Particle Aggregation and Flow Patterns Induced by Ultrasonic Standing Wave and Acoustic Streaming

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Abstract

In this study, control of the aggregation of particles in a suspension solution by ultrasonic standing wave (USW) and acoustic streaming is studied by means of flow visualization (FV) and particle image velocimetry (PIV). The PMMA (Poly(methyl methacrylate)) cuvette of length 12.6mm, width 12.6mm and height 46 mm is filled with water and µm-size particles as the suspension solution, and the flow is excited with a piezoelectric plate operating at MHz frequency oscillation of voltage signal. The driving oscillation frequency is set to the natural frequency of the piezoelectric plate measured by an impedance analyzer. Driving parameters including frequency, voltage and waveform are set to the waveform generator and amplified by a power amplifier to enlarge the amplitude of the driving signal. The oscillation of the piezoelectric plate is conducted to the acrylic resonated chamber by the ultrasonic coupling gel for the experiments. This oscillation generates USW inside the liquid space, while at the same time induce acoustic streaming flows in the confined space. Three particle sizes (5 ~ 18 µm) are tested with frequencies vary from 0.847 ~ 2.032 MHz are tested. Experimental results show that the ultrasonic standing wave is successfully generated, and the error between the standing wavelength in the theory and in the experiment does not exceed 6%. USW is accompanied by the acoustic streaming flow, and within the performed frequency range, the degree of aggregation for particles in different diameters is 18µm>10µm>5µm. With all driving frequencies it is found that the acoustic streaming flow starts as the oscillation is turned on and affecting the flow patterns immediately. At driving frequencies of 0.847, 1.863, 2.032MHz for 10µm and 18µm particles, a stable streaming flow coexists with the USW pattern that cause the flow to move with minimum reduction of the particle aggregation can be observed, indicating the potential to integrate acoustic streaming with USW for applications of particle manipulation and aggregation.

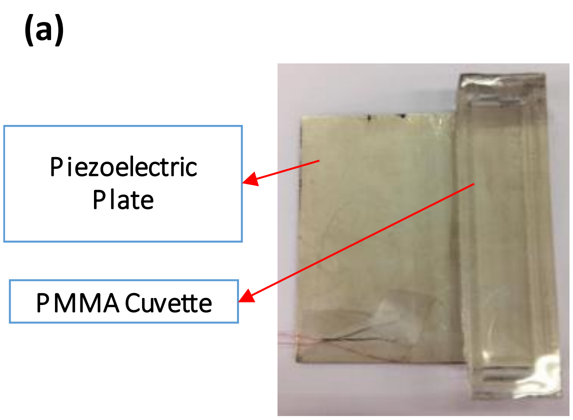
1 Introduction

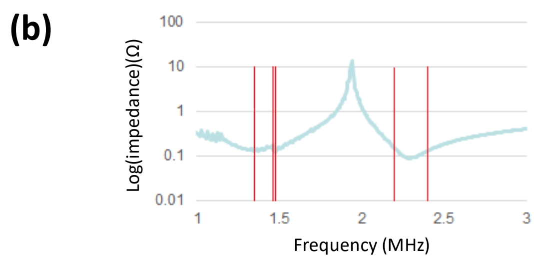
Ultrasonic standing wave (USW) has been known as a technique for manipulating particles cells, and microorganisms (de Godos et al. (2011)). It is recently found applications in harvesting of microalgae because of the ability to efficiently agglomerating microalga (Vinatoru (2001); Veillet et al. (2010);Trujillo et al. (2014)). In the microalga culturing business, 20~30% of the total production cost comes from collecting the microalga, it is this critical to have an efficient yet energy-saving collecting technique (Bosma et al. (2003)). For microalgae harvesting application, it is also important to create a continuous flow in order to dewater the microalgae and increase the throughput. Therefore, a continuous flow device that can simultaneously induce ultrasonic standing wave is of interest. The main advantage of the USW technique is indirect and noncontact method. The main driving force, the acoustic radiation force, is dependent on particle size and density differences between particle and fluid (Petersson et al. (2007); Henrik Bruus (2012);H. Bruus (2012)). For an USW device to be designed and manufactured, it is important to consider factors such as acoustic impedance (Lenshof et al. (2012); Lenshof et al. (2012)), Q-value(quality factor, Q-factor, Dual et al. (2012))。

