STUDY OF BUBBLE COALESCENCE IN MICROFLUIDICS USING GPU ACCELERATED LATTICE BOLTZMANN METHOD

Huidan(Whitney) Yu and Rou Chen

Indiana University-Purdue University, Indianapolis (IUPUI)
Department of Mechanical and Energy Engineering
46202 Indiana, USA
e-mail: whyu@iupui.edu

Key words: lattice Boltzmann method, bubble coalescence, microfluidics, GPU parallelism, damped oscillation

Abstract. We numerically study the underlying physics of bubble coalescence in microfluidics using GPU accelerated lattice Boltzmann method based on the free-energy model, which is suitable for massive parametric simulation of multiphase flows with large density and viscosity ratios. The focus is on the distinct coalescence phenomena, with and without damped oscillation, characterized by Ohnesorge (Oh) number. It is found that there exists a critical damping (corresponding to the shortest coalescence time) of two equal size microbubble coalescence when $Oh \approx 0.477$, which separates two district coalescence behavior with ($Oh < 0.477$) and without($Oh > 0.477$) damped oscillation. The corresponding dynamics of these two coalescence behaviors is the result of imbalanced surface tension and viscous resistance.

1 INTRODUCTION

Understanding the mechanism of microbubble coalescence is critically important for the design, improvement, and optimization of microfluidics with various applications. Damped oscillation due to the imbalance between the driven (surface tension) and resistant (liquid viscous and inertia) forces is a peculiar behavior in microbubble coalescence, featured with a switching of a damping major axis between horizontal and vertical directions in the post coalescence after a neck bridge has formed. While Rayleigh first studied a small-amplitude oscillation of an inviscid droplet from a purely mathematical point in the 18th century, only a few attempts have been made so far to study the bubble oscillation in a more realistic environment. Thus the underlying physics of microbubble oscillation has never been well addressed.

2 METHOD

We use kinetic-based lattice Boltzmann method (LBM) to systematically simulate the whole process of microbubble coalescence using a well developed free energy model[1], suitable for large density gradients of up to 1000 with eliminated parasitic current (an artificial velocity field caused by discretization errors in the simulation of multiphase flows).

The governing equations and the corresponding lattice Boltzmann equations together with their GPU parallelization are referred to the papers [2, 3, 4, 5, 6] from the same research group.

We consider two equal-size air bubbles with radius $R(20\mu m)$ at the center of a square domain (100^2 μm^2). The density and dynamic viscosity of air are $\rho_l = 1.28kg/m^3$ and $\eta_l = 1.74 \times 10^{-5}kg/(m \cdot s)$ respectively. The density of liquid is fixed as $\rho_h = 1840kg/m^3$ but its viscosity η_h varies. Constant surface tension, $\sigma = 7.3 \times 10^{-2}N/m$, is assumed. The spatial resolution was selected 600^2 through a convergence check[5]. The periodic boundary condition is applied in both directions.

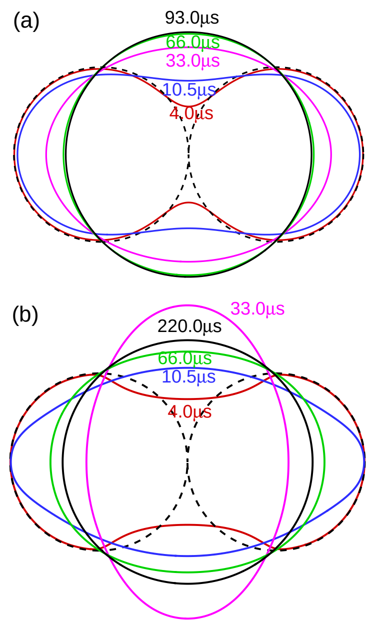

Figure 1: Two distinct coalescence phenomena. (a)$Oh = 0.530$ without oscillation and (b) $Oh = 0.039$ with damped oscillation.

3 RESULTS AND CONCLUSIONS

As shown in Fig. 1, two distinct phenomena are observed in the coalescence from two equal size bubbles (black dashed lines) to a single circular bubble with minimal area surface (black solid line) through 4 intermediate time instants (color lines), which are without and with damped oscillation at (a)$Oh = 0.530$ and (b)$Oh = 0.039$ respectively. In order to explore the dynamics of the damped oscillation, we simulate sixteen cases, shown in Tab.1, varying Oh from 0.039 to 1.543 through the variation of fluid viscosity while maintaining all the other parameters the same. The coalescence time of each case is listed accordingly.

