Multiscale Design of a Laser Actuated Micro Bubble Array Acoustic-Fluidic Microdevice for Bioanalytical and Drug Delivery Applications

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ABSTRACT

Next generation fluidic micro-nano devices will require precise control of force fields within a device and their interaction with a biological sample. Current force field designs use mechanical structures such as cantilevers, optical fields (e.g. laser tweezers), or electrokinetic fields (e.g. dielectrophoretic devices). All of them suffer from design complexity, small forces, long actuation times, and others. We propose a novel opto acoustic device for fast generation of 3D spatially distributed large force fields within the micro/nano fluidic device. The basic concept is to dynamically produce a field of oscillating micro/nano bubbles which will generate desired 3D pressure and/or flow fields within the device. This concept can be used for bioanalytical applications in vitro exploration of novel drug formulations, novel drug delivery modalities, e.g. to cells and tissues, and for micro/nano surgical applications. Wang et. al. showed experimentally that a micro bubble induced by laser pulse can generate a net streaming flow (Wang, 2004). Their results provide a basic understanding how the blood clot could be broken, emulsified and removed. It is obvious that the bubble formation, growth and collapse are the keys to understand the bubble dynamics and its interaction with the medium, such as blood clot, biological cells, or bio device.

Our overall concept as well as the device has been designed based on multiscale simulation of bubble dynamics, laser beam physics, fluid flow, cavitations, and acoustics. The paper presents the concept and preliminary simulation results for selected micro and nano biodevices.

Mathematical modeling of bubble dynamics has been studied theoretically (Feng, 1997) as well as specifically for biomedical applications. A micro bio device using a single bubble generated by laser pulse has been developed before (Hebert, 2001; Esch, 2001). The major innovation of our work is to explore space/time controlled bubble array for the generation of desired force fields.

For laser induced gas bubble in water, the bubble growth and collapse are function of initial bubble size. The initial bubble radius as well as its formation/collapse dynamics is function of laser pulse energy. Therefore a question that one will face is how to determine the laser pulse energy to achieve desired initial bubble size and subsequent bubble dynamics. This paper will present two essential modeling steps: 1) a novel analytical analysis on the relation between initial gas bubble radius and laser pulse energy and 2) CFD simulation results of bubble behaviors in water.

1 GAS BUBBLE RADIUS

Figure 1 shows the configuration of a spherical gas bubble with radius R in liquid water.

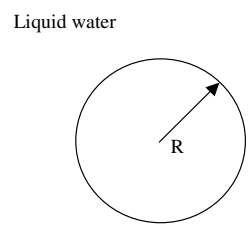

Figure 1. Gas bubble and surrounding liquid water.

The bubble radius is described by Keller-Mikes bubble model (Brennen, 1995):

$$\left(1-\frac{1}{c}\frac{dR}{dt}\right)\cdot R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2\left(1-\frac{1}{3c}\frac{dR}{dt}\right)=\left(1+\frac{1}{c}\frac{dR}{dt}\right)\frac{P_v}{\rho_1}+\frac{1}{c}\frac{R}{\rho_1}\frac{dP_v}{dt} \qquad (1.1)$$

The vapor pressure P_v is determined by

$$P_v=P_i\left(R_i/R\right)^{3\cdot\kappa}-P_0-\frac{2\sigma}{R}-\frac{4\cdot\mu}{R}\frac{dR}{dt} \qquad (1.2)$$

The pressure P_i inside bubble is initial gas pressure and determined by ideal gas law. In equations (1.1) to (1.2), c is speed of sound in water, t is time, ρ and μ are density and

viscosity of water respectively, and σ is surface tension at bubble/water interface, and κ is the polytropic index of gas whose value is 1.33 in our analysis.

2 INITIAL BUBBLE RADIUS

The initial gas bubble radius can be determined by balancing the laser pulse energy and liquid water internal thermal energy:

$$\int \{\rho_l c_p (T_B - T_i) + \rho_l L\} dV = \int E_{aV}(r,z) dV \quad (2.1)$$

Where, T_B is the water boiling temperature, T_i is the water initial temperature, L is the latent heat of water, E_{aV} is water volumetric absorbed laser energy which is defined by Beer's law for Gaussian spatial distribution:

$$E_{aV}(r,z) = \alpha \frac{2E_p}{\pi w^2} \exp\left(-\frac{2r^2}{w^2}\right) \exp(-\alpha \cdot z) \quad (2.2)$$

Where, r and z are radial coordinate and longitudinal distance from the fiber end respectively, E_p is the peak laser energy, α is water absorbed coefficient and w = w(z) is the beam radius at r = 0:

$$w^2(z) = w_o^2 \left[1 + \left(\frac{M^2 \cdot z}{z_R}\right)^2\right] \quad (2.3)$$

