Fluid Streaming in Micro/Mini Bifurcating Networks

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ABSTRACT

In this study, we investigate the phenomena of flow streaming in micro/mini channel networks of symmetrical bifurcations using computer simulations and experimental observations. The phenomena of the flow streaming can be found in zero-mean velocity oscillating flows in a wide range of channel geometries. Although there is no net mass flow (zero-mean velocity) passing through the channel, the discrepancy in velocity profiles between the forward flow and backward flow causes fluid particles near the walls to drift toward one end while particles near the centerline drift to the other end. The unique characteristics of flow streaming could be used for various applications. The advantages include enhanced mixing, pumpless fluid propulsion, multi-channel fluid distribution, easy system integration and cost-effective operation.

Visualization experiment of fluid mixing, propulsion and multi-channel distribution by streaming were conducted in mini-channel networks. Preliminary computer results showed that oscillation amplitude had dominant effects on streaming velocity in channel network. Streaming velocity was directly proportional to the oscillation frequency. Streaming flow can be used as a cost-effective and reliable convective transport means when the particle diffusivity was less than the fluid kinematic viscosity. Considerable amount of work is needed to further study and understand the flow streaming phenomenon.
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<td>A</td>
<td>Oscillation amplitude</td>
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<td>D</td>
<td>Mass diffusivity</td>
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<tr>
<td>$f$</td>
<td>Oscillation frequency</td>
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<tr>
<td>L</td>
<td>The length of the mother or daughter channels</td>
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<tr>
<td>$r$</td>
<td>Mother channel width</td>
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<td>$r_1$</td>
<td>The daughter channel width</td>
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<tr>
<td>$\text{Re}_{st}$</td>
<td>The streaming flow Reynolds number or non-dimensional streaming velocity</td>
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<tr>
<td>$\text{Sc}$</td>
<td>Schmidt number ($\text{Sc} = \nu/D$)</td>
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<tr>
<td>$U_c$</td>
<td>Center velocity</td>
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<td>$U_{\text{max}}$</td>
<td>Maximum inlet velocity</td>
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<tr>
<td>V</td>
<td>Fluid streaming velocity</td>
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<td>$\alpha$</td>
<td>The Womersley number or non-dimensional oscillation frequency</td>
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<td>$\nu$</td>
<td>Fluid kinematics viscosity</td>
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INTRODUCTION

Many papers on steady streaming in macro-channel oscillatory flows have been published in the past few decades [1-15]. Various geometry and flow arrangements were covered in the literature, including: streaming flow induced by a torsionally oscillated disk [2, 3, 6], streaming adjacent to a cylinder oscillating along its diameter [4, 5], streaming in oscillating flow along a curved tube [7], pressure-driven oscillatory flow within a tapered tube [11, 12], oscillatory flow through bifurcations [8, 9; 15], and streaming in the channel entrance region [14].

These previous studies greatly advance our knowledge of flow streaming during flow oscillation. However, still a considerable amount issues have not been studied nor understood. There is a great need for the fundamental understanding of the flow streaming dynamics and for the full exploration of its potential applications, both in macro and micro scales. Many important research questions, including practical applications of flow streaming, have not been addressed. This is particularly true for streaming flow in micro/mini channel; very few studies have been reported so far in the literature.

In this study, we investigate the phenomena of flow streaming in the network of micro/mini bifurcation channel. This research topic is new and has many potential applications including micro/mini channel convective heat and mass transport, fluid mixing, propulsion, multi-channel distribution and heat pipe technology.

