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Shock wave emission from a hemispherical cloud of bubbles in non-Newtonian fluids

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ABSTRACT

Shock wave emission from a hemispherical cloud of bubbles, situated in non-Newtonian fluids, is investigated by high-speed photography, with up to 20 million frames/s and an exposure time of 5 ns, and acoustic measurements. The non-Newtonian fluids consist of a 0.5% polyacrylamide (PAM) aqueous solution, with a strong elastic component, and a 0.5% carboxymethylcellulose (CMC) aqueous solution, with a weak elastic component. In the relatively inelastic CMC solution, the maximum amplitude and the duration of the shock wave emitted during bubble cloud rebound are almost identical to the case of water. A significant reduction of the shock wave pressure was found in the elastic PAM solution. This difference ranges from a factor of 2, for a maximum radius of the bubble cloud $R_{max} \approx 800$ μm, up to a factor of 3, at $R_{max} \approx 270$ μm. A decrease of the shock wave duration was also observed in the elastic PAM solution. The observed reduction is attributed to an increased resistance to extensional flow which is conferred upon the liquid by the polymer additive and to an increase of the cavitation threshold of the liquid. At a maximum radius of about 400 μm, the shock pressure for a bubble cloud, situated in water and 0.5% CMC solution, is with a factor of six larger than the value measured in the case of individual cavitation bubbles. This difference is smaller in the case of a 0.5% PAM solution where the shock pressure for a bubble cloud is only three times larger than for a single bubble. The results are discussed with respect to cavitation erosion in polymer solutions and collateral effects in pulsed high-intensity focused ultrasound surgery, such as histotripsy used for the destruction of blood clots.

1. Introduction

The behavior of cavitation bubbles situated in non-Newtonian fluids irradiated with high-intensity focused ultrasound is a subject of increasing attention in numerous physical and chemical processes. These include cavitation erosion, encapsulation of inorganic particles with polymers, cavitation induced decomposition of solvent or solute, and polymer degradation [1]. The collapse of cavitation bubbles are accompanied by the emission of shock waves and shear forces which can contribute to particle fragmentation and mixing when solid materials are in the close proximity to the bubbles. Besides these applications, it has been recognized that the study of bubble collapse in non-Newtonian fluids is also of interest in the medical field [2,3]. During high-intensity focused ultrasound histotripsy used, for example, for the destruction of blood clots, cavitation bubbles are generated in blood. Structural deformation of the adjacent tissue and damage of vessel wall are typical side effects induced by cavitation. The unwanted collateral effects induced by cavitation, when controlled and well understood, can be used for a variety of desired surgical effects, such as drug and gene delivery into tissue and cells and ablation of tissue.

It has been previously demonstrated that even extremely low concentrations of high molecular weight polymers (parts-per-million) can exhibit remarkable non-Newtonian behavior in uniaxial extensional flows. Perhaps the most striking examples of this are the observation of inhibition of cavitation inception downstream of an orifice and the dramatic decrease of cavitation erosion [4,5]. Non-Newtonian fluids exposed to an extensional flow (where the velocity gradient is in the same direction with the flow) have a much larger resistance to flow than that expected from a shear flow (where the velocity gradient is perpendicular to the flow direction). While the uniaxial extensional viscosity of Newtonian fluids is three times larger than the shear viscosity, non-Newtonian fluids can show much larger values of the extensional viscosity, that can be up to several thousand times larger than the shear viscosity. The oscillation of spherical cavitation bubbles is another typical example of extensional flow. Biaxial extension obtains in growth while the collapse is an uniaxial extensional flow. During the last stages of bubble collapse the velocity of the bubble wall increases significantly

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and the influence of the uniaxial extensional viscosity becomes important.

Most of the previous studies on the behavior of cavitation in non-Newtonian fluids have been focused on the much simpler single bubble systems to study their dynamical behavior [6–9]. However, many realistic systems contain multiple bubbles and their dynamics may exhibit collective behavior due to the interaction between bubbles. In a recent experimental study we have shown that, in water, the collapse of a hemispherical cloud of bubbles attached to a rigid boundary can be more violent than that of an individual bubble [10]. The maximum pressure amplitude of the shock wave emitted during the rebound of a cloud of bubbles (cloud-collapse-induced shock wave) increases with the maximum cloud radius and, for a maximum bubble radius of 1300 μm, can be a factor of three larger than that measured in the case of individual cavitation bubbles. Furthermore, two types of secondary shock wave emission have been identified [11]. In the first case, the secondary shock wave is the result of the free collapse of individual bubbles by the ambient pressure of the liquid while, in the second case, it is a consequence of the interaction of the cloud-collapse-induced shock wave with individual bubbles within the cloud. The maximum pressure of the secondary shock waves can be as high as 0.5 GPa.

