Anlagen haben.

Die Berechnung von Kavitationseffekten ist ein vielversprechender Ansatz zur Optimierung hydraulischer Komponenten, jedoch existieren derzeit keine validierten Kavitationsmodelle inklusive ihrer Parameter für Mineralöl und typischen Geometrien.

Ein aktuelles Forschungsziel ist es, existierende Kavitationsmodelle für Mineralöl zu parametrieren und zu validieren. Dazu wird ein Versuchstand aufgebaut, an dem separat Dampf- und Gaskavitation in einem Ventil oder einer Pumpe optisch mit Hilfe von Hochgeschwindigkeitskameras vermessen werden können. Die Versuchsergebnisse werden mit umfangreichen CFD Ergebnissen verglichen, wodurch ein allgemeingültiger Parametersatz abgeleitet werden kann.

In einigen brand- oder explosionsgefährdeten Bereichen müssen anstatt Mineralöl schwerentflammbare Druckflüssigkeiten eingesetzt werden. Eine typische wasserbasierte Druckflüssigkeit ist HFC (Wasser-Glykol Gemisch), welches jedoch eine sehr starke Kavitationserosivität aufweist. Die CFD kann mit geeigneten Kavitationsmodellen(z.B. Zwart-Gerber-Belamri-Modell) und Kavitationserosionsindikatoren (z.B. Nohmi) die Erosion in Ventilen und Pumpen vorausberechnen. Diese Ergebnisse werden durch umfangreiche experimentelle Arbeiten validiert.

On some aspects of cavitation in holes and tubes

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First I recapitulate results from observations and numerical calculations on acoustic cavitation in small blind and through holes. This work has been done in the framework of the investigation of ultrasound assist for surface plating. The findings comprise wetting of gas-filled blind holes by atomization, and avalanche bubble collapses in such holes. Then I report on investigation of cavitation in submerged flow channels in an ultrasonic bath, intended for flow sono-chemistry. Here, we see bubble nucleation only in a gas-lilquid slug flow, namely by unstable gas-liquid interfaces. The process is similar to the wetting of holes where drops are ejected towards the gas and bubbles are entrained into the liquid. Cavitation bubbles then typically occur in localized structures in the tubes, often in form of clusters. Bubble compression ratios are estimated from experimental data, and simulations by numerical cluster models are discussed.

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Measurement of the thickness of the liquid film that separates a cavitation bubble from a solid during its collapse dynamics

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The time evolution of the liquid-film thickness between a single cavitation bubble in water collapsing onto a solid surface is measured. To this end TIR shadowmetry is developed, a technique based on total internal reflection (TIR) and the imaging of shadows of an optical structure on a polished glass surface. The measurements are performed at frame rates up to 480 kHz. Simultaneous high-speed imaging of the shape of a laser-induced bubble at up to 89 kHz allows relating the evolution of the film thickness to the bubble dynamics. We find that there resides a liquid film between the cavitation bubble and the solid during most of its dynamics and provide the time evolution of its thickness. Consequences for mass and heat transfer between bubble interior and solid are discussed.

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Experimental Investigation of Bubble Dynamics with a Shock Tube

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In this talk, we would like to present our recent experimental work on bubble dynamics conducted with a setup that combines a shock tube and a gelatinous medium as the liquid carrier medium for pure gas bubbles. We will discuss first results, possibilities of the setup as well as challenges and limitations.

The chair of aerodynamics and fluid mechanics acquired and set up a shock tube in recent years. To complement the numerical expertise at the chair, we conduct experiments on corresponding topics, such as bubble collapse and droplet breakup.

For bubble collapses, our recent experimental method relies on two aspects to achieve a constant surrounding pressure and well-defined boundary conditions. First, the shock tube generates a planar shock front which provides an instantaneous pressure jump to a constant high pressure. Second, a gelatinous mixture is used as a water-like carrier medium to contain pure gas bubbles at rest. Although both aspects –using a shock tube and placing bubbles in gelatin – have been used individually in previous studies, the combination expands the methodology in bubble dynamics research and allows getting insight into new aspects.

Capitalizing on the strengths of the setup, our initial research efforts include comparing aspherical bubble collapses using bubbles of different gas content. By using gases with a vapor pressure slightly above atmospheric pressure, also the aspect of phase change during the collapse can be studied. In addition, the setup is very powerful for investigating pairs of bubbles or multi-bubble interaction. Bubble pairs of various size ratios and at various distances can be produced and their reaction to the pressure rise can be studied. Recent work showed that four types of interaction for gas bubble pairs in the free field can be defined by non-dimensional parameters. This classification differs from the literature in some respects due to the use of pure gas bubbles instead of vapor bubbles. Lastly, the aspherical collapse and continuous oscillation of bubbles near solid and soft surfaces is a point of interest that can be studied by carefully placing bubbles adjacent to boundaries.

Apart from the advantages and possibilities of the setup, we also would like to highlight some challenges. An inherent problem of using gelatin is to produce a clear and homogenous mixture that does react as a liquid and does not influence the bubble collapse significantly. In addition, it is essential to create spherical bubbles while not affecting the homogeneity of the gelatin, which makes the bubble production challenging.

Upon conducting experiments, we also realized that the applied pressure rise of several bar can lead to a small but rapid deformation of our metal test sections, which strongly affects rise time and evolution of the pressure. A test section with solid side walls (up to 130mm) shows a fast rise time and a constant pressure that remains at a high value (albeit not at the expected value predicted from ideal wave motion). A test section with side walls of 40mm thick aluminum alloy plates displays only a slow pressure rise that is insufficient to cause strong bubble collapse. This indicates a strong dependency of results on the applied setup, which should be of interest when looking at other experimental setups in the literature.