RESEARCH METHODS

Mechanisms of Flow Streaming in Bifurcation

The mechanisms of flow streaming in a bifurcating channel are illustrated in Figure 1. It shows a qualitative picture of the axial velocity profiles of a Newtonian fluid in a macro-channel bifurcation tube based on the work of [8, 15]. During the inflow (to the right), the parabolic velocity profile in the mother tube is split in half at the location of $U_{\max}$ when entering the daughter tubes, resulting in a nonsymmetrical profile with the maximum velocity skewed to the inner wall of the daughter tubes. During the backflow (to the left), two fully developed, parabolic flow profiles in the daughter tubes merge at the center of the bifurcation and result in an $\varepsilon$-shaped symmetrical profile in the mother tube with a zero velocity at the center. A discrepancy in velocity profiles between inflow and backflow causes fluid elements near the walls to drift toward the mother tube (negative drift) while fluids near the centerline drift to the
daughter tubes (positive drift). We would like to apply this unique flow streaming phenomenon from a single ‘macro’ sized bifurcation to problems of fluid propulsion, mixing and distribution in the network of micro/mini channels.

It is noted that the mechanisms of flow streaming we study are different from those of acoustic streaming. Acoustic flow streaming originates from attenuation of the acoustic field. The attenuation spatially reduces the vibrating amplitude of the acoustic wave and hence generates Reynolds stress distributions and drives the flow to form the acoustic streaming. Acoustic streaming occurs in most geometries when an acoustic field exists, while the streaming flows we study are induced by the pressure-driven asymmetrical oscillating flows. In addition, oscillating parameters are quite different. In most cases, the acoustic vibration has much higher frequency (>100 kHz vs. <0.1 kHz) and much smaller amplitude (<0.1 mm vs. >0.1 mm).

*Dimensional Analysis*

There are six major independent variables that characterize a flow streaming process, e.g., oscillation amplitude $A$, oscillation frequency $f$, fluid kinematics viscosity $\nu$, mother channel width $r$, fluid streaming velocity $V$, and one or more geometry variables. This additional geometry variable could be the length of the mother or daughter channels $L$, the daughter channel width $r_d$, the aspect ratio of the channel to width $L/r$, the bifurcation angle or the slope of the tapered channel, and others. There is a wide range of selections and variations among these geometry variables. Considerable amount of work is needed to identify effects of these variables. They are not the focus of this study. It is assumed that the fluid is in a single phase, surface tension and other surface forces can be neglected.

There are several methods of reducing a number of dimensional variables into a smaller number of dimensionless groups [16]. The Buckingham Pi Theorem was used in this study. The problem of flow streaming contained six variables described by three dimensions, e.g., mass, length and time. According to the Buckingham Pi Theorem, the minimum Pi groups will then be three (i.e. the number of minimum Pi group = 6 – 3). However, it took one more Pi group than the minimum in this case since two geometry variables, mother channel width $r$ and other geometry variable, had the identical dimensions. We selected the fluid viscosity $\nu$ and mother channel width $r$ as the repeating variables in Pi groups, since both $\nu$ and $r$ was used in the
conventional Pi groups, such as flow Reynolds number and Womersley number. The Womersley number \( \alpha \) is a non-dimensional oscillation frequency, defined as \( \alpha = r\left(2\pi f / \nu \right)^{1/2} \).

Based on the above discussion, we combined the six flow streaming variables to yield four chosen non-dimensional groups; \( \text{Re}_{st} = \) function (Womersley number, non-dimensional oscillation amplitude, and non-dimensional geometry factor), where \( \text{Re}_{st} \) is the streaming flow Reynolds number or non-dimensional streaming velocity, defined as \( Vr / \nu \); and the non-dimensional oscillation amplitude is defined as \( A / r \).

**Computer Simulations**

Haselton and Scherer [8] conducted the photographic streaming oscillating flow visualization experiments in a large-scale (2m in length and 3.5 cm inside diameter) Y-shape tube model. Zhang et al. 2008 [15] conducted computer simulation of flow streaming in a Y-channel. No other experimental work or computer simulations of flow streaming in a bifurcation were reported based on our knowledge. In this study, we conducted computer simulations of streaming flow in multi-generation micro bifurcation channels using commercial CFD software Fluent v.6.2 (ANSYS, Inc.). Computer simulation is a necessary tool to display the dynamics distribution patterns of fluid streak line in micro channels and in particular, to theoretically eliminate mass diffusion in fluid. These simulated streaming flow patterns are essential in understanding physics of flow streaming, but not yet possible to obtain experimentally based on current experimental techniques.

