CAVITATION INCEPTION ON MICRO-PARTICLES: A SELF PROPELLED PARTICLE ACCELERATOR

Manish Arora*, Claus-Dieter Ohl*, Knud Aage Mørch**
*Physics of Fluids,TNW, University of Twente, Postbus 217, 7500 AE Enschede, The Netherlands
**Department of Physics and Center of Quantum Protein, Technical University of Denmark, DK-2800 Lyngby

Summary Corrugated, hydrophilic particles with diameters between $30\,\mu$m and $150\,\mu$m are found to cause cavitation inception at their surfaces when they are exposed to a short, intensive tensile stress wave. The growth of cavity and its interaction with the original nucleating particle is recorded by means of digital imaging. 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.

INTRODUCTION

Cavitation (rupture of liquid under tenssile pressure) at much lower values of tensile pressure than thermodynamic estimates is often explained by weak spots -cavitaion nuclei- being present in the liqiuid. The nuclei might be free gas bubbles that are stabilized [1], or interfacial voids at solid surfaces of particles or surrounding walls [2]. The existence of such nuclei has received substantial experimental and also theoretical support [3, 4, 5, 6]. However the actual sequence of events which takes place during the inception of cavitation and interaction of cavity with the nucleating body has not been reported in an experimental or theoretical study. In this work we not only show that the artificially introduced corrugated particlies act as cavitation nuclei by means of direct photographic evidence but also that they are accelarated away from the cavities which originate on them. The process is modeled with a simple force balance model for cavity particle system which explains some of the basic features observed in the experiment.

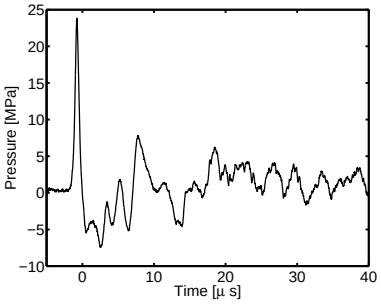

Figure 1. Pressure profile at the acoustic focus

EXPERIMENT

A flask containing filtered and degassed water is seeded with globally spherical particle (hydrophilic polystyrene particles -Copolymer:Divinylbenzol- with a diameter distribution between $30\,\mu$m and $150\,\mu$m) is placed at the acoustic focus of a pizoelectric shockwave device (a slightly modified commercial extracorporeal lithotripter). The pressure signal at the acoustic focus of the device at a dischagre voltage of 5kV is shown in Fig. 1. The cavitaions nuclei expand to form vaporous cavities during the tensile phase of the pressure.

The pictures are taken with a sensitive slow scan CCD camera equipped with a long distance microscope from a working distance of 45mm. 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 LED for exposure times of $1.8\,\mu$s. All devices are triggered from a digital delay generator.

A typical sequence with the particle and an explosively expanding cavity is presented in Fig. 2: The undisturbed particle is depicted in frame 1. The tensile wave act on the particle $8\,\mu$s before frame 2 where an attached cavity of radius $150\,\mu$m has developed. The particle has been accelerated to the right, the cavity to the left. In frame 3 of Fig. 2 taken $24.2\,\mu$s after the impact of the shock wave the cavity has expanded to a radius of $170\,\mu$m. The neck between the particle and the cavity in frame 2 eventually breaks exciting the surface wave propagating on the cavity surface in frame 3

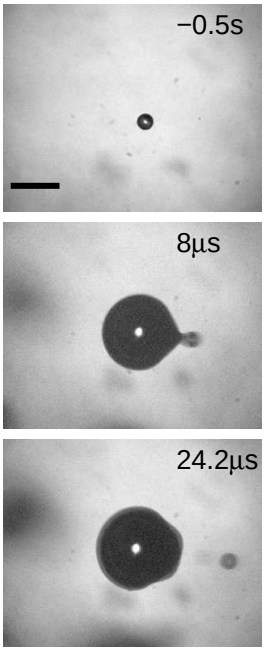

Figure 2. A three frame sequence depicting the explosive growth of a cavitation bubble from a particle, and its later separation.(length of the bar is $200\,\mu$m).