Where, w_o is due to losses at the cladding of the fiber, we assume loss factor F_{cc} to be 5%, so we have

$$w_o = f_r \sqrt{\frac{-2}{\log(F_{cc})}} \quad (2.4)$$

f_r is equal to the $1/e^2$ intensity radius of the Gaussian pulse. And

$$z_r = \frac{\pi w_o^2 n}{\lambda_o} \quad (2.5)$$

n is the refractive index of water whose value is 1.33, λ_o is the laser wave length, its value is 532 nm. M^2 is the laser mode parameter which varies from 1 (single mode) to 16 (multimode).

Equation (2.1) states the energy balance. It assumes that the laser pulse energy heats up the liquid water so that the certain amount of liquid water immediately becomes gas bubble at same volume. The gas bubble V_i generated by laser is then calculated as

$$V_i = \frac{\int E_{aV}(r,z) dV}{\rho_l c_p (T_B - T_i) + \rho_l L} \quad (2.6)$$

The solving process is iterative to obtain the volume V_i. After substituting equation (2.2) into equation (2.6) and assuming the bubble to be spherical shape, we have the final equation for bubble radius:

$$F(r) = R_i^3 - \frac{6\alpha E_p}{\pi \cdot w_o^2 \{\rho_l c_p (T_B - T_i) + \rho_l L\}} \times \int_o^{R_i} \exp\left(-\frac{2r^2}{w_o^2}\right) \cdot r^2 dr \quad (2.7)$$

We assume R_i value at the beginning, and integrate equation (2.7) numerically to see if there is a value R so that the function F(r) reaching to zero, then this R is the initial bubble radius. Newton-Raphson iteration method can be used to determine the radius.

Figure 2 shows the results for equation (2.7). For simplicity, we set specific heat of water to be a constant, 4000 J/(kg K), density of water is 998 kg/m^3, latent heat of water is 2260 kJ/kg (Holman, 2001). We can see that the radius increases when laser pulse energy increases.

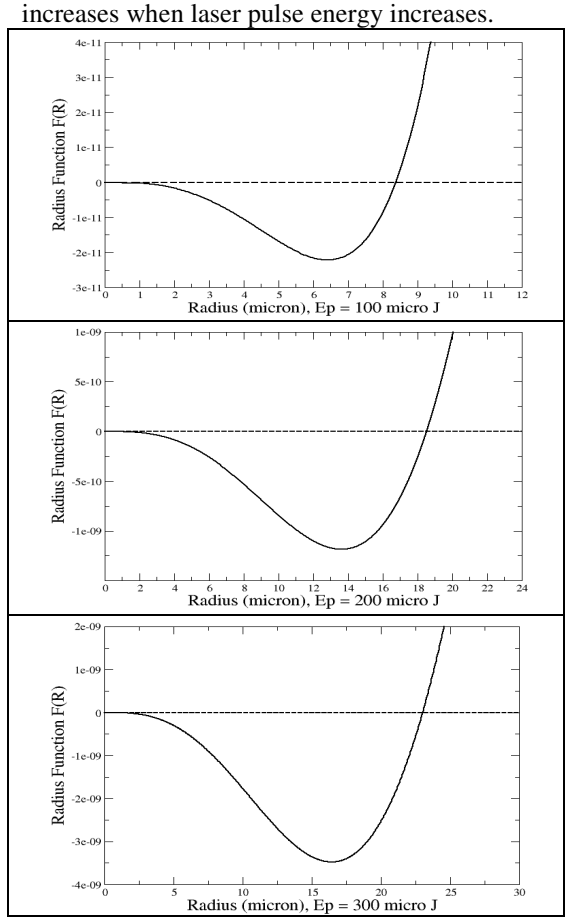

Figure 2. Initial bubble radius at different laser pulse energy E_p.

3 SIMULATION OF BUBBLE BEHAVIOR

Once the laser pulse energy specified, the initial bubble size can be obtained by equation(2.7) and the bubble radius at any time can be obtained by equation(1.1). This is an ODE equation and can be integrated by standard ODE method. The result is shown in figure 3.

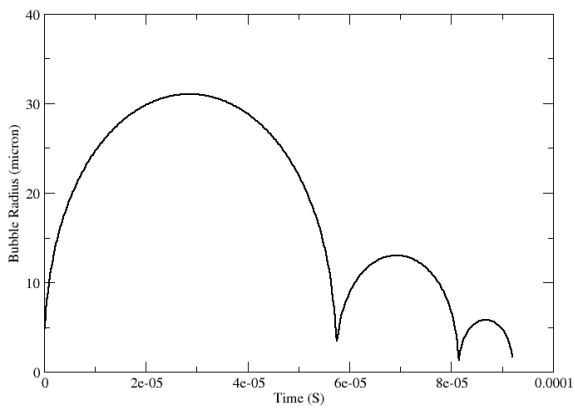

Figure 3. Bubble's radius at different times. The collapse of bubble is shown here.

