2P-32

Proceedings of Symposium on Ultrasonic Electronics, Vol. 31 (2010) pp. 353-354
6-8 December, 2010

Numerical Simulations on Physical Effects of Acoustic Cavitation in Viscous Liquids
粘性流体中での音響キャビテーションの物理効果に関する数値シミュレーション

Kyuichi Yasui†, Toru Tuziuti, Teruyuki Kozuka, Atsuya Towata and Kazumi Kato (AIST.)
安井久一†, 辻内　亨, 小塚晃透, 砥綿篤哉, 加藤一実 (産総研)

1. Introduction

Mixtures of liquid and nano-particles are often called slurries when the concentration of nano-particles is relatively high. In slurries, most of nano-particles are aggregated each other and the mean particle size is much larger than the size of a primary nano-particle. However, the unique physical properties of individual nano-particles are easily lost by the aggregation [1]. For example, optical properties of pigment nano-particles change by the aggregation. For catalyst nano-particles, the surface area and the efficiency of catalysis are reduced by the aggregation. Thus, it is required to break agglomerates of nano-particles and disperse them in the liquid. There are a few methods to disperse nano-particles in liquid [2-5]. One is milling using micro beads. Under stirring, beads collide with agglomerates of nano-particles and break them. Milling using a rotor-stator system is also applicable to collapse the agglomeration. Otherwise, the irradiation of strong ultrasound to slurries is focused because of prevention from contamination. At present, beads milling is widely used and ultrasound systems are less used. One of the problems in ultrasound systems is lack of knowledge on the detailed mechanism in ultrasonic dispersion of nano-particles and its optimum condition such as acoustic and ambient presssures.

Recently, Sauter et al. [3] experimentally reported the influence of ambient pressure on dispersion of nano-particles by a strong ultrasoud. According to them, the mean particle size after the irradiaiton of ultrasound decreases as the ambient pressure increases to 4.5 bar and 6 bar when the vibration amplitude of an ultrasounc horn is 64 μm and 85 μm, respectively, at 20 kHz. From a view point of energy efficiency, however, it is unchanged even at high ambient pressures because more energy is required to maintain the same vibration amplitude of an ultrasonic horn at higher ambient pressure.

In the present study, numerical simulations of bubble pulsation and shock wave emissions from bubbles have been performed in order to investigate the mechanism for the ambient pressure dependence of the efficiency in ultrasonic dispersion of nano-particles. Shock waves emitted from bubbles when they collapse have been optically and acoustically observed [6]. They play an important role in dispersion of nano-particles.

----

† e-mail address: k.yasui@aist.go.jp

2. Model

The bubble pulsation in viscoelastic fluids such as slurries is described by the following modified Rayleigh-Plesset equation [7].

$$\left(1-\frac{\dot{R}}{c_\infty}+\frac{\dot{m}}{c_\infty\rho_{L,i}}\right)R\ddot{R}+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3c_\infty}+\frac{2\dot{m}}{3c_\infty\rho_{L,i}}\right)$$
$$=\frac{1}{\rho_{L,\infty}}\left(1+\frac{\dot{R}}{c_\infty}\right)\left[p_B-p_S\left(t+\frac{R}{c_\infty}\right)-p_\infty\right]+\frac{\ddot{m}R}{\rho_{L,i}}\left(1-\frac{\dot{R}}{c_\infty}+\frac{\dot{m}}{c_\infty\rho_{L,i}}\right)$$
$$+\frac{\dot{m}}{\rho_{L,i}}\left(\dot{R}+\frac{\dot{m}}{2\rho_{L,i}}+\frac{\dot{m}\dot{R}}{2c_\infty\rho_{L,i}}-\frac{R}{\rho_{L,i}}\frac{d\rho_{L,i}}{dt}-\frac{\dot{m}R}{c_\infty\rho_{L,i}^2}\frac{d\rho_{L,i}}{dt}\right)+\frac{R}{c_\infty\rho_{L,\infty}}\frac{dp_B}{dt}$$
$$-S\left(R^2\ddot{R}+2R\dot{R}^2\right) \tag{1}$$

where R is the bubble radius, the dot denotes the time derivative (d/dt), c_∞ is the sound velocity in the liquid (slurry) far from a bubble, $\dot{m}$ is the rate of evaporation of liquid at the bubble wall, $\rho_{L,i}$ ($\rho_{L,\infty}$) is the liquid density at the bubble wall (far from a bubble), p_B is the liquid pressure at the bubble wall, $p_S(t)$ is the acoustic pressure, p_∞ is the ambient pressure, S is the coupling strength of a bubble cloud introduced in Refs. [8, 9]. p_B is estimated by the following relationship.

$$p_B=p_g-\frac{2\sigma}{R}-\frac{4\mu\dot{R}}{R}-12G\int_0^t\exp\left(-\frac{t-t'}{\tau}\right)\frac{R^2(t')\dot{R}(t')In(R(t')/R(t))}{R^3(t')-R^3(t)}dt \tag{2}$$

where p_g is the gas and vapor pressure inside a bubble, σ is the surface tension, μ is the viscosity of the slurry, G is the shear modulus of slurry, and τ is the relaxation time.