The configuration of the bifurcation network model used in the computer simulation is shown in Figure 2. The symmetrical bifurcation channel network consisted of four generations and fifteen channels. All channels had the length of 1 mm except the length of 1.5 mm for the mother channel. The width of the mother tube was 1 mm and it decreased by a half after each bifurcation. As a result, mean oscillation velocities of the fluid in all channels were maintained at the same value, thus providing a meaningful and fair comparison of results. After three bifurcations, the width of the tube at the fourth generation became 125 micrometers. The bifurcating angle was 60 degrees for all bifurcations.

The fluid was modeled as incompressible Newtonian fluid. Two-dimensional flows were simulated for the sake of simplicity. Fluid motion was governed by the Navier-Stokes (N-S)
equations and the continuity equation. The second-order implicit, SIMPLEC numerical scheme was used. The flows were considered to be strictly laminar. Convective mass transport equation was numerically solved simultaneously with the N-S equations. Mass diffusivity D of fluids was set to be zero, so that the effect of mass diffusivity would be theoretically eliminated and the resultant mass concentration distribution patterns were purely created by fluid streaming. Mass concentration of the fluid inside the channel network was initially zero. At \( t > 0 \), fluids, with constant properties but a high mass concentration, entered mother channel. A time dependent parabolic velocity profile, in which the center velocity \( U_c \) is defined as \( U_c = U_{max} \sin(2\pi ft) \), was applied at the inlet of mother tube. Zero-gradient velocity and mass concentration boundary conditions were applied at the outlet of eight daughter channels. Zero mass flux boundary conditions were applied on all wall surfaces. Since mass diffusions between fluids were artificially eliminated in the computer simulations, the unsteady mass concentration patterns mimic the patterns of fluid streak line, displaying the vivid picture of flow streaming.

We used the total friction loss as the benchmark for grid converging tests since wall shear stress was susceptible to mesh size used in simulation. It was the numerical integration of wall shear stress over the entire channel networks surface and over an oscillation cycle at oscillation frequency \( f = 10 \) Hz and amplitude \( A / r = 0.8 \). Three mesh sizes were examined including: A) 40(H) x 100(L); B) 80(H) x 200(L); and C) 160(H) x 400(L). The differences in the calculated total friction loss between sizes A and B was 8.5% and between sizes B and C was 2.5%, respectively. The distribution of mesh size 80(H) x 200(L) among four channel generations was as follows: Generation I, 80(H) x 40(L); Generation II, 40(H) x 40(L); Generation III, 20(H) x 50(L); and Generation IV, 10(H) x 70(L). Figure 3 shows the fluid center axial velocity at the inlet as function of time using time steps per oscillation cycle of 8, 16, 32, and 64, respectively using the oscillating pressure inlet boundary condition. The maximum differences between the time steps of 8, 16 and 32 with 64 were 19%, 9% and 3%, respectively. As a compromise between computational accuracy and the CPU time, mesh size B and time steps of 32 per oscillation cycle (the thick line in Figure 3) were used in all simulations. The residual tolerance for continuity and velocities were 10E-4 and mass transport equation was 10E-6, respectively.

Numerical scheme was validated by analytical solutions since there was no experimental data of oscillating velocity profiles in bifurcation network available in the literature. Computer simulation of a straight long pipe flow due to an oscillating pressure gradient at the oscillation
frequency of $f = 10$ Hz and $r = 0.5$ mm was conducted. Velocity profiles were then compared with the analytical solution of unsteady duct flows due to an oscillating pressure gradient [16]. The maximum difference between velocity values computed from the computer simulation and the approximated high frequency analytical solution for oscillating pressure driven pipe flow described in [16] was less than 4.7%. Simulated velocity profiles clearly demonstrated the unique features of velocity overshoot for an unsteady oscillating pipe flow.

