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Experimental Study of Acoustic Streaming Flow Patterns Induced by Triangular-Shape Obstruction

Yu-Sing Liou[1], Wei-Hsin Tien[1*]

[1] University National Taiwan University of Science and Technology/Department of Mechanical Engineering/Taipei, Taiwan

* whtien@mail.ntust.edu.tw

Abstract

In this study, the micro-scale flow patterns of acoustic streaming flows induced by a single triangular obstruction is investigated by flow visualization (FV) and micro particle tracking velocimetry (μPTV). Different base to altitude ratios from 0.25 to 4 of the isosceles triangular obstructions are tested, corresponding to the top angles of the triangular microstructures varies from 127° to 18°, and the heights from 0.3mm to 0.6mm, and the base width from 1.2 mm to 0.1 mm. By using the piezoelectric plates, the steady acoustic streaming flow patterns are successfully created and observed at a range of driving voltages from 5 to 35 V and frequencies from 0.5 to 3 kHz. The flow field and influenced area of can be found by the vector field calculated using μPTV. The results show that the streaming flow is more concentrated at the vertex of the triangular obstructions, and flow acceleration at the vertex is more significant in the case of small base to altitude ratio. This implies that structures with smaller top angle have better ability in converting oscillatory kinetic energy into the fluid to form steady acoustic streaming vortices. The relationship between the oscillation frequency and the size of the streaming vortices is complicated, but in general the streaming flow is stronger with larger driving voltage. By checking the profile of the vertical component of velocity fields, the region affected by the acoustic streaming can be identified.

1 Introduction

Acoustic streaming (Marmottant et al. (2006); Lutz et al. (2006); Ahmed et al. (2009)) in microfluidics has getting more interests because of its ability to create a hydrodynamic force to move micro particles in the microchannel flow. The flow is usually induced by applying oscillatory motions from the boundaries. Due to the dissipating effect, the time averaging of the Navier-Stokes equation with the oscillatory boundary conditions can create a steady streaming flow, usually in a recirculating nature in a confined space. The flow can be induced by bubbles (Ahmed et al. (2009); Ozcelik et al. (2014)), obstructions at the boundary (Huang et al. (2014); Lieu et al. (2012)) or cylinder in the flow(Lutz et al. (2006); Lieu et al. (2012); Nama et al. (2014)). Compared to other acoustophoresis methods for particle manipulation such as ultrasonic standing waves (Trujillo et al. (2014); Petersson et al. (2004)), it is more complicated because the streaming flow pattern is affected by the geometry of boundaries. The triangular shape obstruction has been proposed for micromixer and pumping purposes (Huang et al. (2013);Huang et al. (2014); Nama et al. (2014)). Lieu et al. (2012) investigated 9 different geometries that can generates streaming flow and discussed about the strength of the streaming vortices by FV. Though simulation and experiments, Nama et al. (2014) design and compare the effect of sharp edges as a pumping source for microfluidic device. Different parameters such as top angle, amplitude, aspect ratio of the channel are investigated for their effects to the streaming flows.

In this study, the effect of triangular geometry to the streaming flow patterns is studied with micro-particle tracking velocimetry (μPTV). PTV is a technique closely related to particle image velocimetry (PIV), except the flow vectors are determined by a tracking algorithm instead of a cross-correlation scheme. PTV techniques has been extensively developed for 2-D applications(Lei et al. (2012); Mikheev et al. (2008); Panday et al. (2011)). It is suitable for the flows has medium to low particle seeding density yet require high spatial resolution. For streaming flows in microchannels, due to the size of the obstruction and seeding particles, µPTV is an appropriate option and is used as the main technique for the research.