The talk can be given in German or in English.

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Sonolumineszenz in einer Water-hammer tube

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Eine mit verschiedenen Flüssigkeiten gefüllte PMMA-Röhre wird geschüttelt und mittels Photomultiplier, Kamera und Beschleunigungssensor auf die Entstehung von Kavitation und Sonolumineszenz untersucht. Dazu werden für zwei Frequenzen und drei Flüssigkeiten die Photomultiplier-Signale ausgewertet und mit dem Hintergrundrauschen verglichen, die Röhre in Bereiche aufgeteilt und auf Aktivität untersucht, und die Phasenbeziehung zwischen Schüttelapperat und Auftreten von Sonolumineszenz gemessen.

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Thermal effects on bubble growth in discrete n-alkanes mixtures

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Hydraulic systems usually do not use water as working medium. For example, for direct injection into internal combustion engines the fuel may be approximated as a discrete mixture of n-alkanes. At cavitation conditions, the growth of the bubbles is influenced by the properties of the fluid that depend on the molar fraction of the individual species as well as the spatially and temporally varying mixture composition.
The characteristics of bubble dynamics in the presence of thermal effects on a discrete multicomponent bubble is investigated. Brennen[1] defined a critical time in which the order of magnitude of the thermal term becomes equal to the remaining terms. The thermal term in the Rayleigh – Plesset Equation will gain in magnitude over the other terms in the equation when the critical time has passed. The growth behavior will change and the inertial, viscous, gaseous, and surface tension terms in the Rayleigh-Plesset equation rapidly decline in importance. While thermal growth has been observed by many researchers for single-component fluids, e.g. water, we study it by simulation for n-alkane mixtures.
An in-house code based on the spherical bubble dynamic model by Kawashima, et al.[3] and Nigmatulin, et al.[4] is developed that includes mass and heat transport. The phase change as well the diffusive transport and de-/adsorption of non-condensable gases i.e. air is considered. The method is validated by the water measurements of Dergarabedian[2] and extended for discrete mixtures of n-alkanes. It is applied to study the thermally controlled growth of a multicomponent spherical single bubble. A strong local de-mixing of initial liquid mixture occurs during phase transfer, and an in-homogenous composition and species distribution within the bubble is found. It is shown that bubble dynamics in mixtures is strongly influenced by the presence of highly-volatile components. These species dominate the composition inside the bubble which contribute to reach the critical time at lower times than expected.

[1] C. E. Brennen, *Cavitation and bubble dynamics*. The Oxford engineering science series: 44, New York, Oxford Univ. Press, 1995.

[2] P. Dergarabedian, *The rate of growth of vapor bubbles in superheated water*. ASME J. Appl. Mech., 20, 537–545, 1953.

[3] H. Kawashima and M. Kameda, *Dynamics of a spherical vapor/gas bubble in varying pressure fields*, Journal of Fluid Science and Technology, vol. 3, no. 8, pp. 943–955, 2008.

[4] R.I. Nigmatulin, N.S. Khabeev and F.B. Nagiev, *Dynamics, Heat and Mass Transfer of Vapour-Gas Bubbles in a liquid*. Int. J. Heat Mass Transfer, vol. 24, no. 6, pp. 1033-1044, 1981.

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Predicting bubble collapse: numerical algorithms and thermodynamic closures

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Simulating compressible gas-liquid flows, such as cavitation and shock-driven bubble collapse, presents considerable numerical challenges due to the stiff pressure-density-temperature relationship of the liquid and the sharp difference in compressibility of the fluids at the interface. In addition, different Mach number regimes are present, such as essentially quiescent flow in the bubble in conjunction with shock formation and propagation in the surrounding liquid during violent bubble collapse, which further exacerbates the numerical complexity.

We present a fully-coupled pressure-based algorithm for the simulation of interfacial flows in all Mach number regimes, based on a conservative finite-volume discretisation and a VOF method to represent the interface, which treats the continuity equation as an equation for pressure and solves the discrete governing equations in a single linearised system of equations. The bulk phases are coupled by an acoustically-conservative interface discretisation method that retains the acoustic properties of the flow and does not require a Riemann solver. This allows for the interacting fluids to be treated as incompressible fluids, ρ = const., as polytropic fluids, $\rho = f(p)$, or as fully-compressible fluids, $\rho = f(p,T)$, using the same numerical discretisation and algorithm.

Results of representative test-cases, such as the Rayleigh collapse of a bubble or the shock-driven bubble collapse, are presented to scrutinise the presented algorithm and to demonstrate the utility of this algorithm in predicting cavitation processes.

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Self-organization of laser induced bubbles under the influence of strong acoustic pressure fields in phosphoric acid

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In this talk we will discuss some basic characteristics of the temporal evolution of a cluster of bubbles initially arranged over a line while being driven by a strong acoustic excitation. The experimental results are mainly given by high-speed video recordings of a laser induced multi-bubble system in concentrated phosphoric acid. The videos shown a significant effect of the bubble interaction which leads to a self-organization in several small spherical clusters immediately after the bubble seeding. These sub-clusters are driven away from the acoustic pressure anti-node in the same way it occurs to single bubbles, producing a clear streamer. The role of the shape instabilities and the principal forces affecting both the individual and collective behaviour of the bubbles is analysed, and also compared with a series of preliminary results obtained from numerical simulations.

