Cavitation Inception on Microparticles: A Self-Propelled Particle Accelerator

Arora, M.; Ohl, C.-D.; Mørch, Knud Aage

Published in:
Physical Review Letters

Link to article, DOI:
10.1103/PhysRevLett.92.174501

Publication date:
2004

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Cavitation Inception on Microparticles: A Self-Propelled Particle Accelerator

Manish Arora,1 Claus-Dieter Ohl,1,* and Knud Aage Mørch2

1Department of Applied Physics, Physics of Fluids, University of Twente, Postbus 217, 7500 AE Enschede, The Netherlands
2Department of Physics and Center of Quantum Protein, Technical University of Denmark, DK-2800 Lyngby, Denmark

(Received 24 June 2003; published 29 April 2004)

Corrugated, hydrophilic particles with diameters between 30 and 150 μm are found to cause cavitation inception at their surfaces when they are exposed to a short, intensive tensile stress wave. The growing cavity accelerates the particle into translatory motion until the tensile stress decreases, and subsequently the particle separates from the cavity. The cavity growth and particle detachment are modeled by considering the momentum of the particle and the displaced liquid. The analysis suggests that all particles which cause cavitation are accelerated into translatory motion, and separate from the cavities they themselves nucleate. Thus, in the research of cavitation nuclei the link is established between developed cavitation bubbles and their origin.

DOI: 10.1103/PhysRevLett.92.174501 PACS numbers: 47.55.Bx

Introduction.—When plain water is exposed to a sufficient tensile stress it ruptures, and explosively expanding bubbles develop. This phenomenon, commonly termed cavitation, is found to occur at very low tensile stress, while thermodynamic calculations predict the stress to be very high [1]. This discrepancy can be explained by weak spots—cavitation nuclei—being present in water. The nuclei might be free gas bubbles that are stabilized [2], but this idea is not satisfactorily supported experimentally. Alternatively they are interfacial voids at solid surfaces of particles or surrounding walls [3]. The existence of such nuclei has received substantial experimental and also theoretical support [4–10].

In this Letter, we focus on the dynamics of a cavity expanding rapidly from a spherical microparticle and we show that at tensile stress in bulk water large vapor cavities grow from small surface regions on solid particles. The high speed photographs shown depict the explosive growth and the—at first sight unexpected—process of detachment of the particle from the surface of the cavity. Thus the particle gains a speed of more than 10 m/s in the cases investigated. A force balance model has sufficient accuracy to describe the acceleration and detachment in the particle-cavity system. This phenomenon has a bolder perspective: With strong acoustic transients, able to accelerate particles by this generic mechanism of self-propulsion, the technique if downscaled to submicron sized particles might allow for a novel method of drug delivery into biological cells. Particles coated with or consisting of a specific drug could be sonically propelled into neighboring cells or tissue.

Experiment.—The experimental setup, depicted in Fig. 1, consists of the shock wave source, a polystyrene flask (Nalge Nunc 50 ml) containing the suspension of particles, the imaging and illumination devices, and digital delay lines. A single finite amplitude wave is generated by a focused piezoelectric source; it is a slightly modified commercial extracorporeal lithotripter Piezolith 3000 (Richard Wolf GmbH, Knittlingen, Germany). The diameter of the shock wave source is 255 mm and the focusing angle 83°. The axis of the source is placed at an angle of 45° to the horizontal plane at the bottom of a container. The container and the flask are filled with filtered, deionized, and degassed water (O2 concentration 3.3 mg/l of water) at room temperature. The pictures are taken with a sensitive slow scan CCD (charged coupled device) camera (Imager 3S with 320 × 256 pixels at a binning mode of 2 × 2 and 9 μm pixel size, LaVision GmbH, Germany) equipped with a long distance microscope (K2, CF4 objective, Infinity, USA). The microscope operates from a working distance of 45 mm giving a maximum resolution of 3.4 μm per binned pixel. The CCD camera is operated in a double-frame mode, which allows two images to be taken in rapid succession before they are transferred to a computer. Both frames are strobe illuminated with a light emitting diode for exposure times of 1.8 μs.

Figure 2 displays a typical pressure recording, taken with a fiber optical hydrophone FOP-500 (Dr. Pecha, University of Stuttgart, see Ref. [11]) for a discharge voltage set to 5 kV. The tensile stress wave, which at

FIG. 1. Sketch of the experimental setup: The microscope, embedded partly in a cylindrical glass housing, is operated at a working distance of 45 mm from the focus of the shock wave generator. The flask is positioned with an xyz-translation stage.
The further experiments were performed using the polystyrene particles [Fig. 3(a)]. Many of these caused cavitation, but certainly not all of them. This is understood from the observation, that some of them had a highly corrugated surface [Fig. 3(a)], others had a relatively smooth surface. In each experiment the camera was first operated in a continuous mode, displaying the motion of the particles (density \( \rho_p = 1.07 \times 10^3 \text{ kg/m}^3 \)) due to gravity and secondary flow. When a particle moved into the focal zone, the first frame was taken, automatically the camera switched to the double framing mode, and the shock wave generator was activated. The first frame was taken about half a second before the double-frame sequence, which had an interframe time adjustable from 0.4 to several \( \mu\text{s} \).

Two typical sequences of explosively expanding cavities on particles are depicted in Figs. 4(a) and 4(b). Figure 4(a) displays three particles indicated with arrows, which are slowly sinking in the top frame. The second frame is taken just after the arrival of the tensile wave. Expanding cavities attached to two of the particles are visible, captured in motion, and blurred due to the finite exposure time. 6.2 \( \mu\text{s} \) later these cavities have expanded further and the particles are accelerated in directions opposite to the cavity growth. The shock wave arrives from below, and at an angle of 45\( ^\circ \) from behind the picture plane. The directions of the particle ejection are seen to be stochastic and independent of the shock wave direction.

