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Swirl mixing at microfluidic junctions due to low frequency side channel fluidic perturbations

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ABSTRACT

Swirl mixing between the input arms of a microfluidic system using vibration (Lab Chip 9 (2009) 1435–1438 [20]) has been shown to provide rigorous blending within a very short length along the flow stream. Investigations here, both numerical and experimental, indicate that this is due to an asymmetry in the manner in which liquid enters and exits a channel into a confined space. Based on this understanding, we demonstrate an alternative approach that applies low frequency side channel fluidic perturbations. This approach permits versatility in having mixing occur selectively anywhere along the flow stream, isolates and ensures that mixing occurs only at these locations, as well as minimizes movement so that image blurring, which limits the ability to assess mixing effectiveness optically, is reduced.

1. Introduction

Microfluidic systems are now widely used in chemical and biochemical applications in which efficient mixing of two or more streams of fluids is highly sought after. The challenge of mixing at the microscale lies with the domination of viscous over inertia forces which engender laminar flows. Passive microfluidic mixers are simple and inexpensive to operate. They typically require the induction of complex flow schemes along the fluidic channel [1–3]. Active systems, alternatively, require external energy input for mixing and have been based on cross-stream architectures [4,5], bacterial chemotaxis [6], electrokinetic instabilities [7], and laser excitation [8]. The benchmark of a highly efficient mixer nevertheless lies not only on the ability to achieve rigorous blending, but also within a short length along the flow stream. In this respect, the use of mechanical perturbation appears to offer advantages.

While there is increasing interest in the use of vibration as an actuation method within microfluidic systems, most efforts are concerned with high frequency schemes. Acoustic radiation forces have been widely used to manipulate suspended particles in microfluidic channels [9,10] and chambers [11,12]. Typically frequencies in the high kHz/low MHz range are used to achieve this. As these forces arise due to non-linear terms in the Navier–Stokes equations which time average (over an oscillatory cycle) to non-zero values, a net (time independent) force can be established by appropriate integration over the particle surface. These non-linear terms can also act directly on the fluid causing acoustic streaming which can be used to cause active mixing [13,14] or movement of droplets in open systems [15]. Typically high frequency waves are actuated via relatively complicated micromachined actuators [16,17]. Droplet movement up an inclined surface [18] and particle manipulation [19] have both been recently demonstrated using low frequency excitation which has an inherently far simpler actuator requirement involving mounting the system on a shaker.

A recent active mixing approach of using low frequency vibration for mixing has been demonstrated to introduce unexpected strong swirling flow patterns at the inlet T-junction of a microfluidic system [20]. This contrasts with the type of mixing obtained through axis-symmetrical flow conditions at inlet T-junctions [21]. It is well known that swirling engenders high degrees of mixing in macroscale systems [22]. It should be noted that mixing by mechanical perturbations has been rarely reported at low frequencies. A method that applies peristaltic flow variations has been demonstrated [23] and modelled [24] in which the flow passing through the two arms leading to the T-junction (when most effective) has an out-of-phase pulsing nature (of the type $A + B\cos(\omega t)$ in one arm and $A - B\cos(\omega t)$ in the other). The mechanism in which mixing ensues is ascribed to the increasing surface area between the two fluids as they meet. As the higher velocity fluid penetrates into the lower velocity fluid, it results in a finger formation that reverses in the direction of each cycle. A somewhat parallel approach has the perturbation delivered through multiple side channels present along the flow stream [4,5]. The essential idea is then to interrupt the flow to the extent that chaotic patterns appear in order to facil-

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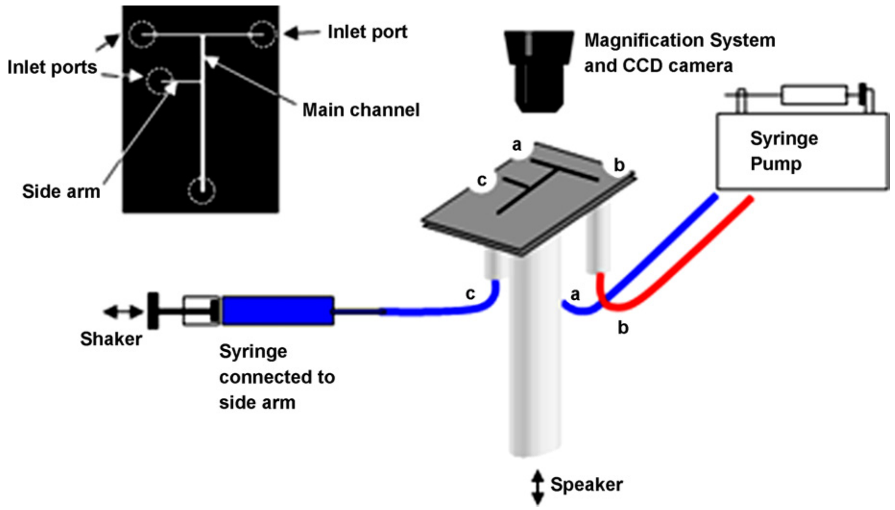