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Ultrasonic pretreatment of lignocellulosic feedstock as substrate for sugar based biotechnology in an industrial scale

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Agro-industrial residues generated by agricultural crops processing are abundant sources of lignocellulosic feedstocks, which could be further processed into added-value platform chemicals (sugars, lignin, polyphenols etc.). Using wheat straw as feedstock and following the biorefinery concept, this topic was investigated within the BBI project US4Greenchem (H2020) developing a versatile integrated protocol.

Delignification is a primary step in biomass pretreatment for further fermentation to sugars. Besides mechanical grinding, the ultrasonic pretreatment in flow-mode exploiting strong acoustic cavitation at room temperatures. The aim of the pretreatment was to enhance the sugar yields after the following enzymatic hydrolysis.

Herein we report the successful process scaling-up to an industrial demonstration setup. Starting from a preliminary study using ultrasonic baths all the main working parameters have been optimized and transferred to larger scale flow reactors. Thanks to the strong cavitation fields by optimizing the sonication parameters the yield of the enzymatic hydrolysis could be significantly improved even in larger scales. As a result, the ultrasonic pretreatment of biomass could provide an energy saving and efficient alternative to other established pretreatment methods.

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Numerically investigated dual-frequency driven sonochemistry

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One of the 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 (sonochemistry). According to many experimental observations, the chemical yield can be further increased by the use of dual-frequency 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 between the two harmonic components is still missing in the literature. Our aim is to provide a theoretical basis for dual-frequency synergy. Our main 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 — e.g. simulation of bubble clusters — until a suitable explanation for the experimental observation is found.

As an initial step, this study presents numerical simulations obtained by solving the Keller—Miksis equation well known in sonochemistry that is a second order ordinary differential equation describing the dynamics of a single spherical gas bubble. The investigated 6-dimensional parameter space is composed by the pressure amplitudes, driving frequencies, phase shift between the harmonic components of the driving and the bubble size. Due to the large number of involved parameters, the studied parameter combinations are approximately two billion. In order to obtain results within reasonable time, the high computational capacities of professional GPUs were exploited. The initial evaluation of the results shows that applying low-high frequency combination, the active cavitation threshold for chemical activity can be significantly decreased in a large range of bubble sizes. It is caused by the synergy of the Giant Response of the bubble (low frequency) and the main resonance of the system (high frequency).

It is very likely that the synergetic effect cannot be explained via a single phenomenon. Thus, our further goal in the future, is to study the number of the strong collapses in a unit time (how frequent the chemical activity of a bubble is), the spherical stability (how the dual-frequency driving can stabilize/destabilize the spherical shape) and the effect of the rectified diffusion (how fast a bubble can grow to a chemically active size). Furthermore, one of our recent results revealed a clear relationship between the chemical yield and the relative expansion of a bubble collapse. The model included chemical kinetics of 44 reactions and 9 species, and performed only on a few millions of parameter combinations due to the model complexity. This will allow us to estimate the chemical output on our large-scale (two billion) parameter study and determine parameter combinations for maximum chemical output. The final, long-term, objective is to work out optimal operation strategies with the help of reinforcement learning, where the driving parameters can be arbitrary functions of time approximated by piecewise constant segments.

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Stoffumsetzung mittels Strahlkavitation

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In den letzten Jahren wurde eine stetig steigende Schadstoffkonzentration in Gewässern festgestellt. Diese unerwünschten Substanzen stellen eine Gefahr für die Umwelt dar, sind nur sehr schwierig und kostspielig aus dem Wasser zu entfernen.

Eine der Möglichkeiten zum Abbau dieser Stoffe ist die Behandlung des Wassers durch hydrodynamische Kavitation (HC). Der Prozess der Kavitation ist gekennzeichnet durch das Wachstum, den Transport und den Kollaps von Dampf-Gasblasen. Beim Kollaps entstehen extreme thermodynamische Zustände, die zur homolytischen Spaltung des Wassers führen. Dabei entstehen unter anderem hochreaktive Hydroxylgruppen, die Schadstoffe im Wasser oxidieren können. Dies wird allgemein als „AOP -Advanced Oxidation Process“ bezeichnet.

Die hier vorgestellten Forschungsergebnisse der Professur für Strömungsmechanik sind Bestandteil der Entwicklung eines Verfahrens zur Reinigung von Wasser mittels Kavitation mit möglichst geringem Energieeinsatz. Das Kavitationsgebiet wird mittels einer Drosselstelle (Lochblende oder Düse) erzeugt, es bildet sich vorrangig Kavitation in der Scherschicht und damit ein kavitierender Freistrahl aus.

Während sich frühere Studien hauptsächlich auf den Abbau bzw. die Konzentrationsänderung von Medikamenten, Bakterien, Viren oder Farbstoffen konzentrierten und das Kavitationsgebiet, als das eigentliche Gebiet der chemischen Reaktion, als „Black Box“ behandelten, beschäftigt sich diese Arbeit mit der Erforschung der lokalen Prozessbedingungen im Kavitationsreaktor. Das Ziel ist es, eine Korrelation zwischen den lokalen Bedingungen des kavitierenden Freistrahls und der lokalen Umwandlung der im Wasser gelösten Substanzen zu erhalten, um darauf aufbauend eine Optimierung des Reaktors durchführen zu können.