2 Methods

The microchannels used in this study are made by poly(dimethylsiloxane) (PDMS) using a standard fabrication process of a microfluidic device Xia et al. (1998). The casts are made by micro-milling process to reduce the manufacturing cost. The microchannel device setup is shown in Figure 1(a). The 6 triangle structures made for this study are isosceles triangles with 6 different top angle from 18° to 127° with 3 different heights (0.3, 0.4 and 0.6mm). The optical setup for FV and PTV experiments are shown in Figure 1(b). An invert microscope (WI-400 from Whited Ltd.) with continuous LED light source. A CCD camera (G-503B/C from Allied Vision Technologies) is mounted to the microscope for image recording. 300 images are taken in one experimental run. In post processing the images are overlapped to get the background image, and the particle image can be obtained from subtracting the background image from the raw images. These processed images pairs are first processed by particle tracking algorithm proposed by Lei et al. (2012) to generate 2-frame tracking results. These results are then overlapped and interpolated onto a uniform grid to produce the velocity field results.
To generate the acoustic streaming flow, two piezoelectric bending disk (T216-A4NO-273X from Piezo System) are placed at the sides of the device driven by a signal generator (HDG2022B from Hantek) with an amplifier (HSA 4012 from NF corp.). The piezo disks are attached to the device with 1mm thick ultrasound hydrogel (XY-35 from Taiwan Stanch Co., Ltd.) to reduce the acoustic impedance. The driving signal is sinusoidal waveform of various frequencies from 0.1 kHz to 3 kHz, and the voltages are magnified by the amplifier from 5V to 35V. The tracer particles are 5µm polyamide particles (PSP-5 from Dantec) suspended in water. With the 6 triangular structures designed and manufactured as described previously, the experiment test condition set is listed in **Table 1**.

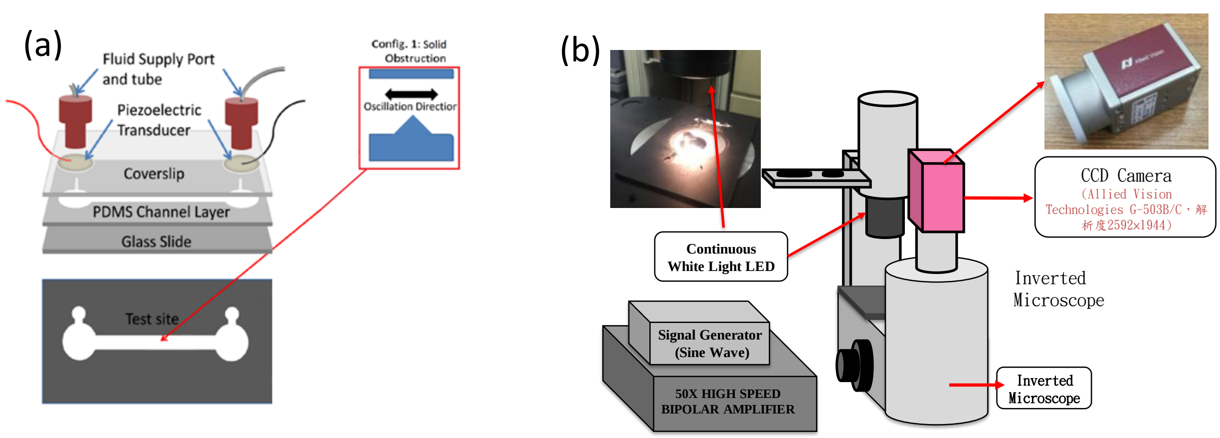

Figure 1: Experimental Setup in this study: (a) Microchannel device concept (b) Optics for FV and PTV experiments

Test Matrix		
Top Angle ($\alpha°$)	Frequency (kHz)	Voltage (V)
127°	0.5、0.7、1、2、3	25
90°	0.5、0.7、1、2、3	15
18°	0.5、0.7、1、2、3	5
28°	0.5、0.7、1、2、3	15
41°	0.5、0.7、1、2、3	15
53°	0.1、0.3、0.5、0.7、1、2、3、4、5、6	5、15、25、35

Table 1 Test Condition Matrix in the present study

3 Results and Discussion

The experimental results, including the triangular geometry, overlapped particle trajectories and processed tracking results are shown in Figure **2** and Figure **3**. In all cases two steady streaming vortices form a pair at the tip of the triangular structures. The induced streaming flow is outward from the vertex and return from the sides. The area affected by the streaming flow has a limit and depends on the top angle of the triangular structure. For the cases of $\alpha < 90°$, the regions of streaming flow are considerably larger than the cases of $\alpha \geq 90°$. Compare the 3 cases in Figure **2**, it is apparent that with a smaller top angle, the streaming flow becomes stronger and the affecting range is larger. For the obtuse and right angle cases in Figure **2**, the affected area is never exceed the area of the triangular structure itself. On the other hand, for acute angles in Figure **3**, the affected regions are all larger than the area occupied by the triangular structure.