According to numerical simulations, under most circumstances, the term containing G in Eq.(2) is negligible. Thus in the present study, slurry is characterized only by viscosity and the term containing G in Eq. (2) was neglected.

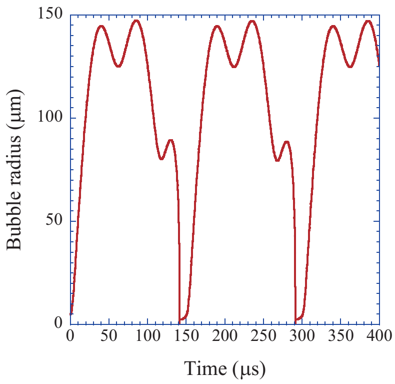
The energy (E) of a shock wave emitted from a bubble is estimated by Eq. (3).

$$E = \frac{4\pi\rho}{c}\int\left(R^2\ddot{R} + 2R\dot{R}^2\right)^2 dt \tag{3}$$

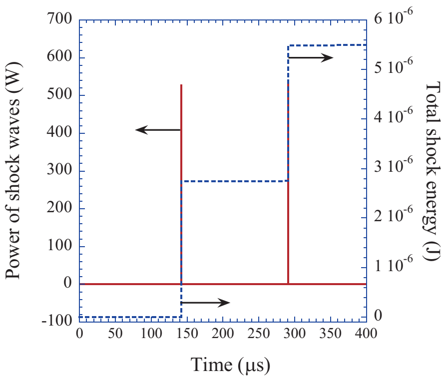
where ρ is the density of slurry, and c is the sound velocity in slurry.

3. Results and Discussions

In **Fig.1**, the calculated results are shown as a function of time for 8 acoustic cycles when frequency and pressure amplitude of ultrasound are 20 kHz and 20 bar, respectively. The viscosity is 200 mPa s and the ambient pressure is 2 atm. It is seen that the bubble pulsation is periodic with triple acoustic cycles. A shock wave is emitted at each bubble collapse.



(a)



(b)

Fig. 1 The calculated results for 8 acoustic cycles. (a) The bubble radius. (b) The power of a shock wave (left) and its time integration (right).

In **Fig. 2**, the calculated radius-time curves are shown for various ambient pressures when the ultrasonic frequency and pressure amplitude are 20 kHz and 10 bar, respectively. For the ambient pressure of 1 atm, a bubble collapses once in two acoustic cycles. For the ambient pressure of 3 atm, on the other hand, a bubble collapses every acoustic cycle. Thus, the energy of shock waves emitted from a bubble per unit time is larger for the latter case. On the other hand, the bubble collapse is weaker for the ambient pressure of 5 atm than that for 3 atm because the bubble expansion is suppressed more for the former case. Accordingly the energy of shock waves emitted from a bubble per unit time is largest at the ambient pressure of 3 atm.

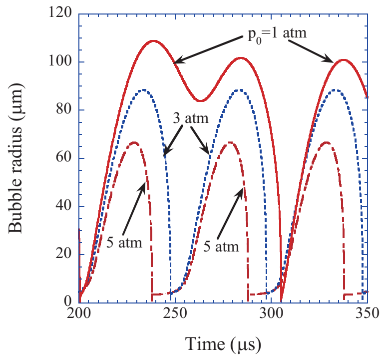


Fig. 2 The calculated radius-time curves for various ambient pressures.

4. Conclusion

According to the present numerical simulations, the optimum ambient pressure which maximizes the energy of shock waves emitted from a bubble per unit time increases as the acoustic pressure amplitude increases or viscosity of slurry decreases.

References

1. F.Muller, W.Peukert, R.Polke, and F.Stenger, Int.J.Miner.Process. **74S** (2004) S31.
2. M.Inkyo, T.Tahara, T.Iwaki, F.Iskandar, C.J.Hogan Jr., and K.Okuyama, J.Colloid Interf.Sci. **304** (2006) 535.
3. C.Sauter, M.A.Emin, H.P.Schuchmann, and S.Tavman, Ultrason.Sonochem. **15** (2008) 517.
4. K.Sato, J.G.Li, H.Kamiya, and T.Ishigaki, J.Am.Ceram.Soc. **91** (2008) 2481.
5. T.Uchida, T.Kikuchi, T.Aoki, N.Kawashima, and S.Takeuchi, Jpn.J.Appl.Phys. **48** (2009) 07GH03
6. D.F.Gaitan et al., J.Acoust.Soc.Am. **127** (2010) 3456.
7. M.Ichihara, H.Ohkunitani, Y.Ida, and M.Kameda, J.Volcanology Geothermal Res. **129** (2004) 37.
8. K.Yasui, Y.Iida, T.Tuziuti, T.Kozuka, and A.Towata, Phys.Rev.E **77** (2008) 016609.
9. K.Yasui, J.Lee, T.Tuziuti, A.Towata, T.Kozuka, and Y.Iida, J.Acoust.Soc.Am. **126** (2009) 973.