In ersten Untersuchungen wurden dafür die Blasenverteilung und die Blasengrößen mit einer Hochgeschwindigkeitskamera und einem Laserlichtschnitt aufgenommen und mittels Auswerteroutinen bestimmt. Darüber hinaus wurden Experimente zur Chemolumineszenz von Luminol durchgeführt, welche den Reaktionsbereich von Hydroxylradikalen sichtbar macht. Es wird gezeigt, dass die höchsten Abbauraten mit dem Einsatz kleinerer Düsen erreicht werden, was mit einem zunehmenden Anteil kleiner Blasen mit einem Durchmesser unter 50 µm erklärt werden kann.

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Materials synthesis in a cavitation bubble

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Laser Synthesis and Processing of Colloids (LSPC) [1] is a modern technique for materials synthesis linked to the formation and collapse of cavitation bubbles. This contribution will provide an overview of the physics of laser-induced bubble oscillations and describe how the high pressures and temperatures associated with ablation and bubble collapse take part in nanomaterial synthesis inside and around the bubble [2]. A step-by-step account of the events from laser ablation through interaction of ablation products with the surrounding liquid up to the modification or aggregation of particles within the bubble is given. Furthermore, synchrotron SAXS and WAXS measurements to map the bubble's interior solid matter with picosecond to microsecond resolution will be shown [3, 4]. We will conclude showing the unique properties of these laser-generated colloidal nanoparticles, their scalability and their connection to the cavitation bubble dynamics will be described [5].

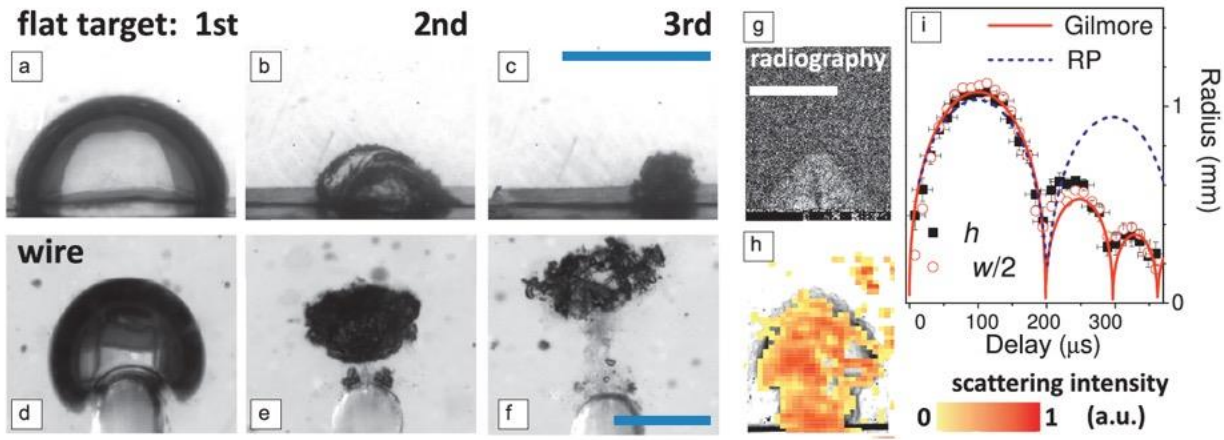

Figure 1. Time-resolved imaging of a macroscopic laser ablation in liquids-induced cavitation bubble (a–c, g on a flat target and (d–f, h) on a wire target during (a, d) first, (b, e, h) second, and (c, f, g) third bubble oscillations. The radius evolution h) of a bubble on a flat target is shown in (i) together with calculations using the Rayleigh–Plesset and Gilmore models. X-ray radiographs in (g) bright and (h) dark field are shown with color-coded scattering from microbubbles and nanoparticles, overlaid onto a bright field edge-enhanced image. Scale bars = 2 mm, except for 0.5 mm in (g). [2]

References:

[1] D. Zhang, B. Gökce, S. Barcikowski, Laser Synthesis and Processing of Colloids – Fundamentals and Applications, Chemical Reviews 117, 3990 (2017)

[2] S. Barcikowski, A. Plech, K. S. Suslick, A. Vogel, Materials synthesis in a bubble, MRS Bulletin 44, 382, (2019)

[3] P. Wagener, S. Ibrahimkutty, A. Menzel, A. Plech, S. Barcikowski, Dynamics of silver nanoparticle formation and agglomeration inside the cavitation bubble after pulsed laser ablation in liquid, Physical Chemistry Chemical Physics 15, 3068, (2013)

[4] S. Ibrahimkutty, P. Wagener, A. Menzel, A. Plech, S. Barcikowski, Nanoparticle formation in a cavitation bubble after pulsed laser ablation in liquid studied with high time resolution small angle x-ray scattering. Applied Physics Letters 101, 103104, (2012)

[5] S. Kohsakowski, B. Gökce, R. Tanabe, P. Wagener, A. Plech, Y. Ito, S. Barcikowski, Target geometry and rigidity determines laser-induced cavitation bubble transport and nanoparticle productivity– A high-speed videography study, Physical Chemistry Chemical Physics 18, 16585 (2016)

„Standard" jets and fast jets from laser-generated bubbles close to a solid boundary

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Cavitation bubbles expanding and collapsing close to a solid wall are known to develop a liquid jet that is directed towards the solid. Its formation can be attributed to the presence of the wall causing an asymmetric inflow during the collapse phase. Jet speeds typically are of the order of 100 m/s[1]. Recently, it has been demonstrated numerically, that this standard picture of jet formation loses its applicability, when the bubble is generated very close to the wall[2]. For an initial dimensionless distance less than 0.2 from the wall, very thin jets with speeds of the order of 1000 m/s are formed. We present numerical results from finite volume simulations in axial symmetry describing the mechanism leading to fast jet formation, as well as the regimes of the „standard" jet and the fast jet as functions of the bubble's initial distance from the wall.

