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Characterization of Jet Formation and Flow Field Produced by Tandem Bubbles

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Abstract. Tandem bubble (TB) interactions have been shown to produce directional jets that can be used to create membrane poration on single cells. Jet speed and associated flow field produced around the TB have been postulated to play an important role in TB-induced bioeffects. In this study, dynamics of tandem bubble interaction in a microfluidic channel (25 \(\mu\)m in height) was analyzed by high-speed imaging and simulated using 3DYNAFS-BEM\textsuperscript{D} (Dynaflow, Inc.). The results suggest that jet size and geometry are primarily controlled by the maximum diameter of the first bubble \((D_1)\) while jet speed is about linearly correlated with maximum diameter of the second bubble \((D_2)\).

INTRODUCTION

Jet formation from tandem bubble interaction in a microfluidic channel has been shown to produce site-specific membrane poration with potential applications in targeted drug delivery [1, 2]. In addition, this method may provide a new tool for probing the bioeffects induced by cavitation bubbles at the single cell level [2]. Previous studies [1] have shown that a single bubble of 50 \(\mu\)m in maximum diameter produced in a microfluidic channel of 25 \(\mu\)m in height will collapse without jet formation and cell membrane poration. However, introducing a second bubble of similar size in close proximity (i.e., 40 \(\mu\)m) from the first bubble during its maximum expansion will lead to anti-phase bubble-bubble interaction. As a result, the tandem bubbles will deform and collapse asymmetrically, producing a pair of re-entrant jets in opposite directions, which can be used to produce directional and localized membrane poration of individual cells cultured nearby. A numerical model based on the Boundary Element Method (BEM) has been developed to simulate tandem bubble (TB) interactions and reasonable agreements with experimental data have been observed [3]. The goal of this study is to combine experimental observations with numerical analysis to investigate the effects of bubble size on TB interaction.

MATERIALS AND METHODS

The experimental setup is shown in Fig. 1. The PDMS-glass microfluidic channel used for tandem bubble generation was designed and fabricated following an established protocol described in [4]. A pair of micron-sized gold dots was coated on the channel’s glass substrate. Anti-phase TBs with maximum projected diameters in the range of 40 to 60 \(\mu\)m were generated in the microfluidic channel with a nominal height of 25 \(\mu\)m, by two Nd: YAG pulsed lasers of 532 nm wavelength and 5 ns duration strongly absorbed by the gold dots. The transient interaction of the TBs and the resultant jet formation were captured by two high-speed video cameras with a framing rate up to 5 \(\times\) 10\textsuperscript{6} frames/sec, through a 63X objective lens.
The TB interactions were also simulated numerically using the BEM module of 3DYNAS©. In addition, the flow field around the TB was characterized by Particle Image Velocimetry (PIV) technique with polystyrene beads of 1 µm in diameter seeded in the medium with a seeding density corresponding to about 10 particles per interrogation window.

**MODEL SIMULATION OF TANDEM BUBBLE INTERACTION**

In addition to experiments, the TB interactions were also simulated numerically using the potential flow solver 3DYNAS-BEM©, which is based on the Boundary Element Method (BEM) and has been extensively applied to the study of bubble dynamics related problems, e.g. ultrasound contrast agents [5, 6], cavitation and underwater explosion bubbles [7, 8], tandem bubble interactions [3], and cavitation erosion [9].

**Governing Equations**

Following the laser discharge, the liquid flow velocity due to the bubble wall motion is large enough to overcome viscous effects but still much smaller than the sound speed in the liquid. This justifies considering the liquid as irrotational and incompressible during the TB dynamics and interaction. A velocity potential $\phi$ can be introduced such that the velocity vector $u$ is given by:

$$u = \nabla \phi$$

The continuity equation then gives:

$$\nabla^2 \phi = 0$$

Equation (2) can be solved based on the second Green’s theorem, which provides a relationship between the velocity potential in any point, $x$, in the liquid domain knowing the velocity potential and its normal derivative $\partial \phi / \partial n$ at boundaries, $S$, of the computational domain.

$$a\phi(x) = \iint_S \left\{ -\frac{\partial \phi}{\partial n}(y)G(y) + \phi(y)\frac{\partial G}{\partial n}(y) \right\}dS,$$

where $y$ is an integration point on the domain boundary, $G$ is the harmonic Green function,

$$G = \frac{1}{|x-y|},$$

and $a$ is the solid angle from which $y$ locally “sees” the domain $D$.

- $a = 4 \pi$, if $x$ is a point in the fluid,
- $a = 2 \pi$, if $x$ is a point on a smooth surface, and
- $a < 4 \pi$, if $x$ is a point at a sharp corner of the discretized surface.

Equation (3) can be solved numerically by discretizing all the boundaries into either triangular or quadrilateral panels $S_k$, in which all the quantities are assumed to vary linearly. Using the BEM, equation (3) can be written in a discretized form:

$$a\phi_j = \sum_{k=1}^{N} \sum_{l=1}^{m} B_j^k \phi_{i_l} - A_j^k \left( \frac{\partial \phi}{\partial n} \right)_{i_l}, \quad j = 1, N, \quad m = \begin{cases} 3, & \text{triangular element,} \\ 4, & \text{quadrilateral element,} \end{cases}$$

where $\phi^k_i$ and $\partial \phi^k_i / \partial n^k_i$ are the potential and its normal derivative at node $i$ of panel $k$, and $A^k_j$ and $B^k_j$ are elements of the influence matrices obtained from the elementary integrations.