The process of detachment of the particle from the cavity is visualized in Fig. 4(b) where the fast frames are taken at later times: Again the undisturbed particle is depicted in the top frame. In the next one, taken 8 \( \mu\text{s} \) after the tensile stress wave has arrived, an attached cavity of radius 150 \( \mu\text{m} \) has developed. Here, the particle has moved away from the bubble, thereby forming a necklike structure connecting the cavity with the particle. In the last frame of Fig. 4(b), taken 24 \( \mu\text{s} \) after the stress wave
arrival, the cavity has expanded to a radius of 170 μm and the neck between the particle and the cavity eventually has broken. Thereby, a surface wave has been excited and propagates on the cavity surface.

**Force balance model.**—Let us consider a cavity that develops in water from a cavitation nucleus on the surface of an almost spherical solid particle of radius $R_p$ when it is exposed to the stress wave from the lithotripter. Such a wave is shown in Fig. 2. The pressure pulse $P(t)$ is superposed on the atmospheric pressure $P_0$ to give the far field pressure $P_\infty(t) = P_0 + P(t)$. The tensile part of the stress perturbation is initiated at the time $t = 0$. We approximate $P(t)$ with the measured data.

For simplicity we assume that when the tensile strength of the liquid-particle system is exceeded at the time $t = t_{\text{crit}}$, an attached spherical cavity of radius $(R_c)_{\text{crit}}$ is developed, and that $(dR_c/dt)_{\text{crit}} = 0$. We assume that the dynamics of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.

During the growth of a cavitation nucleus, the pressure inside the void very quickly drops to the vapor pressure $P_v$. When it reaches critical size it grows explosively and becomes an attached spherical cavity as assumed above. A stress relaxation wave is released, and the pressure becomes an attached spherical cavity as assumed above. The motion of the center of the cavity is governed by the Rayleigh-Plesset equation

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2} \left( \frac{dR_c}{dt} \right)^2 = \rho_l \left[ P_v - \frac{2\sigma}{R_c} - P_\infty(t) \right],$$

where $\rho_l = 10^3$ kg/m$^3$ is the density of the liquid, $\sigma = 7.3 \times 10^{-2}$ kg/s$^2$ is the surface tension, and $P_v = 3.2$ kPa is the vapor pressure.
time 

\[ t = 24 \mu s \]

The experimentally recorded positions and sizes of the cavity and particle diameter from Fig. 4(b) are plotted as solid bars. Qualitative agreement is seen, but quantitatively only the order of magnitude is correct. This is not unexpected as we assume a too simple model for the inception and bubble dynamics. The right-hand side of (1) is overestimated already when the cavity becomes of size as the particle. Further, in the experiments the bubble growth is affected by the presence of nearby expanding bubbles. Thus, the velocity field surrounding the bubble becomes important and may explain the smaller bubble radius, and thereby the lower translatory velocity of the particle measured after separation. The inset of Fig. 5 depicts the measured velocities of the particles for multiple experimental runs before and after separation from the cavity. The size of the disk symbols scales linearly with the particle diameter from 56 to 108 \( \mu m \).

**Discussion and conclusions.**—The finding that a self-propelled particle accelerator results from cavity nucleation can be considered a generic process: Whenever a cavity grows rapidly from the surface of a small particle, the particle eventually detaches at high speed from the cavity which it has itself nucleated.

This is a result that is important in connection with the study of cavitation nuclei. The discussion of their nature—stabilized spherical gas bubbles or surface nuclei on particles—has been ongoing. Though [3,5,8,9] point to the latter ones, the direct observation of cavity-particle separation has been missing until now. Further, the particle ejection suggests that accelerated particles may penetrate into nearby soft surfaces, e.g., biological tissue or cells during exposure to strong, focused sound fields. A possible beneficial application might be the acceleration of micro- or nanometer-sized particles, made from or coated with specific drugs, at exposure to strong transient, ultrasound waves in a suspension of biological cells. The accelerated particles may permeate cell membranes and deposit the drugs (e.g., toxins) into the cytoplasm of the cells. However, for smaller sized particles the energy needed to form the gaseous neck [see second frame in Fig. 4(b)] could be higher than the kinetic energy of the particle, thus preventing the particle from separating from the cavity. To estimate the energy loss, we assume that during separation a cylindrical neck with a radius \( r_n \) and length \( x \) is created. Equating the kinetic energy of the particle with the surface energy of the neck, 

\[ \int_0^2 \pi \sigma r_n dx = 2/3 \pi p x r_n^3 \]

allows us to estimate the maximum achievable length of the neck as 

\[ x = 1/3 \pi \sigma p r_n^3 / r_n \]

Additionally separation of the particle from the cavity depends on the stability of the neck.

Possible damage effects of the cavitation mechanism considered here are governed by the growth phase of the bubbles in contrast to the well-established damage due to the collapse of cavitation bubbles where microjetting, high pressure, and temperature are responsible.

The authors gratefully acknowledge inspiring discussions with Detlef Lohse (U Twente) and the preparation of SEM pictures by Flemming Kragh, the Center of Quantum Protein, TU Denmark. The work was supported by FOM (The Netherlands) under Grants No. 99MS07 and No. 02PMT04.

*Electronic address: c.d.ohl@tnw.utwente.nl