We have applied the above technique into full CFD simulation on bubble behaviors. By arranging bubble array in the device, such as shown in figure 5, a desired pressure and/or flow fields within the device can be generated. Figure 4 shows pressure field in water induced by single bubble.

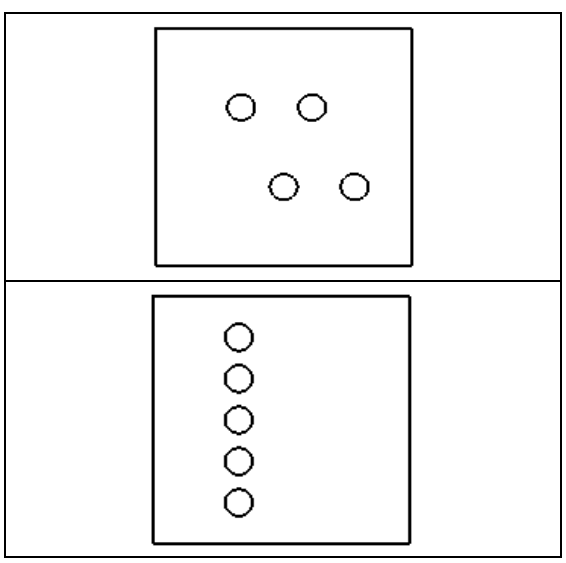

Figure 5. Bubble arraies for desired flow field.

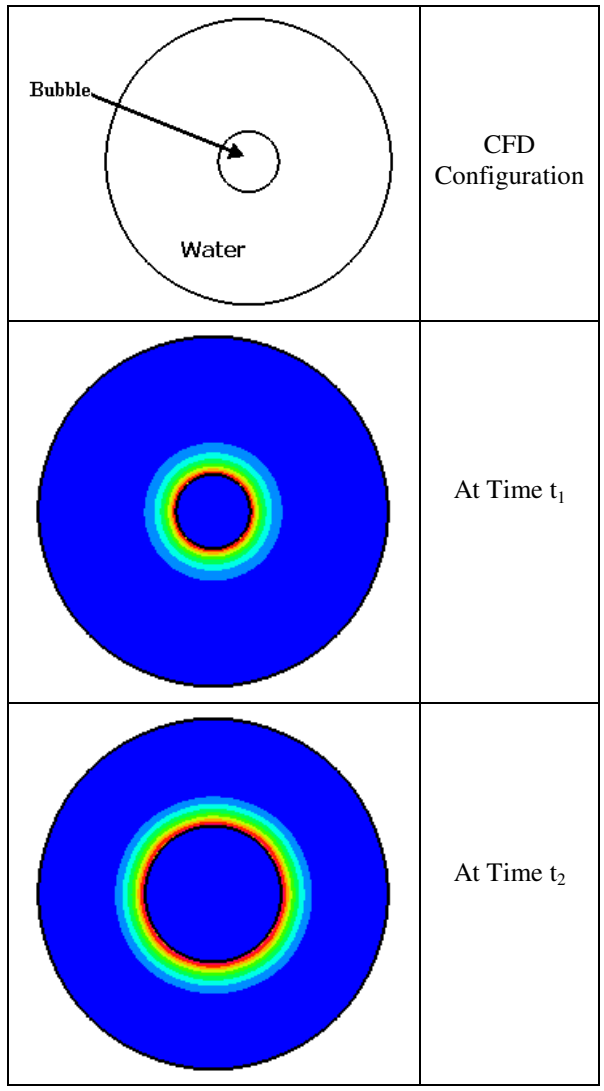

Figure 4. Pressure field in water induced by single bubble's oscillation.

4 CONCLUSION

We have proposed a concept to cerate a desired pressure and/or flow field in micro/nano device by using laser induced gas bubble technique. In the application, the initial gas bubble size is critical for a given laser impulse energy. We have analytically obtained the initial gas bubble size based on the laser energy released in water. We also performed CFD simulation of bubble's behaviors including bubble collapse. By arranging a array of bubbles induced by laser pulse, a certain flow field patter can be achieved. Such device can be applied in many bio areas, such as in vitro exploration of novel drug formulations, drug delivery modalities, e.g. to

cells and tissues, and for micro/nano surgical applications.

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