Acoustic streaming is another phenomenon comes from the non-linear effect of the Navier-Stokes equation (Henrik Bruus (2008); Lutz et al. (2005); Marmottant et al. (2006); Huang et al. (2013)). It creates a recirculating flow in a confined space, and the flow is steady. In previous studies acoustic streaming and USW are usually two separated research fields, and their effects are exclusive to each other. In this study, it is shown to have a coexisting condition for both mechanisms, and a potential to improve the microalga collector's efficiency.

2 Methods

The PMMA cuvette used in this study has an inner dimension of 10mm × 10mm × 46mm. During the experiment, the cuvette is filled with water and μm-size particles as the suspension solution, and the flow is excited by a piezoelectric plate (PEL4545T12-QA, Eleceram Technology Co., Ltd, 46×46×1.2 mm). The plate is attached to the cuvette with ultrasound gel and the air in the cuvette completely displaced to minimize the acoustic impedance. The assembly of the cuvette and the piezoelectric plate is shown in Figure **1**(a). To make sure the appropriate driving frequency can be found, an impedance analyzer (KEYSIGHT E4990A, Keysight Technologies) is used to find the resonance frequencies of the piezoelectric plate. The results of the analysis show peaks at 1.35, 1.475, 1.48, 2.22~2.40 MHz as shown in Figure **1** (b). It is interesting to find that in the real test runs the USW is generated at the vicinity of these frequencies but with a considerable difference, which indicates that the resonance frequency of the system is affected significantly by other factors, such as the mass of the cuvette and water solution, ultrasound gel, … etc.





Frequency(MHz)	Log(impedance)(Ω)
1.350	0.1290
1.475	0.1237
1.480	0.1291
2.220 ~2.400	0.0887 ~0.1289

Figure 1: Experimental setup: (a) The assembly of the PMMA cuvette and the piezoelectric plate (b) Results of the impedance analysis

The experimental setup for the FV and PIV experiments is shown in Figure 2. The cuvette-Piezo assembly is connected to a signal generating unit, which consists of a function generator (HDG2022B, Hantek) and the power amplifier (HSA4012, NF corporation) to operate at MHz frequency oscillation of sine wave voltage signal. This oscillation generates USW inside the liquid space, while at the same time induce acoustic streaming flows in the confined space. The test assembly is illuminated by a continuous laser (diode pumped green laser module, 523nm, 40mW, Blue Sky Tec Co., Ltd). The 2mm diameter laser beam is expanded by a set of cylindrical lenses to create a 46mm width laser sheet. Images are taken by a Zyla 5.5 sCMOS, ANDOR) high-resolution camera.

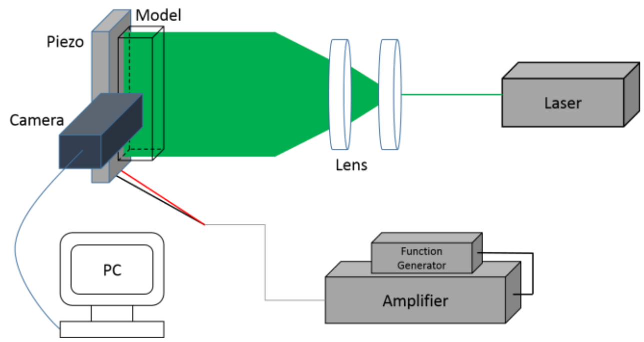


Figure 2: The FV and PIV setup of the USW generating device used in this study.