**Experimental Studies**

We conducted the photographic streaming flow visualization experiments in a mini-channel bifurcation network. The purpose of the experiments was to qualitatively study and visualize the flow streaming within micro/mini scale of network of channels. The experimental setup and channel network configurations used in experiments were shown in Figure 4. Flow was generated by an in-house made syringe oscillator, which was in turn driven by an electromagnetic device. An electrical signal generator with variable voltage and frequency output controlled the electromagnetic device. Open mini-channel networks, with square cross-sectional channel geometries of 0.8 x 0.8 mm (1/32 inch width x 1/32 inch depth) were milled into an 80 x 80 x 5 mm transparent Plexiglas panel. The network had three channel generations. Each mother channel was branched to four daughter channels. There was one channel in Generation I, four channels in Generation II and sixteen channels in Generation III. The lengths of the channels were 40 mm, 20 mm and 10 mm for Generation I, II, and III, respectively. Branching angles were 22.5 degree for all channels.

Mini tube fittings were glued to the Plexiglas panel at the bottom forming the fluid entrance and exit. A clear PVC tubing of 0.8 mm inner diameter connected oscillator with the tube fitting at the inlet. It is noted that flow streaming is a phenomenon of bi-directional flow in a single tube, there is no need of looped tubing arrangement, as required in conventional pumping. A small water balloon was connected to the outlet (from bottom) and served as an elastic water reservoir to accommodate oscillating fluid pressure and volumes. The second Plexiglas panel was then clipped from the top of the first Plexiglas panel by four mini-clamps to form the closed fluid passages. A sample input port of diameter 0.4 mm was constructed by drilling through the top Plexiglas panel and connecting to the mother channels at the mid-section. The sample port was sealed during the experiments. To facilitate the viewing of streaming patterns, food dyes
(red and green) (McCormick & Co. Inc., relative density = 1) were used. The experiment started with the water filling. Air bubbles trapped in the channels were removed before the experiments. Then one drop of red dye was injected and followed by one drop of green dye through the sample port using PS-26 needles (Pepper & Sons, Inc).

**Results and Discussion**

Figure 4 is the photography of the food dye distribution before the flow oscillation. The picture was taken about six seconds after the injections of food colorings. The injection of green dye pushed the injected red dye away from the sample port as shown in Figure 4. It was observed that diffusion front of the dyes moved fast initially, gradually slowed down and became stationary when the distance was approximately several channel diameters away from the injection port.

Flow mixing and oscillation (frequency = 4 Hz, Amplitude = 4d) were started after the sample injection. Although oscillating tide volume was only about 10% of the mother tube volume, food colorings were propelled quickly into branching networks. Figures 5 shows the pattern of food dye distribution at T = 8 sec after the starting of oscillation. The red and green dyes, initially located around the sample port, were completely mixed and then distributed almost uniformly into the entire generation II and III channels as well as back flowed to entrance, demonstrating the two-way fluid propulsion, multi-channel distribution and highly efficient mixing.

The same experiment was also carried out at frequency = 2 Hz with the same oscillation amplitude. It was found that the rate of fluid mixing and fluid propulsion were slower compared with the higher frequency experiment. It took approximately twice as much time (17 seconds after the flow oscillation) for food dyes to arrive at the end of Generation III channels.

Quantitative experimental results on flow streaming were scarce in literature. The current experimental system was not capable of producing detailed and accurate experimental measurements as well. However, the above experiment did successfully demonstrate the potentials of streaming based fluid mixing, propulsion and multi-channel distribution phenomenon in mini channel networks.