Case	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$Oh \times 10$	0.39	0.67	1.25	1.77	2.64	3.47	4.07	4.77	5.30	6.75	7.72	8.68	9.65	10.61	13.51	15.43
$\eta_h \times 10^3$ $(kg/m \cdot s)$	2.0	3.5	6.5	9.2	13.7	18.0	21.0	24.7	27.5	35.0	40.0	45.0	50.0	55.0	70.0	80.0
$T(\mu s)$	395	280	219	155	136	108	99	72	90	155	170	240	250	282	366	375

Table 1: Sixteen cases with the variation of fluid viscosity η_h resulting in different Oh numbers and coalescence time T.

A shape factor($\Delta = D_y/D_x$) is defined to track the time evolution of coalescing interface, starting from 0 (initial touched bubble) and ending at 1 (single coalesced bubble). Here D_x and D_y are the distances between the bubble edge and the mass center O in the horizontal and vertical directions respectively as schematized in Fig. 2(a) and (b). Figure 2(c) shows the time evolution of Δ at three representative Ohs with and without oscillations. It is found that the two distinct coalescence phenomena are determined by the Oh number. Damped oscillation (blue lines in Fig. 2(c)) occurs at small Oh, i.e. $Oh < 0.477$, as blue side in Table 1. When $Oh > 0.477$ (green side in Table 1, no oscillation occurs and Δ monotonically increases from 0 to 1, see green line in Fig. 2(c). Another finding is on the coalescence time. Table 1 exhibits opposite tendencies of T when increases Oh: T reduces with damped oscillation (blue side) but increase without oscillation (green side). $Oh = 0.477$ (red) serves as the critical damping corresponding the smallest T. The mechanisms of the Oh effects on T have been revealed [6].

Figure 3 shows the dynamics of hydrodynamic variables including (a) $\mathbf{U} = u_x\mathbf{i} + u_y\mathbf{j}$, (b)$\partial u_x/\partial y$, (c)$\partial u_y/\partial y$, (d)$\Omega_z = \partial u_y/\partial x - \partial u_x/\partial y$, and (e) total pressure at $Oh = 0.039$ (1), 0.177(2), and 0.868(3) at an early time $t = 0.037\mu s$. The focus area and the time point are indicated in Fig.2 using red dashed lines and red point respectively. From small Oh at

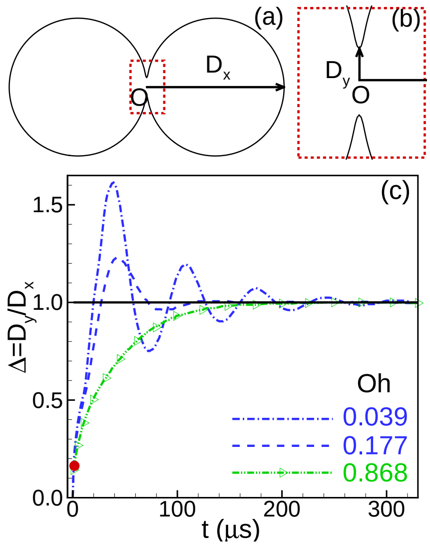

Figure 2: Definitions of (a) D_x and (b) D_y. (c) Time evolution of shape factor ($\Delta = D_y/D_x$) of 3 representative cases.