Fig. 1. A depiction of the micromachined fluidic channel, consisting of a main channel (formed at the junction of two smaller channels with inlets “a” and “b”), and of a side arm which forms a right angle junction with the main channel and is accessed via port “c”. The experimental set-up required vibration to be induced, this was done in one of two ways. The first method was to use a speaker (driven by a signal generator) to vibrate the whole chip vertically. The second was to vibrate the fluid in the side arm, this used a shaker (driven by signal generator and amplifier) for activation. A syringe pump was used for controlled flow through the main channel and a magnification system and CCD camera for image capture.

itate mixing. A modification of this approach by changing the flow frequency and amplitude across the side channels has been shown to produce mixing that is attributed mainly to vortices that create multiple layers of liquid and Taylor–Aris dispersion [25].

In the prior demonstration of the vibration based method [20], the entire microfluidic system in which two liquids were incoming at a T-junction was vibrated predominantly in the orthogonal direction (to the plane of the chip). Here, we investigated, numerically and experimentally, the mechanics of the swirl mix phenomenon reported earlier [20] and reveal that it is predominantly driven by an asymmetric input and output of flow from side channels. This results in an ability to mix at the location of input of two incoming fluids when they first merge into a single stream. Using the understanding of the mechanism gained we offer, through a different set-up, the additional feature that mixing can be caused at defined location in the two fluid flow stream. In addition, this method will be ideal to be able to isolate and ensure that mixing occurs only at selected specific locations in the microfluidic system. An added advantageous feature will be a minimization in movement so that image blurring, which limits the ability to assess mixing effectiveness optically, is reduced.

2. Experimental and numerical method

The microfluidic channel used consists of two T-Junctions; firstly two channels measuring 250 μm in width joined to form a channel of 500 μm. At a distance of 5 mm from this junction a channel of width 250 μm (we will refer to this, henceforth, as the side arm) meets with the main 500 μm wide channel at 90° (forming the second T-junction). The structure has been dry etched into a 300 μm thick silicon wafer to a depth of 200 μm. Subsequently, this was sealed with a 500 μm thick glass wafer using anodic bonding. The reverse side of the silicon was etched such that open ports allowed fluidic connection with each channel end. A diagram is shown in Fig. 1. The fluid is pumped through the channels using a syringe pump (KD Scientific, model 200 series) with pipes connected to Luer-lok fittings on the reverse side.

In contrast to the previous approach of obtaining mixing at the fluid inlets [20], we focus on the ability to do so at the vicinity of a side channel of the microfluidic channel. Low frequency mechanical perturbation was achieved in two ways; via the entire system, and thru a liquid column that feeds into the system. With the former, actuation is primarily in the vertical direction with a speaker that is driven by a signal generator (Stanford Research SDR 345). With the latter, actuation was done via pulsing a syringe attached to a shaker (LDS, model V201) excited by the same signal generator through a power amplifier (LDS, model PA25E).

Image recordings were made using a CCD camera (KP-D20AU, Hitachi) connected to a magnification lens (InfiniVar Video Microscope, Infinity Photo-Optical Company). The images were recorded at 25 frames per second directly onto a standard DVD recorder. Subsequently images obtained by playback from the DVD were transferred into a PC via a frame grabber driven by imaging software (Alliance Vision, Vision Stage).

Numerical simulations were computed using an incompressible Navier–Stokes solver employing a high-order spectral-element method for discretization in space and a third-order scheme for time integration [26,27]. A two-dimensional model of the second T-junction was produced which discretized the vicinity of the inter-

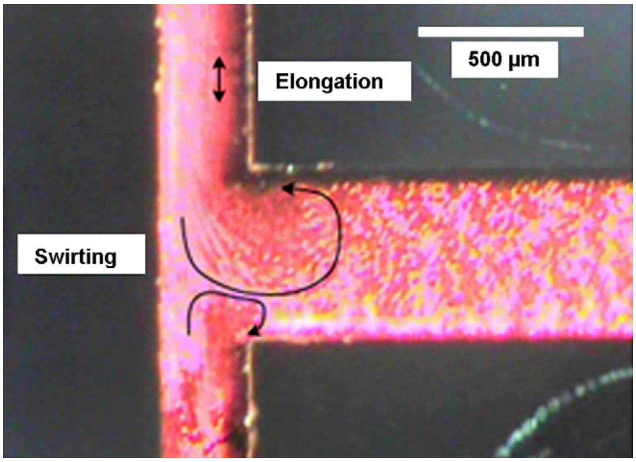

Fig. 2. An images showing the motion of suspended particles within a fluidic chip, when the whole chip is oscillated vertically (out of image plane). The shutter speed of the camera is slower than the vibrational frequency so the particles appear elongated (as labelled), the swirling effect (more clearly observed from video footage) has been indicated by arrows.