Figure 6 illustrates the effects of oscillation amplitude and frequency on streaming velocities. Streaming flow Reynolds numbers were presented as a function of Womersley
number (dimensionless frequency) using non-dimensional oscillation amplitudes as references. Streaming velocity was the rate of fluid streak line advancement or the rate of streaming front movement from one end to another. The discussions on streaming velocity were rare in literature, nor its measurement. For lack of unified definition as well as for the simplicity, we employed the position of the 20% mass concentration contour to represent the frontier of the streaming flow. The rate of this contour line advancement was reported as the streaming velocity. The average streaming velocity in a channel generation was calculated based on the channel length and time elapsed for streaming flow travel from one end to the other. In Figure 6, Panels A, B and C display the streaming flow Reynolds number as a function of Womersley number using oscillation amplitude as the reference parameter for the first, second and third channel generation, respectively. The mother channel width $r$ was used as the characteristic length in both streaming flow Reynolds number and Womersley number. Since mass diffusivity of the fluid was set to be zero in simulations, the resultant streaming patterns were supposedly free of diffusion. This was difficult to do experimentally. Meanwhile, it was also noted that there was always a finite amount of numerical diffusions in the simulation due to inherent errors of numerical method.

Computer simulations revealed that streaming flow velocities highly depended on its location within the network. The streaming Reynolds number present in Figure 6, Panels A, B, and C were the mean velocity value averaged over the entire channel generation. Neglecting the end effects (entrance and outlet), bifurcations were the only sources of fluid disturbances that created flow streaming. It was observed from dynamics simulation results that at a distance away from the bifurcation, flow disturbances induced at the bifurcation diminished and streaming flow slowly faded out. At a distance closer to the bifurcation, streaming flow picked up strength and accelerated. Bifurcation configurations practically served as pumps in the channel networks to move streaming flows forward.

Figure 6 showed that at the fixed oscillation amplitude, streaming velocity increased proportionally with the oscillation frequency for all parameters we simulated. This suggested that streaming flow velocity had a linear relation with the oscillation frequency. Oscillation frequency varied between 1 Hz to 12.5 Hz in the simulations.

Panels A, B and C of Figure 6 also showed that oscillation amplitude had a dominant effect on streaming velocity than oscillation frequency. In Figure 7, Panels A, B, and C displayed the
effects of oscillation amplitude on flow streaming in generation #1, 2, and 3, respectively, using oscillation frequency as a reference. In the entire range of the frequency we studied, the rate of streaming velocity enhancement accelerated from low to high amplitude. For example, at an oscillation frequency of 8 Hz, the enhancement in streaming flow Reynolds number from an oscillation amplitude of 0.2mm to 0.4mm and then to 0.8mm increased from 171% to 251% in generation #1, from 199% to 220% in generation #2, and from 214% to 229% in generation #3. This may attribute to the fact that high oscillation amplitudes pushed the fluid directly close to the location of the channel bifurcation (e.g. source of streaming), bypassed or reduced the zone of low-streaming, and therefore, enhanced the averaged streaming velocity.

Figures 6 and 7 showed that streaming velocity decreased from mother channels to daughter channels. This may be caused by two factors: a) Streaming flow was a two way, bi-directional flow. As streaming flow traveled from mother to daughter channels, mass concentration decreased as well. Consequently, the spreading rate of the mass concentration contour line slowed down, and b) Flow disturbances induced at the bifurcation would fade away within a distance equivalent to the flow entrance length. Flow entrance length was proportional to the square of channel diameter [16].

Effects of mean fluid oscillation velocity on streaming distribution patterns are shown in Figure 8. The mean oscillation fluid velocity was calculated as $u = 2A \cdot f$. Streaming flow profile with mean oscillation velocity of 0.004 and 0.016 m/s ($A = 0.2\text{mm}$ and 0.8mm, $f = 10$), are shown in Panels A and B, respectively. Three distinct features of streaming flow could be observed in Figure 8: a) The waves of layered mass concentration contours clearly displaying marching steps of the streaming flow left during oscillating cycles; b) The skewed velocity profile at the entrance of the daughter tubes. During the inflow, the parabolic velocity profile in the mother tube was split in half at the ridge of bifurcation with the maximum velocity $U_{\text{max}}$ when entering the daughter tubes, resulting in a nonsymmetrical profile with the maximum velocity skewed to the inner wall of the daughter tubes. At a low velocity, the daughter channel velocity profile was blunt as shown in Panel A. The degrees of skewness increased with the mean oscillation velocity $u$ as shown in Panel B; and c) The demonstration of the $\varepsilon$-shaped streaming profile in the mother channel. During the backflow, two fully developed, parabolic flow profiles in the daughter tubes merge at the center of the bifurcation and result in an $\varepsilon$-shaped symmetrical profile in the mother tube with a zero velocity at the center. The $\varepsilon$-shaped
backflow produces layers of sharp-tongue-like concentration profile at the centerline as shown in Figure 8. Both sharp-tongue and $\varepsilon$-shaped streaming phenomena were reported by [8].