FORCE BALANCE MODEL

Since no external force acts on the particle cavity system the dynamics of the system can be adequately explained by a simple momentum a balance model. When the tensile stress passes below the critical pressure cavitation nuclei begins to expand explosively as a vaporous cavity. The expansion of the cavity is assumed to be

governed by the well known Rayleigh equation:

$$R_c \frac{d^2 R_c}{dt^2} + \frac{3}{2}\left(\frac{dR_c}{dt}\right)^2 = \rho_l^{-1}\left(P_v - \frac{2\sigma}{R_c} - P_\infty\right) \quad (1)$$

where $\rho_l = 10^3\,\mathrm{kg/m^3}$ is the density of the liquid, $\sigma = 7.3 \cdot 10^{-2}\,\mathrm{kg/s^2}$ is the surface tension, and $P_v = 3.2\,\mathrm{kPa}$ is the vapor pressure. P_∞ is far field pressure which is approximated with the measured value.

As long as the far field tensile stress increases, the particle moves with the velocity of the cavity surface at the contact point. However, at the time t_{sep} when the rate of expansion of the cavity passes its maximum, the particle detaches from the cavity and moves on through the liquid, though motion is attunuated first by the detachment process and second by viscous drag.

From cavitation inception at critical tensile stress when $t = t_{\mathrm{crit}}$ until the moment of separation of the particle from the cavity at $t = t_{\mathrm{sep}}$ momentum balance demands that

$$\frac{d}{dt}\left[u_c\left(\frac{1}{2}\rho_l \frac{4}{3}\pi {R_c}^3\right) + u_p\left(\rho_p \frac{4}{3}\pi {R_p}^3\right)\right] = 0 \quad . \quad (2)$$

where u_c and u_p are translation velocities of the centers of cavity and nucleating particle.

The particle-cavity contact condition gives

$$u_c + \frac{dR_c}{dt} = u_p \quad . \quad (3)$$

When the radial expansion of the cavity decelerates, the particle is no longer pushed by the cavity wall, but detaches with the momentum gained. Hence, from this time the analysis of the forces due to drag and added mass acting on the particle need to be incorporated.

Figure 3 presents the calculated motions of the cavity and the particle of Fig. 2 under above considerations.

This model predicts that particle cavity seperation takes place at $t_{\mathrm{sep}} = 5.0\,\mu$s after start of tensile pressure phase and subsequently the particle moves away at speed of 38 m/s. During the initial growth of the cavity (left) its center moves approximately $62\,\mu$m to the left due to the conservation of momentum, and the cavity collapses at $t \approx 24\,\mu$s. 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. In the experiments, the bubble growth is affected by the presence of nearby expanding bubbles which may explain the lower translatory velocity of the particle measured after separation.

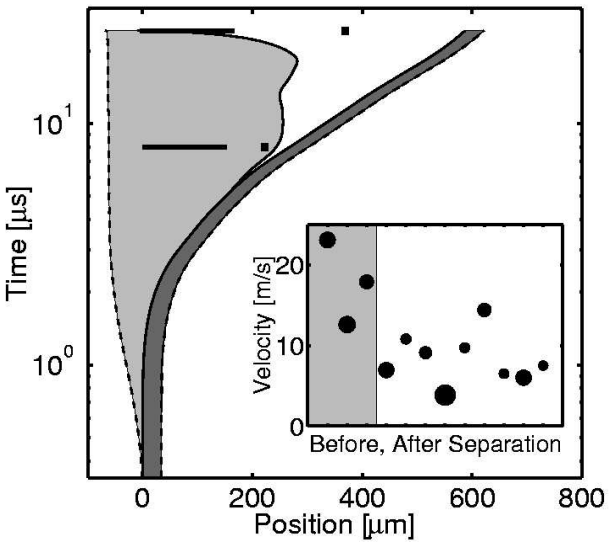

Figure 3. Position and size of the particle-cavity system versus time (note the logarithmic scale). The black squares and bars correspond to the particle and cavity radii, respectively, in the two lower frames of Fig. 2. Left and right dotted lines show the cavity and particle centers, respectively; left and right full lines show the right cavity and left particle surface positions, respectively from the calculations. The inset shows the measurements of the instanteous velocity of the particle before and after separation from the cavity from other experimental runs. The size of the disk symbol scales linearly with the particle diamater from $56\,\mu$m to $108\,\mu$m.

DISCUSSION AND CONCLUSIONS

The finding that a self propelled particle accelerator results from cavitation 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 pertinent in connection with the study of cavitation nuclei. 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, for drug delivery applications. However, for smaller sized particles the energy needed to form the gaseous neck (see second frame in Fig. 2) could be higher than the kinetic energy of the particle, thus preventing the particle from separating from the cavity.

References

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