To simulate the different sizes of microalga in this study, three different types of particles are used: 5μm polyamid seeding particles (PSP-5, Dantec), 10μm polystyrene particles (PPX-100-10, Spherotec Inc.)and 18μm polystyrene articles (PPX-200-10, Spherotec Inc.). In order to capture the long-term evolution of acoustic streaming flow and the short-term USW phenomenon, the recordings of the FV and PIV are taken and the start of each test run for 1 sec or 5 sec, and the recordings are taken every 1 minute or 3~5 min, total elapse time is 300s. The resulting test matrix is shown in **Table 1**.

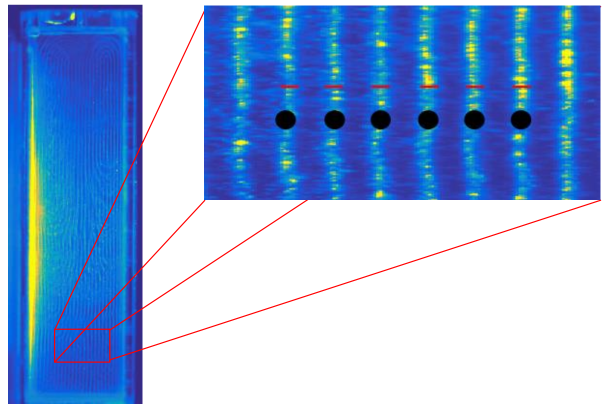
Particle Size	Exposure time	Total Elapse Time	Total Sections	Record Interval	Recording length	FPS	Driving frequency	Drive Voltage
5μm	0.01s	300s	11	60s	5s	30fps	2.032MHz	600mV*50
10μm	0.0015s	300s	11	60s	5s	30fps	2.032MHz	600mV*50
18μm	0.0015s	300s	11	60s	5s	30fps	2.032MHz	600mV*50
10μm	0.0015s	30s	12	3min~5min	1s	30fps	0.1693MHz~2.032MHz	600mV*50
18μm	0.0015s	30s	12	3min~5min	1s	30fps	0.1693MHz~2.032MHz	600mV*50

Table 1 The test matrix in this study

3 Results and Discussion

Figure **3** shows the standing wave pattern induced by the piezo oscillation. The pattern is analyzed by MATLAB to calculate the average spacing between the high intensity node-lines, as shown in the zoom-in image on the upper right. Bottom is the evaluation of the standing wavelength of different particle sizes and compared to the theoretical values. It turns out the errors in wavelength is the lowest when the particle size is the smallest. In the case of the larger particles, the calculated wavelength is more off maybe caused by the uncertainty of selecting the particle aggregation center on the node line. The number of nodes is not available for the 5μm case, because the streaming flow skews the pattern and no complete node lines for the calculation.

Figure 4、 Figure 5 and Figure 6 show the FV (left) and PIV (right) results of 3 particle sizes (5, 10 and 18μm) under a driving frequency of 2.032 MHz. Color bar on the right image is the speed (magnitude of the velocity vector containing u, v and w). the snapshot images are taken at different time points from the start at t = 3sec to t =300 sec, so that the evolution of the standing wave flow patterns skewed by the acoustic streaming can be compared. In these results, it can be seen that the aggregating patterns caused by USW are instantly visible at t = 3 sec for all three particle sizes. From the PIV results it can be observed that the acoustic streaming phenomenon also starts at the t = 3 sec, and for case of 18µm particles the flow pattern is different than the other two cases. USW patterns keep to be obvious in the cases of 5 and 10 µm particles throughout the entire 300 sec observation period, but for the case of 18 µm particles, the aggregation of particles makes it heavy and drop to the grounds quickly and the USW patterns starts to disconnect and disappear. On the other hand, the PIV results show that the acoustic streaming flow is slow but steadily skewed the USW patterns for the smaller particle sizes. The streaming velocities and recirculation patterns are the strongest for the 5µm particle case and are the weakest for the 18 µm case. These results are in general agreement with other studies discuss about the size effect of the acoustic streaming flows and USW phenomenon.