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1 A. Philipp and W. Lauterborn, *J. Fluid Mech.*, **361**: 75--116, 1998.

2 C. Lechner, W. Lauterborn, M. Koch and R. Mettin. *Phys. Rev. Fluids*, **4,** 021601(R), 2019.

Extremely fast jets and vortex dynamics of single laser bubbles

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An extreme fast jet has recently been predicted by the authors [1] for cavitation bubbles close to a solid boundary. Until then jet velocities were known only in the order of ~100 m/s for large distances from the boundary, whereas the extreme fast jet is supposed to reach orders of ~1000 m/s when the bubble collapses in the direct vicinity. The lifetime of this jet is in sub- or few microseconds range. These properties make the experimental confirmation a laborous task. However, the authors claim to have photographed it. The results are discussed and a considerable lower bound for the jet velocity of ~300 m/s can be given.

[1]: Christiane Lechner, Werner Lauterborn, Max Koch and Robert Mettin; „Fast, thin jets from bubbles expanding and collapsing in extreme vicinity to a solid boundary: A numerical study“ Phys. Rev. Fl. 4 021601(R) (2019)

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Numerische Vorhersage von Kavitationserosion mit einem Multiskalen-Euler-Lagrange-Verfahren

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Hydrodynamische Kavitation entsteht in technischen Strömungen infolge Druckschwankungen. Sobald der Druck in der Flüssigkeit Werte im Bereich des Fluid-Dampfdruckes erreicht, beginnt das Wachstum von mikroskopischen, gasgefüllten Kavitationskeimen zu Kavitationsblasen. Unter größeren Flüssigkeitsdrücken kollabieren die dampfgefüllten Blasen schlagartig und emittieren Druckwellen, deren Druckspitzen in der Größenordnung von einem Gigapascal liegen können. Das wiederholte Auftreten dieser Blasenkollapse in der Nähe von festen Strukturen kann selbst Werkstoffe von großer Härte schädigen und zum Materialabtrag (Erosion) führen. In ingenieurstechnischen Anwendungen sind neben Schiffspropellern und –rudern auch Dieseleinspritzdüsen und Pumpen von kavitationsinduzierter Erosion betroffen. Zwar bieten experimentelle Methoden eine Möglichkeit zur Vorhersage von Kavitationserosion für makroskopische, technische Strömungsprobleme, allerdings sind diese Methoden von Maßstabseffekten, sowohl in Bezug auf die Abbildung der Strömung und des Blasenverhaltens, als auch im Hinblick auf die Abbildung des Werkstoffverhaltens, betroffen. Im Zuge dessen bedarf es numerischer Vorhersagen von Kavitationserosion zur Ergänzung der experimentellen Methoden.

Zur Simulation der kavitierenden Strömung in einer rotationssymmetrischen Düse verwenden wir ein Multi-Skalen-Euler-Lagrange-Verfahren, welches große Dampfstrukturen in einem Euler'schen Bezugssystem behandelt und kleine Dampfstrukturen als sphärische, Lagrange'sche Einzelblasen abbildet. Das numerische Verfahren zur Strömungslösung auf Basis der Reynolds-gemittelten Navier-Stokes-Gleichungen (RANSE) verwendet die Finite-Volumen-Methode (FVM) zur räumlichen Diskretisierung der Strömungsgleichungen und die Volume-of-Fluid (VoF)- Methode zur Erfassung von Phasengrenzen zwischen Euler'schen Dampfstrukturen und der Flüssigphase. Für jede sphärische Einzelblase wird die Bewegung anhand der Lagrange'schen Bewegungsgleichung berechnet, so dass Blasentrajektorien von den Stromlinien der Trägerströmung abweichen können. Die Dynamik der Lagrange'schen Dampfblasen – Wachstum und Kollaps – wird unter Berücksichtigung der Kompressibilität der Flüssigphase, Oberflächenspannung und Viskositätseffekten bestimmt. Auf Basis der berechneten Lagrange'schen Blasenkollapse in der Nähe von festen Wänden, werden Effekte des asymmetrischen Kollapsverhaltens, wie z.B. Microjet, Bewegung der Blase zur Wand, emittierte Stoßwellenenergie, anhand von fundierten experimentellen und theoretischen Untersuchungen aus der Literatur modelliert. Der Vergleich unserer numerischen Erosionsvorhersage mit der gemessenen Erosion aus dem Versuch weist gute Übereinstimmungen der erosiven Regionen auf.

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Experimentelle und numerische Untersuchung der Strömungsaggressivität von Sonotroden zur Analyse der Kavitationserosion