In this paper, we investigate the shock wave emission from a hemispherical cloud of bubbles attached to a rigid boundary and situated in non-Newtonian fluids. The non-Newtonian fluids consist of a 0.5% carboxymethylcellulose aqueous solution, with a weak elastic component, and a 0.5% polyacrylamide aqueous solution, with a strong elastic component. The present results are compared with a case of a single bubble attached to a rigid wall. The results are then discussed with respect to cavitation erosion and collateral effects in high-intensity focused ultrasound surgery.

2. Experimental

The experimental set-up used for investigating the shock wave emission from a cloud of bubbles is illustrated in Fig. 1. Cavitation bubble clouds are produced using short pulses of high-intensity focused ultrasound waves generated by an air-backed 2 mm thick ultrasound transducer with a concave PZT ceramic element (C-213, Fuji Ceramics) with an outer diameter and a focal length of 80 mm. A function generator (33120A, Agilent Technologies) creates the driving sinusoidal signal that is amplified by a 63-dB radio-frequency-band amplifier (AG1024, T&C Power Conversion). An aluminum plate is placed at the ultrasound focus to create cavitation bubbles on its surface. Hemispherical cloud of bubbles were generated using 30 sine waves with a frequency of 1.08 MHz. The short pulses of ultrasound are only used to induce the generation of the cavitation bubbles. After the ultrasound is stopped, the bubble cloud expands to the maximum volume and under the static pressure of the ambient liquid it collapses violently accompanied by strong shock wave emission. The maximum radius of the bubble cloud was controlled by modifying the pressure amplitude of the ultrasound. The O_2 concentration in all fluids is kept below 2 ppm by a continuous degassing unit (ERC-3302W). The motion of the bubbles was recorded with a high-speed image converter camera (DRS Hadland, Imacon 200), at framing rates of 500,000 frames/s and an exposure time of 5 ns. The image on the fluorescent screen was recorded with an intensified scan ICCD camera with a 1360 × 1024 pixel array. The signal from the ICCD camera was then digitized with 12-bit resolution and passed to a computer. A maximum resolution of 1 μm/pixel was achieved with a Questar long-distance microscope (QM-100, focal length 150–350 mm) together with a positive Barlow lens. The mean resolution used in the present study, however, is 2 μm/pixel. Illumination into the focal region of focused ultrasound is done by a short arc power strobe (LH-SA3H, Nissin Electronic) with a maximum output of 200 J, half-bandwidth 260–350 μs, and rise time 50 μs. A PVDF needle hydrophone, with a constant frequency response up to 10 MHz (type 80–0.5–4.0; rise time 25 ns, sensitivity 77.8 kPa/mV, Imotec Messtechnik), was used to measure the pressure amplitude of the shock waves emitted during the rebound of a cloud of bubbles up to a distance of 10 mm from the ultrasound focus.

Aqueous solutions of carboxymethylcellulose (CMC-L, molecular weight 4×10^5 g/mol) and polyacrylamide (PAM-HHR, molecular weight 5×10^6 g/mol) in a concentration of 0.5% are used as test fluids. The rheological measurements consisted of characterizing

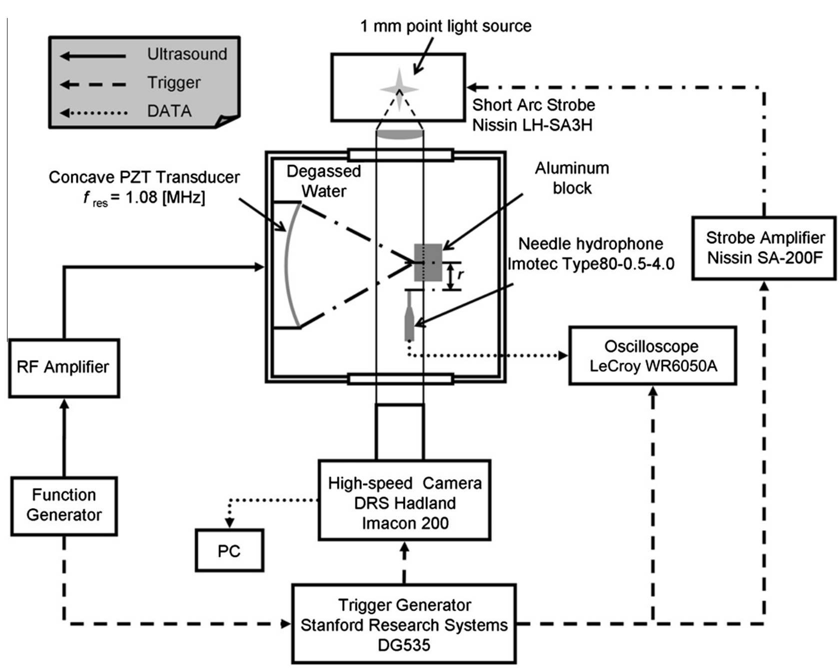

Fig. 1. Experimental arrangement for the investigation of shock wave emission from a cloud of bubbles.