Next, we considered the total mass transport by mass diffusion and mass streaming convection. Figure 9 showed the effects of mass diffusivity on effective (overall) streaming velocity. With a non-zero mass diffusivity, mass transport mechanisms included both streaming advection and mass diffusion. The effective streaming velocity, again defined as the rate of 20% mass concentration contour traveling down the channel network, as a function of Schmidt number ($Sc = \nu/D$), was presented. Oscillation amplitude $A = 0.3$ mm and frequency $f = 10$ Hz were used in the simulation while the Schmidt number varied from 0.07 to 700. Figure 9 showed that there were no significant changes in streaming flow Reynolds number, for the entire range of Schmidt numbers that greater than one and for all channel generations. In other words, mass transport by convective flow streaming was the dominant transport mechanism if mass diffusivity of fluid was less than the kinetic viscosity of the fluid. Due to similarity between the mass and heat transfer problem, this finding may be extended to other applications involving fluid/particle transport. For example, streaming flow can be used as a convective heat transfer means when the Prandtl number is greater than one, or as an effective means to transport particles entrained in fluids (such as cells, bacteria and other fluid suspensions) when the particle diffusivities in fluids are less than the fluid kinematic viscosity.

Effects of Schmidt number on mass concentration patterns during streaming was shown in Figure 10. Oscillation amplitude $A = 0.3$ mm and frequency $f = 10$ Hz were used. The Schmidt number and elapsed time in Panels A, B, C and D were $Sc = \infty$, 700, 0.7, 0.07 and $t = 6.15, 6.15, 4.95$ and 1.45 seconds, respectively. Figure 10 showed that there were virtually no differences between the concentration patterns between $Sc$ number of $\infty$ and 700, due to the dominance of convective streaming mechanism in total mass transport as shown in Panels A and B. The transition between the convection dominance to diffusion dominance started around $Sc = 1$. Although there was no significant difference in effective streaming Reynolds number for $Sc = \infty$ and $Sc = 0.7$ as demonstrated in Figure 9, mass concentration distribution patterns were starting to change around $Sc = 1$. Concentration profiles shown in Figure 10, Panel B were convective streaming dominant, where the skewed concentration profiles to inner wall in the daughter channel are clearly visible. Concentration profiles shown in Panel C were diffusion dominant, where the concentration contours were smooth and uniformly distributed in all directions. There
were no visible differences between concentration profiles shown in Panels C and D, with both concentration patterns diffusion dominated. However, the elapsed time was quite different. Elapsed time in Panels C and D were 4.95 and 1.45 seconds, respectively. The effective streaming velocity for $Sc = 0.07$, in Panel D was about 340% of that for $Sc = 0.7$, in Panel C.