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Es wird der standardisierte Kavitationserosions-Testfall einer Sonotrode experimentell und numerisch untersucht. Zur experimentellen Ermittlung einer zeitlich hochaufgelösten Wandlast werden Polyvinylidendifluorid (PVDF)-basierte Drucksensoren auf der Gegenprobe verwendet und numerisch nachgebildet. Zur CFD-Simulation wird ein kompressibler in-house Löser verwendet, der mit zeitlicher Auflösung im Bereich von Nanosekunden die Druckwellendynamik akkurat abbildet. Eine Variation des Spaltabstandes zwischen dem oszillierenden Sonotrodenkopf und der stationären Gegenprobe resultiert in Betriebszuständen unterschiedlich stark ausgeprägter Strömungsaggressivität. Diese wird auf der Gegenprobe mittels Wandlast-Spektren bewertet, welche aus den Sensorsignalen generiert werden. Zusätzlich ermöglicht die Analyse des Frequenzspektrums der gemessenen und in der Simulation reproduzierten Wandlasten eine Beurteilung der Schädigungsdynamik. So lässt sich der mit starker Schädigung verbundene gewaltige Kollaps eines sich über mehrere harmonische Schwingungszyklen des Sonotrodenkopfes aufbauenden Hohlraumes als subharmonische Frequenz des Sensorsignals identifizieren, wie Mottyll & Skoda[1] bereits zeigten. Mit zunehmendem Spaltabstand wird eine Abnahme der Wandlast auf der Gegenprobe und ein Anstieg der subharmonischen Frequenz deutlich. Es zeigt sich eine gute Übereinstimmung zwischen Messung und Simulation. Aus den numerischen Ergebnissen wird weiterhin die lokale Verteilung der Strömungsaggressivität für unterschiedliche Wandbereiche jeweils am Sonotrodenkopf und an der Gegenprobe abgeleitet. Hierzu werden erosionssensitive Wandzonen in der Form einer Erosionswahrscheinlichkeit, siehe Skoda et al. [2], ermittelt und Wandlasten durch statistische Auswertung von wandnahen Einzelblasenkollapsen (siehe Mihatsch et al. [3]und Blume & Skoda [4]) bestimmt. Die gemessene Abnahme der Last auf der Gegenprobe mit zunehmendem Spaltabstand wird bestätigt, während lokal die Aggressivität am Sonotrodenkopf zunimmt. Die statistische Verteilung der Kollapse dient zusätzlich als Eingabe in ein Erosionsmodell.

[1] S. Mottyll, R. Skoda. Numerical 3D flow simulation of ultrasonic horns with attached cavitation structures and assessment of flow aggressiveness and cavitation erosion sensitive wall zones. *Ultrasonics Sonochemistry*, **31**:570-589 (2016).

[2] R. Skoda, U. Iben, A. Morozov, M. S. Mihatsch, S. J. Schmidt, N. A. Adams. Numerical simulation of collapse induced shock dynamics forthe prediction of the geometry, pressure and temperature impact on the cavitation erosion in micro channels. *WIMRC 3rdInternational Cavitation Forum 2011*(2011).

[3] M. S. Mihatsch, S. J. Schmidt, N. A. Adams. Cavitation erosion prediction based on analysis of flow dynamics andimpact load spectra. *Physics of Fluids*, **27**:103302 (2015).

[4] M. Blume, R. Skoda. 3D flow simulation of a circular leading edge hydrofoil and assessment of cavitation erosion by the statistical evaluation of void collapses and cavitation structures, *Wear*, **428-429**: 457-469 (2019).

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ALPACA - a Versatile Multiresolution Compressible Flow Framework for high-resolution Simulations

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Computational Fluid Dynamics of compressible flow phenomena has become an important tool in research and industry. Improvements in numerical model development for multi-physics problems has enabled the research in fluid mechanics nowadays to consider very complex problems by high-performance computation. Such problems are characterized by nonlinear mechanisms that generate multiple temporal and spatial scales. Whereas turbulence is a broad-band phenomenon whose largest scales are determined by flow boundaries and exterior forcing, and whose smallest scales are determined by viscous dissipation length scales, singularities such as shocks and interfaces do not possess inherent length and time scales if considered in a continuum description. They generate small scales by instabilities, driven through their mutual interaction, and interact with broad-band flow structures, creating a scenario which is extremely complex for numerical flow modeling: high-resolution requirement of broad-band scales and instabilities, monotonic capturing of shocks and interface, tracking of interfaces without artificial diffusion and mass loss. Unfortunately, as increased computational power to handle extreme resolutions does not come “for free” anymore [1], large-scale simulations of compressible flows need to exploit multiple levels of parallelism [2] in order to benefit from current and future high-performance computing hardware.

In this talk, we present the open-source multi-phase compressible flow simulation framework ALPACA [3], developed at the TUM Chair of Aerodynamics and Fluid Mechanics. ALPACA provides a full compressible Navier-Stokes finite-volume solver for large-scale distributed memory architectures. Multi-phase problems can be considered via a level-set formulation with conservative interface interactions. Temporal and spatial discretization schemes follow state-of-the-art methods including strongly-stable adaptive time-stepping [4], high-order WENO reconstruction and various approximate Riemann solver. The full range of spatial scales in the simulations is compressed by a block-based multiresolution (MR) scheme [5,6] that allows for SIMD optimization [7]. Furthermore, Message Passing Interface (MPI) is used to run ALPACA on large distributed-memory machines like the SuperMUC-NG at LRZ. Written in C++17, the modular structure of the framework allows to exchange the compute kernels for the spatial and temporal discretization freely without impact on the parallel performance [6,7]. Based on classical compressible benchmark problems (Sod shock tube, Air-Helium bubble collapse), we will present the concept behind ALPACA and demonstrate its parallel performance. Moreover, the modularity and versatility is illustrated with examples of solidification simulations [8] and fluid-structure interactions for cavitation effects in soft tissues.

We hope that by presenting this state-of-the-art simulation environment to the community we stimulate cooperation on further code development and interest to employ the tool for own research.

[1] H. Sutter, “The free lunch is over: A fundamental turn toward concurrency in software,” *Dr. Dobb’s J.*, pp. 1–9, 2005.

[2] G. Hager and G. Wellein, *Introduction to high performance computing for scientists and engineers*. CRC Press, 2011.