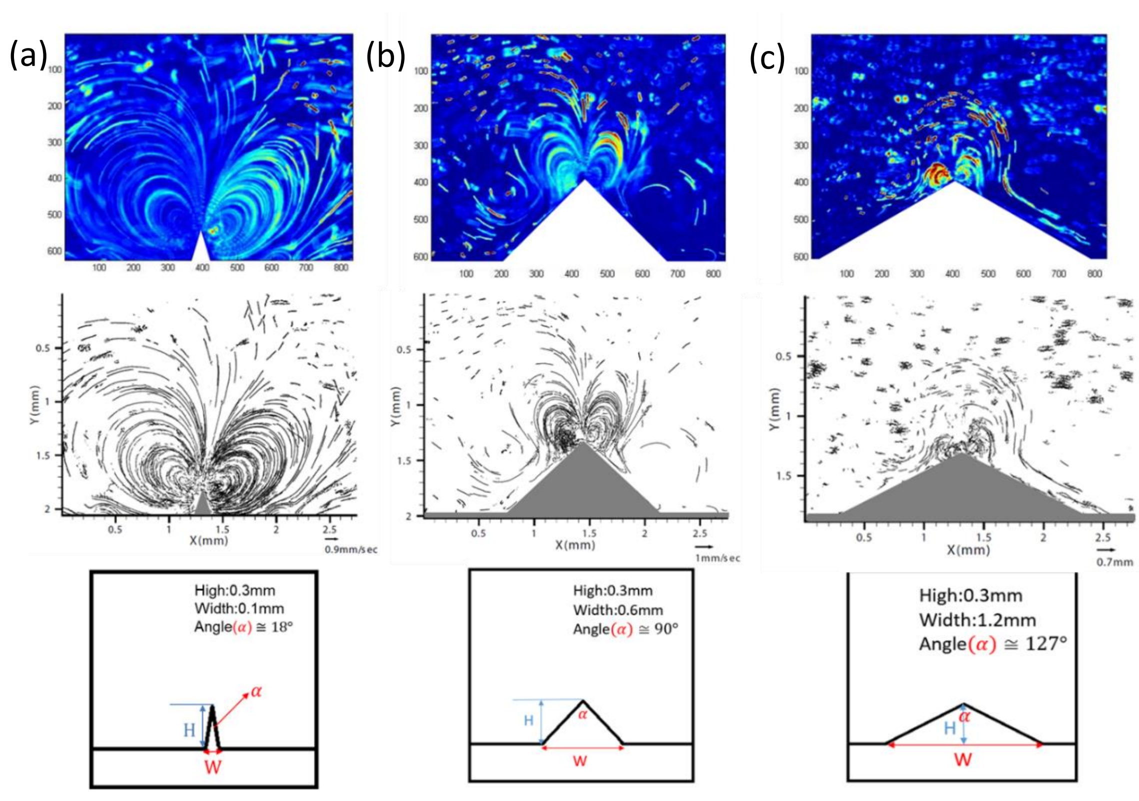

Figure 2: Triangular structure configurations, particle trajectories and PTV results of triangular structures of different α: (a)$\alpha = 18°$ (b) $\alpha = 90°$(c) $\alpha = 127°$