**Model Calibration and Comparison with Experiments**
In the 3D YNAFS-BEM© code, the initial gas pressure inside the bubble \( (p_{g0}) \) and the radius of the disk used to mimic the boundaries \( (R_{disk}) \) are the two variables that affect the maximum bubble size and bubble oscillation period. In this study, we first use data from single bubble dynamics to select the value of \( (p_{g0}, R_{disk}) \) to best match with the experimental data. Thereafter, the simulations for TBs are carried out under identical model parameters, except that the second bubble was introduced with a 2.0 \( \mu \)s delay from the first one. The simulation results, shown in Fig. 2, capture the main features of the TB interaction in terms of size, asymmetric bubble deformation and the early stage of jet formation before jet touchdown on the opposite bubble wall.

![Image](image-url)

**FIGURE 2.** Model validation via experiment-simulation comparison. (a) Experiment; (b) Simulation

## RESULTS

### Jet Speed

The average speed of the jet tip advancing from initiation to touchdown was determined from both experimental data and simulation results. As shown in Fig. 3(a), a linear fit of the proximal and distal end positions was made to determine the touchdown time of jet from the first bubble collapse \( (J_1) \), and the average jet speed was determined by the slope of the regression line. Fig. 3(b) shows that the average speed of \( J_1 \) is linearly correlated with the maximum diameter of the second bubble \( (D_2) \). Similar observations were obtained from model simulation (Fig. 4).

![Image](image-url)

**FIGURE 3.** Experimental results of jet tip position variation with time. (a) A linear fit was used for determining the touchdown time and the average speed of \( J_1 \); (b) the correlation between jet speed and \( D_2 \).

### Jet Geometry of Volume

The simulation model was further used to analyze the geometry of the jet produced by TB interaction. As shown in Fig. 5(a), the base radius \( (BR) \) was defined as half of the base width or as the distance from the jet inflection point to the center axis of the tandem bubbles. Similarly, the halfway radius \( (HR) \) was defined as half the jet width in the middle of the jet height \( (h) \). The radius ratio \( (RR = HR/BR, 0 < RR \leq 1) \) was used to characterize the jet shape. The maximum jet volume \( (Vol_{max}) \) was calculated by the volume of fluid enclosed by the jet.
boundaries. Figure 5(b) and 5(c) show, the relationship between RR and Vol\textsubscript{max} (representing the jet size) and $D_1$ or $D_2$, respectively. Both RR and Vol\textsubscript{max} were found to change significantly with $D_1$ and much less with $D_2$. It can be seen from Fig. 5(b) that when $D_1$ was less than 50 $\mu$m, RR remained almost constant around 0.4, indicating the jets were close to a conical shape. When $D_1$ became larger than 50 $\mu$m, RR was found to increase approximately linearly, suggesting that the jet was transitioning from a conical shape to a cylindrical one (see top to bottom images in Fig. 5(a)). Figure 5(c) shows that Vol\textsubscript{max} increased almost linearly with $D_1$ before $D_1 = 50$ $\mu$m, and more rapidly thereafter. Altogether, the transition was noted from both Fig. 5(b) and 5(c) at around $D_1 = 50$ $\mu$m when the expansion of the first bubble touches the ceiling of the microfluidic channel.

**FIGURE 4.** Numerical model simulation results of jet speed in relation to the maximum diameter of the first ($D_1$) and second ($D_2$) bubbles.

**FIGURE 5.** Numerical model simulation results of jet geometry (top view). (a) Definitions of parameters, conical (top) to cylindrical (bottom) jet shape transition; (b) Radius Ratio (calculated using projected images from the side view) and (c) maximum jet volume in relation to the maximum diameter of the first ($D_1$) and second ($D_2$) bubbles.

**Flow Field**

Using PIV software (DaVis 7.2, LaVision), vortices and flow field around the TBs were analyzed. Figure 6 shows the vortex development and flow velocity profile at different standoff distances from the TB. In Fig. 7, comparison of the velocity field produced by single bubble (that only contains the first peak) and those produced by TB interaction shows that the second peak, which is stronger, was produced by the jetting effect. As shown previously, the oscillation of a single bubble only deforms the cell without causing dye uptake [1]. The results thus suggest that the second peak in the flow velocity profile is more important for TB induced membrane poration.
When the standoff distance was increased from 30 to 50 µm, the second peak in TB velocity profile dropped significantly, which is consistent with the reduced probability for membrane poration at larger standoff distances observed in previous studies [1, 2].

**FIGURE 6.** Vortex and flow field development following tandem bubble interaction.

**FIGURE 7.** Comparison of flow velocity produced by single vs. tandem bubble at standoff distance (Sd) of 30 and 50 µm.

**SUMMARY**

Our results suggest that during the tandem bubble interaction in a 25 µm height microfluidic channel, the average speed of the jet tip correlates linearly with $D_2$, which has been confirmed by model simulations. A parametric study of the TB interaction using the numerical model suggests that the geometry of the jet is determined predominately by $D_1$ and is minimally influenced by $D_2$. In particular, there is a transition of the jet from a conical to a cylindrical shape when the expansion of the first bubble reaches the top of the microfluidic channel. The results from PIV measurements suggest that the poration of cell membrane by the TBs may be correlated with the velocity and characteristics of the flow field produced by the jet, which warrants further investigation.

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