[3] N. A. Adams, “Nanoshock” [Online]. Available: https://nanoshock.org. [Accessed: 30-Aug-2019].

[4] J. W. J. Kaiser, N. Hoppe, S. Adami, and N. A. Adams, “An Adaptive Local Time-Stepping Scheme for Multiresolution Simulations of Hyperbolic Conservation Laws,” *J. Comput. Phys.*, accepted, 2019.

[5] A. Harten, “Multiresolution algorithms for the numerical solution of hyperbolic conservation laws,” *Commun. Pure Appl. Math.*, vol. 48, no. 12, pp. 1305–1342, 1995.

[6] N. Hoppe, S. Adami, and N. A. Adams, “A modular massively parallel computing strategy for three-dimensional multiresolution simulations.”, in preparation.

[7] N. Hoppe, I. Pasichnyk, M. Allalen, S. Adami, and N. A. Adams, “Node-Level Optimization of a 3D Block-Based Multiresolution Compressible Flow Solver with Emphasis on Performance Portability,” in *International Conference on High Performance Computing & Simulation (HPCS)*, 2019.

[8] J. W. J. Kaiser, S. Adami, I. S. Akhatov, and N. A. Adams, “A Conservative Sharp-Interface Model for Liquid-Solid Phase Transition,” *J. Comput. Phys.,* submitted.

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Sharp-interface modeling of laser-induced rapid cavity formation

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Droplet breakup can be initiated by rapid deposition of thermal energy within a droplet through a laser. This causes locally higher pressure than in the remaining droplet. Shock and expansion waves form and propagate through the droplet. Due to reflection at the phase-interface and three-dimensional focusing effects, strong tension arises within the droplet. Subsequently, cavitation can occur in the liquid that disintegrates the droplet explosively. In recent experiments water microdrops were subjected to high-energy laser pulses that deposited energy equivalent to a pressure on the order of 100 GPa in a small region along the drop axis [1,2]. The initial stages of the subsequent violent droplet breakup were investigated by numerical simulation in a previous work, in which the model was restricted to a core vapor cavity along the drop axis [3]. Therefore, off-axis cavitation effects that dominate the explosive breakup stages were not captured.

In this work, we present our extended numerical model as well as results of cavity formation for the laser-induced droplet breakup using the high-resolution compressible finite-volume solver ALPACA [4]. Particular focus is on the modeling of vapor formation and its transformation into distinct cavities within the liquid. The underlying multi-phase system is modeled by the level-set approach and a conservative interface-interaction method. The sharp-interface representation is combined with a homogeneous-mixture relaxation model to allow for phase-change within the bulk liquid. Larger clusters of vapor are then transformed into bulk vapor cavities enclosed by a newly created level-set interface.

[1] C. A. Stan et al., "Negative Pressures and Spallation in Water Drops Subjected to Nanosecond Shock Waves", in *Journal of Physical Chemistry Letters* 7.11, 2016

[2] C. A. Stan et al., "Liquid explosions induced by X-ray laser pulses", in *Nature Physics* 12.10, 2016.

[3] T. Paula, S. Adami, and N. A. Adams, "Analysis of the early stages of liquid-water-drop explosion by numerical simulation", in *Physical Review Fluids* 4.4, 2019

[4] N. A. Adams, "Alpaca Open-Source." [Online]. Available: https://nanoshock.org. [Accessed: 30-Aug-2019].

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Eindimensionale Modellierung von Kavitationswolken in kompressibler Strömung

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The present work analyses the dynamics of cloud cavitation in a compressible flow. Recent experiments 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 void fraction α and the single bubble radius R. By doing so, the bubble radii are a function of the radial position inside the cloud and time only. The individual bubble dynamics depend on the given dynamic and kinematic boundary conditions of the model. A pressure history at infinity and a strain rate or circulation represent these two types of excitations. The problem results in a system of non-linear differential equations consisting of the Gilmore equation, the continuity equation and the Euler equation. The Gilmore equation describes the dynamics of the individual bubbles inside the cloud whereas the continuity and Euler equations describe the movement and interaction of the bubbles.

The resulting pressure and the bubble radii inside the cloud as well as the cloud radius are highlighted and analysed. They depend on the excitation of the cloud and the different time scales of the system.

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Investigation of cavitation suppression in high-pressure nozzles and its application to geothermal drilling technologies

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In water jet cutting high-pressure nozzles are used to generate a focused beam of fluid with high energy to separate work pieces. These nozzles are specifically designed for operating conditions of water jet cutting. If the technique of water jet cutting is transferred to another field of application, those design parameters for operation will change and with this the generated high-pressure water jet, too.

One possible transfer is the implementation of water jets into a drilling and stimulation method for geothermal related operations in order to develop an efficient and cost-effective drilling process. In this case, the environmental conditions vary strongly from those in conventional water jet cutting. The environment is submerged and pressurised due to the hydraulic and lithostatic pressure in depths of several hundred metres. This has an influence on the occurrence of cavitation in the applied high-pressure nozzles and thus also on the formation of the high-pressure water jet. The elevated back pressure in high depths will lead to suppression of cavitation if critical values are obtained. The examination of cavitation suppression of high-pressure nozzles used for water jet cutting in a drilling environment is done by the following experimental investigation.

The first set of experiments investigates the cavitation behaviour of the nozzles by measuring the flow rate as a function of the applied pressures. Gas bubbles formed in the nozzle outlet due to cavitation or degassing cause a choked flow and result in a limitation of the flow rate. Thus, the suppression of cavitation in a nozzle can be determined by observing the flow rate at different pressure levels. The experiments show that the suppression of cavitation is not primary determined by the pressure drop at the nozzle exit but mainly on the pressure ratio of backpressure and nozzle exit pressure.