	Theory	5µm	10µm	18µm
Wavelength (mm)	0.733	0.735	0.776	0.757
Error(%)	NA	0.27	5.87	3.27
No. of Nodes	28	★	24	24

Figure 3: Evaluation of the actual standing wavelength based on the image analysis and comparison to theory.

The most interesting point in these observations is that during the 300 sec period, the USW patterns are not destroyed by the streaming patterns for the 10 and 5µm particle cases, but both effect coexists and last for a considerably long period. It is usually the difficult part of the design for the USW device to keep the particles in aggregated status and transport to the collecting area in the flow field. Therefore, this results seems to indicates that it is possible to utilize these flow feature to transport the aggregated particles (microalga) by a carefully designed streaming flow pattern for further collection.

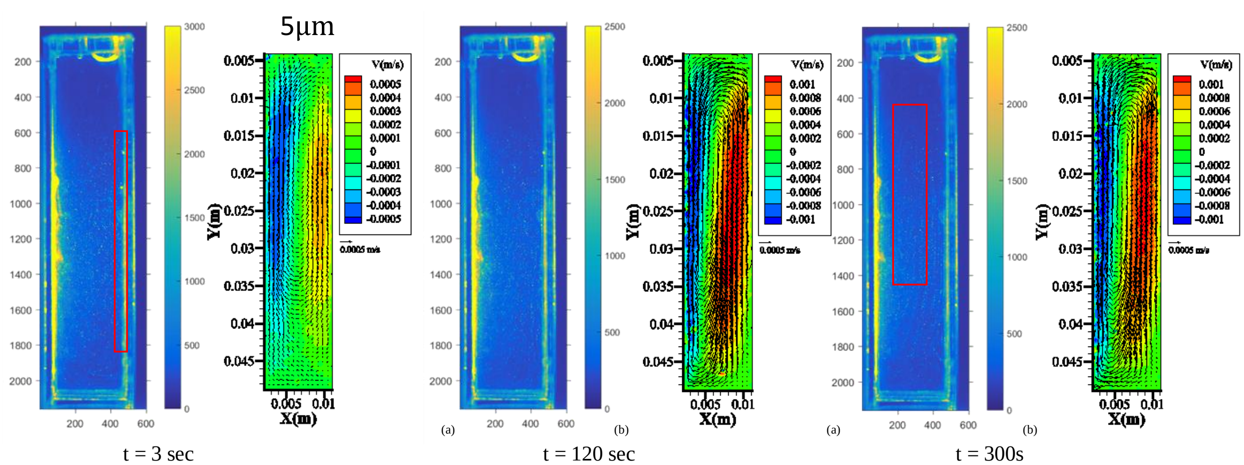


Figure 4: Results of FV and PIV for the case of 5 µm particles during the 300sec observation period