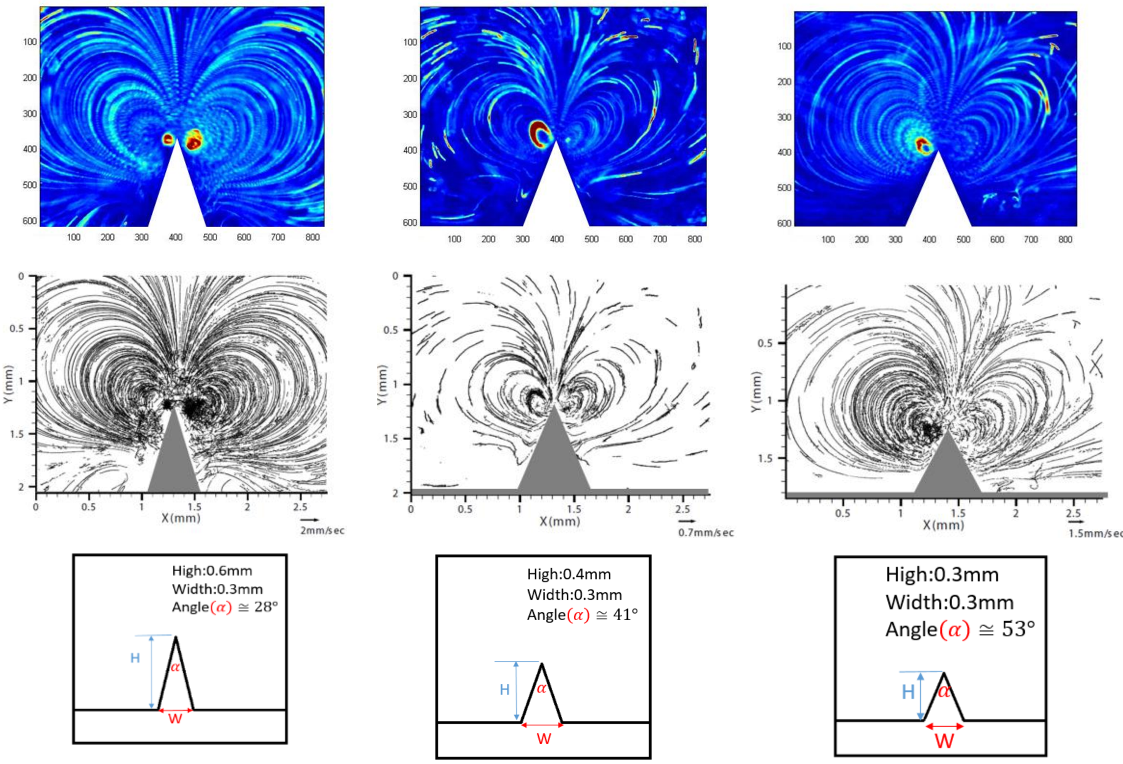

Figure 3: Triangular structure configurations, particle trajectories and PTV results of triangular structures of different α: (a)$\alpha = 28°$ (b) $\alpha = 41°$(c) $\alpha = 53°$

The effects of applied oscillation frequency and voltage are tested and compared using the structures of acute angles. The results are shown in Figure **4** and Figure **5**, with the color bar showing the magnitude of the flow vectors. The interpolated flow fields on uniform grid provides a more convenient way to compare the flow regimes under a single parameter. Figure **4** shows the effect of the oscillation frequency from 0.5 kHz to 3 kHz on the structure of $\alpha = 41°$. It can be observed that the relations between the streaming flow region and the flow magnitude to frequency are both complicated. This is probably due to the acoustic impedance of the entire microchannel device. Because of the incompressible nature of the solid structures, the streaming flow strength is more reply on the efficient transfer of the acoustic (oscillatory) energy from the piezo disks. When the whole device is considered as a system, the nature frequency of the system is hard to be estimated and achieved, therefore the nonlinear relations between the applied frequency. However, the relation between the applied voltage and the streaming flow shows a strong positive correlation. The higher the voltage, the larger the affected area. This is because once the applied frequency is fixed, the effect of the acoustic impedance is fixed with it, and the applied voltage is proportional to the energy transferred to the flow field.