The second set of experiments investigates the influence of cavitation on the development of the high-pressure water jet by laser-optical measurements. The flow field generated by the high-pressure nozzle is measured by particle image velocimetry (PIV) to obtain a two-dimensional velocity distribution of the water jet and its surrounding flow field. The influence of cavitation is identified by the resulting length of the potential core of the water jet, which is the region in which the jet remains unaffected by the surrounding flow, and the spreading angle of the jet. The PIV analysis reveals that the potential core is shorter and the spreading angle larger if cavitation occurs inside the nozzle.

The core length and the spreading angle are important jet parameters for possible application in drilling technology. The core length, i.e. the zone of the water jet with approximately constant high velocity, is a factor to determine the optimum working distance between the high-pressure nozzle and the rock surface. The spreading angle describes the maximum area that can be eroded depending on the selected working distance. Thus, the influence of cavitation and its dependence on the drilling operational parameters is crucial for an efficient and cost-effective drilling process.

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Issue of salicylic acid dosimetry for quantifying radical production in cavitation

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Cavitation leads to many (key) engineering problems: material loss, noise, and vibration of hydraulic machinery. On the other hand, cavitation is a potentially useful phenomenon: the extreme conditions are increasingly used for a wide variety of applications such as surface cleaning, enhanced chemistry, and wastewater treatment (bacteria eradication and virus inactivation).
Despite this significant progress, a large gap persists 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: *What precisely are the mechanisms how bubbles can clean, disinfect, kill bacteria and enhance chemical activity?*

One of the most widespread and acknowledged explanation is that the implosion of bubbles and consequent formation of local hot spots is responsible for homolytic cleavage of H_2O molecules and formation of free radicals (•OH and •H). Being one of the strongest oxidants, •OH readily oxidize any species they encounter. The amount of generated radicals is affected by several variables such as: cavitation extent and type, cavitation time, temperature, presence of dissolved gases, viscosity and surface tension of the liquid medium, vapor pressure and above all the design of the device.

In the experimental study we set out to determine the free radical production in cavitating flow. For this, we used one of the most commonly used techniques - salicylic acid dosimetry. Radicals formed during cavitation react with salicylic acid, which leads to the formation of several products - mostly 2,3- and 2,5-dihydroxybenzoic acids. To assure that the highest amount of salicylic acid reaches the gas bubble interface, where the radicals mostly form, it is suggested to acidify the samples with HCl.

However, during the course of our experiments we noticed that cavitation dynamics is significantly different in acidified water (pH = 2.5) containing 300 mg/L of salicylic acid (the concentration selected based on the previously published studies) compared to water or acidified water alone (Fig. 1). This fact puts into question all the previous studies, where the salicylic acid dosimetry was used to determine the production of radicals in cavitation. Furthermore, it even casts a shade of doubt on the conclusions of reports of other advanced oxidation processes, where flowing water is present (ozonation, UV, plasma…).

Figure 1: Image of cavitation in water and in water + 300mg/L $C_7H_6O_3$

We investigated the properties of the liquids (vapor pressure, surface tension, viscosity and gas dissolvability), yet no significant deviation in the properties was found. One possible explanation is that the addition of HCl and salicylic acid to water, which results in a protonated form of salicylic acid, promotes nucleation of the gas bubbles and results in the change of cavitation dynamics. Although the conclusions are not yet final.

Finally, a proposal for an improved and optimized salicylic acid dosimetry is given, which should be closely followed if one is to evaluate the production of free radicals in a given cavitation generator.

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Akustische Strömung bei Frequenzen nahe 1 GHz

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Acoustic streaming in liquids beyond frequencies of about 100 MHz shows peculiar characteristics due to the high dissipation of the sound wave. Within less than some hundreds of wavelengths, acoustic energy and momentum flux are nearly completely transferred to the liquid, and the inertia of the induced streaming flow cannot be neglected. Thus fast jet flows can emerge, extending far beyond the acoustic penetration depth. Here we investigate such jets generated by bulk acoustic wave transducers operating around 750 MHz in water. The experimental methods comprise particle image velocimetry, ink front tracking and schlieren imaging. Results show jet flow peak velocities up to about 14 m/s in a pulsed mode. Theoretical and numerical treatments can well reproduce the findings if nonlinear damping effects are included to account for the high acoustic Reynolds numbers occurring in the experimental system.

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Cavitation from transverse waves

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It is well known that longitudinal acoustic waves in liquids of sufficient tension can nucleate cavitation bubbles. Here, we demonstrate that acoustic cavitation can also be generated from transverse waves at a solid-liquid boundary. Experimentally we launch the transverse waves with a laser generated plasma on the surface of two glass plates forming a 10-20um thin liquid gap. Three distinct waves in the solid and liquid are observed. The fastest is the bulk wave in the solid, followed by a leaky Rayleigh wave at the liquid-solid contact which is trailed by a Lamb-type wave. For the latter the two solid boundaries act as a wave guide and generate intense and short-lived cavitation activity within the gap. Streak and high-speed photography reveal the microsecond duration cavitation bubble dynamics and sub-picosecond strobe photography visualizes the mechanism of bubble nucleation from the accelerated surface. Simulations coupling the solids mechanics with the acoustics support the experimentally observed mechanisms of transverse wave induced cavitation inception.

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