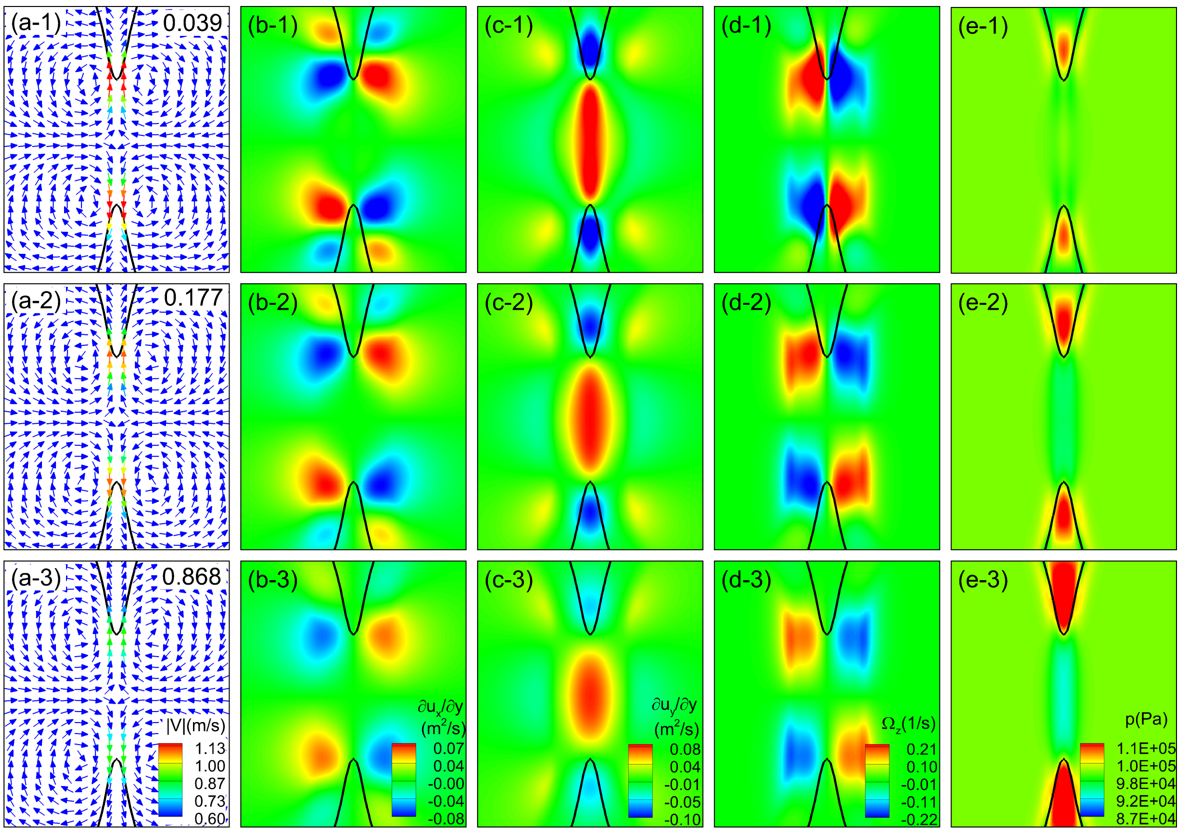

Figure 3: (a) Velocity vector field ($\mathbf{U} = u_x\mathbf{i} + u_y\mathbf{j}$) and contours of velocity gradient (b) $\partial u_x/\partial y$, (c) $\partial u_y/\partial y$, (d) vorticity($\Omega_z = \partial u_y/\partial x - \partial u_x/\partial y$), and (e) total pressure at $Oh = 0.039(1)$, 0.177(2), and 0.868(3) at an early time $t = 0.037\mu s$

the top, surface tension dominatingly drives the neck bridge up with insignificant energy loss, behaving as a damped harmonic oscillator. When Oh is large, the driving force is weakened due to the strong viscous resistance, causing the neck growth much slower. When Oh is small at the top, the energy dissipation due to viscous effect is insignificant, sufficient surface energy initiates a strong inertia and overshoots the neck movement. It results in a successive energy transformation between surface energy and kinetic energy of the coalescing bubble. Whereas at the bottom where Oh is large, the viscous force becomes significant. The neck growth is much slower and no overshooting of the bubble interface occurs and the shape factor asymptotically grows from 0 to 1.

REFERENCES

[1] T. Lee, P. Fischer, Eliminating parasitic currents in the lattice Boltzmann equation method for nonideal gases, Physical Review E 74 (4) (2006) 046709.

[2] R. Chen, H. Yu, L. Zhu, L. Taehun, R. Patil, Spatial and temporal scaling of unequal microbubble coalescence, The AIChE Journal 63 (2017) 1441 – 1450.

[3] R. Chen, H. Yu, L. Zhu, Effects of initial conditions on the coalescence of micro-bubbles, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science (2017) 0954406217742941.

[4] S. Zhou, Y. Cao, R. Chen, T. Sun, K. Fezzaa, H. Yu, L. Zhu, Study on coalescence dynamics of unequal-sized microbubbles captive on solid substrate, Experimental Thermal and Fluid Science 98 (2018) 362–368.

[5] R. Chen, H. Yu, L. Zhu, General power-law temporal scaling for unequal microbubble coalescence, Phy. Rev.E (2018) In review.

[6] R. Chen, J. Zeng, H. Yu, Mechanism of damping oscillation in the bubble coalescence, Computer & Fluids (2018) In review.