Fluid entrance boundary conditions have crucial effects on downstream fluid velocity patterns. Therefore, it will certainly impact the streaming flow patterns as well. A pure pulsating flow in a circular pipe driven by a periodic pressure difference was investigated experimentally by Richardson and Tyler [17], and its exact analytic solution was obtained by Sexl [18] and Uchida [19]. The nontrivial feature of this flow was that for a high flow oscillation frequency, the time-mean velocity squared, had a maximum, which occurs near the wall instead of the center. This overshoot phenomenon was called Richardson’s annular effect, which also took place for oscillating flows in ducts of arbitrary cross-sectional shapes including the geometry we simulated [18]. Figure 11 displayed the instantaneous fluid streaming patterns for at for oscillation frequency $f = 10$ Hz, oscillation amplitude $A = 0.414$mm and time at the end of 10 cycles or $t = 1$ sec for two different boundary conditions: Panel A, parabolic velocity boundary condition and Panel B, pressure boundary condition. The sharp-tongue and ε-shaped streaming phenomena were shown in Panel A. For pressure boundary conditions, the streaming pattern was blunt and uniform. This was caused by the Richardson’s annular effect. Velocity overshoot near the wall enhanced the flow velocity in the peripheral region and reduced the flow velocity near the center.

Compared with the oscillating pressure condition, parabolic velocity boundary condition was less realistic since two profiles will be identical only at low oscillating frequencies. However, th differences in streaming velocity values were negligible for the frequency range we simulated ($f < 12$). The maximum difference in streaming velocity between the two boundary conditions were less than 5%, with the oscillating pressure inlet conditions consistently having a slightly greater streaming velocity. It was also noted that the maximum oscillation amplitude of velocity profile for oscillating pressure condition was not only a function of pressure, bust also a function of frequency as well as a function of latitudinal position due to the Rachardson’s annular effect. It posed a challenge for us to compare the streaming flow results using the oscillation amplitude as the (fixed) reference parameter. From the above considerations, despite
oscillating pressure inlet was a more realistic inlet boundary condition, parabolic velocity inlet boundary conditions were used mainly for computer simulation and discussion.

The influences of Rachardson’s annual effect on streaming increased with the frequency. Also, as discussed in dimensional analysis, there is a wide range of variations among geometry variables to construct a bifurcation network. The potential interaction or resonance of overshoot velocity with the bifurcating network structure should create different streaming flow patterns to make this topic interesting and challenging. Considerable amount of work is needed on this rewarding topic.

**Discussions on Applications**

The proposed streaming flow based fluid propulsion technique in micro_mini channel has both limitations and advantages. The major disadvantage is its low efficiency in transport of sample flows. Compared to the main current of the oscillating channel flow, flow streaming is always a second order flow. Oscillatory flow increases friction losses. Clearly, this inefficiency could limit its applications where direct pumping can be easily applied. However, it has a great potential in micro_mini channels where various cost-effective and reliable micro pumps are still under development.

The oscillation flow in micro_mini channels can be generated by piezoelectric (PZT) diaphragms. Streaming flow based micro fluidics driven PZT diaphragms provide many potential advantages. It will be valve-less (no check valves needed), low cost (under $1/piece for a dime_size PZT under mass production condition and no need of looped piping), reliable (no moving parts except the motion of the PZT), regular battery compatible and easily system integration.

Flow streaming in channel networks can also be used in Lab-on-chip device, micro cooling, micro reactors, micro mixers and micro heat pipe. Streaming flow will not only preserve the high heat transfer coefficients near the entrance and exit regions as conventional oscillation flow does, but also has the higher heat/mass transfer coefficients in the middle section of the channel. The bi-directional flow streaming, or the sliding of the warmer (or high concentration) liquid layer near the channel circumference region over the cooler (or low concentration) liquid layer near the channel core region, should effectively disrupt the low laminar heat/mass transfer
gradient, stretch the total surface area of heat/mass transfer interface, and therefore enhance heat/mass transfer in micro channels.

CONCLUSION

Visualization experiment of fluid mixing, propulsion and multi-channel distribution by streaming were conducted in mini-channel networks. Preliminary computer results showed that oscillation amplitude had dominant effects on streaming velocity in channel network. Streaming velocity was directly proportional to the oscillation frequency. Streaming flow can be used as a cost-effective and reliable convective transport means when the particle diffusivity was less than the fluid kinematic viscosity. Considerable amount of work is needed to further study and understand the flow streaming phenomenon.
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