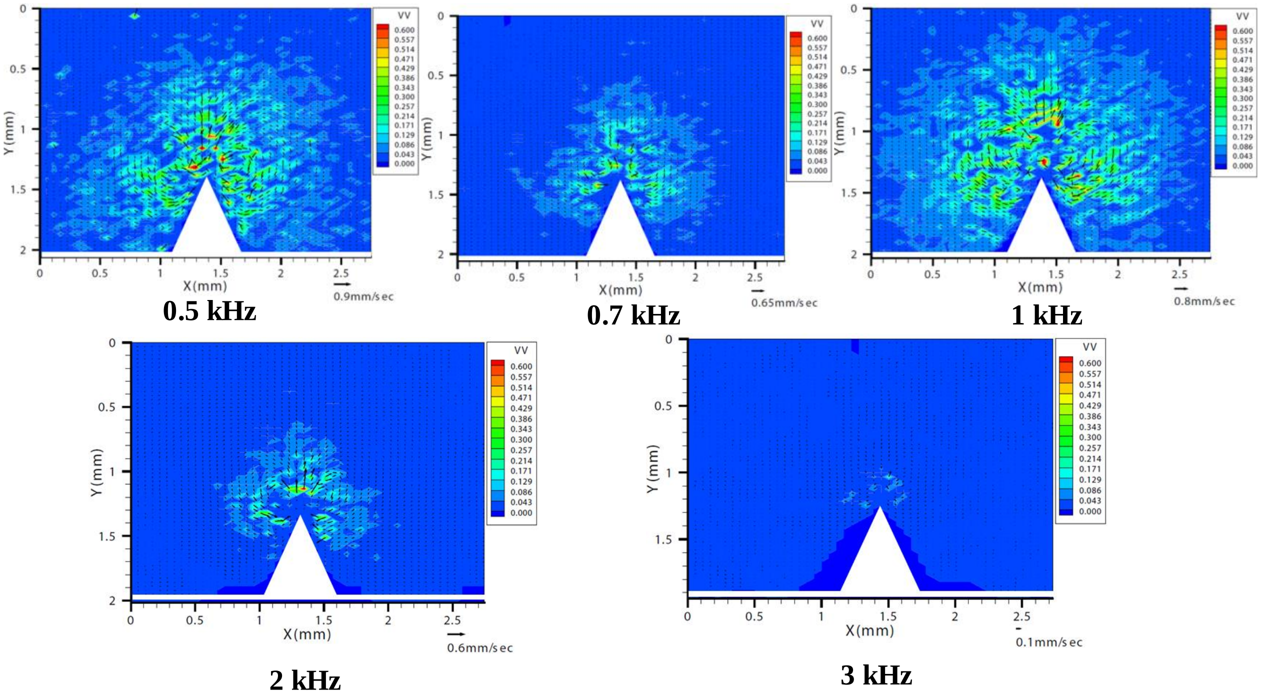

Figure 4: Interpolated velocity field of the case $\alpha = 41°$ at different frequencies. VV of the color bar indicates the flow speed (magnitude of the velocity)

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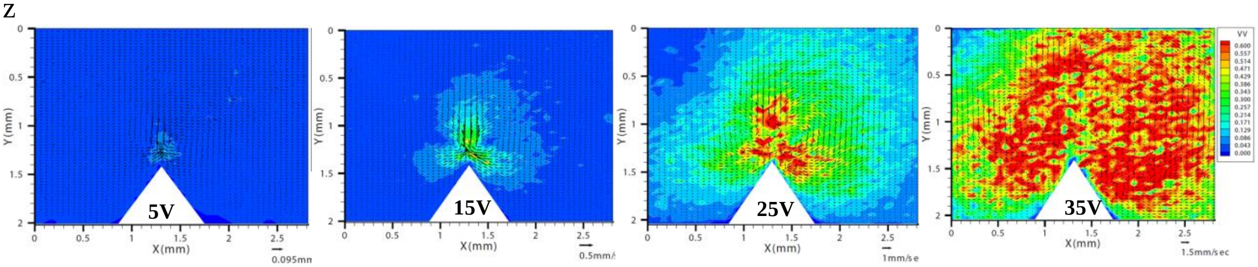

Figure 5: Interpolated velocity field of the case $\alpha = 53°$ at different driving voltage. VV of the color bar indicates the flow speed (magnitude of the velocity)

4 Conclusion

The acoustic streaming flow patterns induced by single triangular microstructures inside a microchannel is visualized by FV and µPTV techniques, and parameters such as top angle, oscillation frequency and applied voltage are investigated. The results show that the effect of applied voltage is positively correlated to the strength of the streaming flow, while the effect of oscillation frequency has a more complicated relation to the streaming flows. This is because the acoustic impedance of the whole microchannel does not efficiently transfer the oscillation energy to the flow at all frequencies. The strength of the streaming flows at the vertex is higher in the case of small base to altitude ratio or smaller top angle. This implies that structures with smaller top angle is more efficient in converting oscillatory kinetic energy into the fluid to form steady acoustic streaming vortices.

Acknowledgements

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