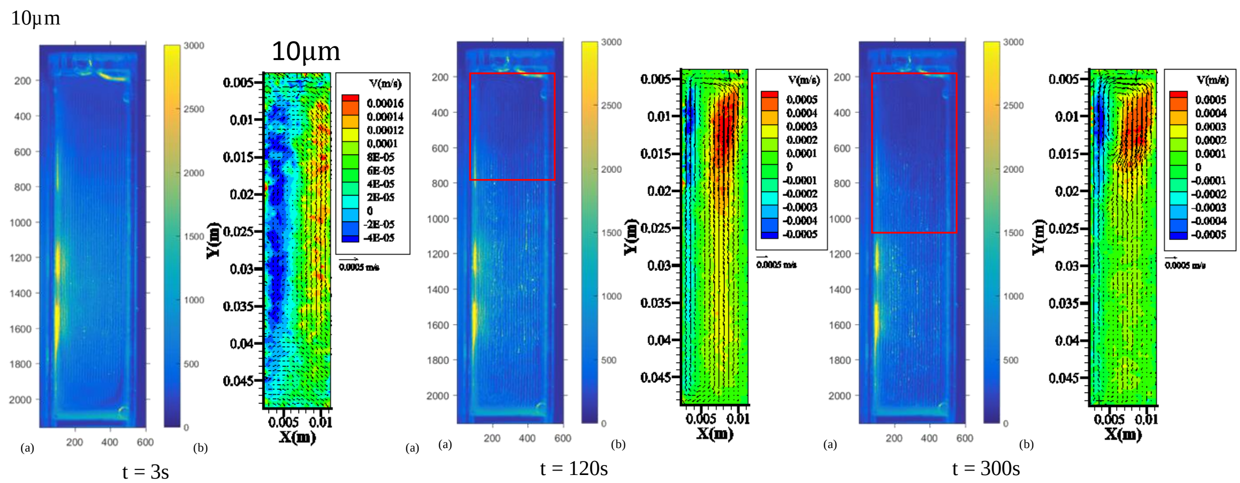


Figure 5: Results of FV and PIV for the case of 10 µm particles during the 300sec observation period

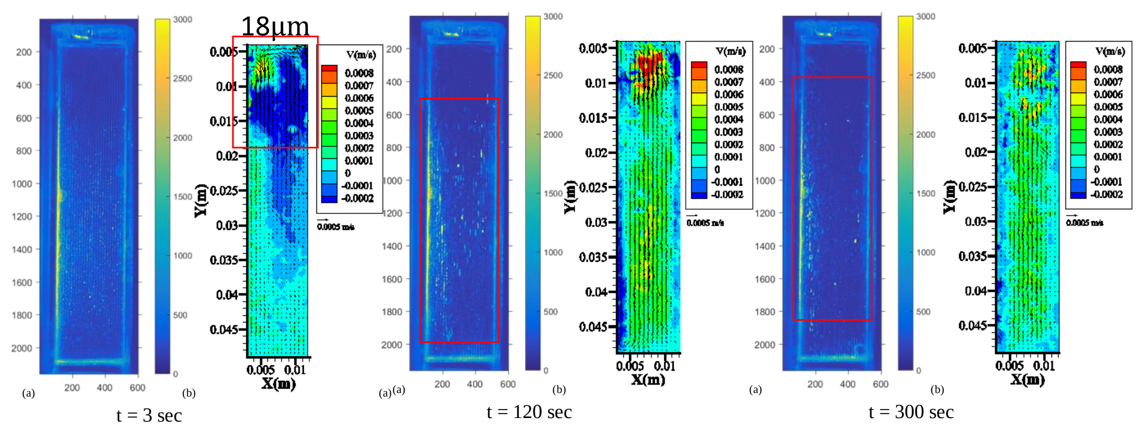


Figure 6: Experimental setup: (a) The assembly of the PMMA cuvette and the piezoelectric plate (b) The FV and

4 Conclusion

Ultrasound standing wave is successfully generated in a PMMA cuvette by high frequency oscillation of piezoelectric plate. The short-term particle aggregation behavior and long-term acoustic streaming steady flow behavior are both captured by FV and PIV techniques. Image analysis of the standing wave pattern shows reasonable agreement with theoretical results. Three particle sizes (5~18 µm) are tested for collection efficiency and for controllability 18 µm > 10 µm > 5µm. At all frequencies tested from 0.847 ~ 2.032 MHz, for 18 µm particles the collection efficiencies are 45.8% ~ 85.7%, which are always better than the 35.5% ~ 68.8% for 10 µm particles. At 0.847, 1.863 and 2.032 MHz, the acoustic streaming flows are generated and coexists with the USW. These stable flow patterns suggest the probability and potential to move and control the aggregated particles by USW using acoustic streaming flows

Acknowledgements

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