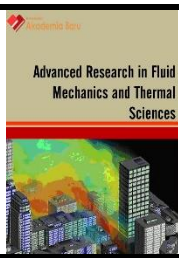
Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 73, Issue 1 (2020) 13-24

Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Chaotic Mixing of Microdroplets Using Surface Acoustic Waves Device

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ARTICLE INFO

Article history:
Received 10 January 2020
Received in revised form 10 April 2020
Accepted 11 April 2020
Available online 5 July 2020

Keywords:
Surface acoustic wave; focused-SAW; micromixing; Y-channel microfluidic

ABSTRACT

Small-scale mixing or actively known as micromixing had an utmost importance in the biological and chemical applications using micro total analysis systems (TAS) or lab-on-chips. Micromixing is achieved by stirring or agitating liquid or particles. However, in microfluidic technology, it is very difficult to do mixing for a very small amount of liquid including microliter volume. Chemical reactions are often involved in most microfluidic applications, hence making the fluid diffusivity to become very low. Thus, chaotic advection was introduced in this study to shorten the reaction time. Conveniently, a new method was proposed to actively mix micro volume liquid. In this study, we developed focused-surface acoustic wave (F-SAW) fabricated on a piezoelectric substrate to manipulate or mix two different color dyes with low concentration. Operation frequency of 50 MHz was used to generate acoustic waves along the substrate surface and we varied the droplet volume and input power on the F-SAW mixing. Method comparison between passive and active mixing was done by studying the time taken for diffusion mixing. Designing, fabrication and test on Y-junction channel micromixers were done to compare and examine the mixing performance and time. Experimental results showed that mixing by F-SAW device has achieved high efficiency of 91 – 84% in droplet volume of 1 – 5 µL. Therefore, F-SAW mixing has been proven more efficient and fast response compared to diffusion mixing.

1.Introduction

Mixing has been recognized as one of the most basic and hard-to-reach problems in microfluidic applications. To date, several mixers have been developed and proposed to be used in different application areas such as bio-, nano- and environmental technologies. However, users or designers of microfluidic mixers have to be very careful in selecting mixers for their particular application since the advantages have been stressed more in papers and patents compared to the disadvantages. Microfluidic lab-on-a-chip devices [1,2] for high-performance drug screening offer the ability to work

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https://doi.org/10.37934/arfmts.73.1.1324

with small amounts of fluids, which can significantly reduce costs by reducing the volumes of expensive reagents required.

At microscale level, mixing can be achieved by stirring or agitating fluids. There are several methods applied in micromixing that are widely used in bio-molecular and medical applications such as dielectrophoresis (DEP) [3], magnetohydrodynamic (MHD) [4] and acoustic [5]. In depth, dielectrophoresis technique can separate, transport, trap and sort various biological particles by varying the applied electric field frequency [6]. Method of DEP and MHD requires high power to perform mixing process. Mixing small liquid volume or often referred to as micromixing is crucial in microfluidic application especially for analysis that utilizes rare or valuable samples or high cost reagents. Micromixing in microfluidics can be classified into active and passive mixers [7]. In order to achieve mixing operation, active mixers rely on an external energy source, while passive mixers depend on the phenomenon of mass transport achieved by molecular diffusion and chaotic advection. Passive mixer can be categorized into T- [8] and Y- shaped [9], which recruit lamination mixing and droplet-based mixing [10].

Types of propagating waves at the center of AIDT depend on the width of electrodes, which produce different types of wave propagation including Standing Surface Acoustic Wave (SSAW) and Focused Surface Acoustic Wave (F-SAW). In this study, an active mixing operation of two droplets was introduced utilizing focused-surface acoustic waves (F-SAW) device. F-SAW device consists of an annular interdigital transducer (AIDT) fabricated on piezoelectric substrate [11]. When a radio frequency (RF) signal is connected to AIDT, surface acoustic waves are generated and propagated constructively by following the shape of AIDT on the substrate's surface [12]. The surface waves are then converged and focused at the center of AIDT. The focused-SAW induces an acoustic streaming or strong internal flow in the liquid, thus enhancing the mixing speed of two droplets [13]. We used low concentration dye droplets namely blue and yellow.

Research gap in this study was in terms of acous to fluidics concept possessed by a surface acoustic wave device. In biomedical study, very minute number of samples or reagents is used in mixing, but the concern is that big machine requires big scale of samples and reagents; hence, this lab on chip device was fabricated to meet the demand of mixing (other process of exosome/biological sample). Y-junction channel was fabricated to be used in microfluidics devices, but the novelty of this study is that we fabricated a y-channel that has a region of interest (ROI) of 80micrometer in height for the sample to mix.

Chaotic mixing by surface acoustic wave device in this study was studied to prove that surface acoustic wave can perform mixing faster than diffusion or passive mixing. Cavitation energy is generated due to mechanical oscillations and high intensive waves that cause the formation, expansion and implosion of microscopic gas bubbles [14]. This hence creates a force that can lyse cells, which is really useful in sample extraction and purification. However, restriction happens when the device does not have a system to properly expose the sample wholly because when the sample is dropped onto the device, the upper part of the sample might not be exposed to the wave propagation. The novelty of this work is in proving that mixing can be done more rapidly on SAW device, which provides a platform by fabricating the Y-channel for a more efficient and rapid mixing compared to diffusion.

The advantages of F-SAW include the ability to efficiently induce internal stirring in small liquid volume and the acoustic streaming that could be focused at a certain location. It also presents a great potential for using F-SAW device to achieve fast response mixing of micro droplets. This mixing technique was proven more reliable and efficient compared to passive diffusion mixing technique.

2. Operating Principle

When an alternating electrical signal is applied to a piezoelectric medium, a mechanical wave is produced and propagated in the substrate by either a Rayleigh mode or shear mode wave through the piezoelectric effect. Bulk Acoustic Wave (BAW) and Surface Acoustic Wave (SAW) are the two types of acoustic wave. BAW propagates throughout the thickness of a substrate, whereas SAW propagates only on the surface of a substrate, which defines the differences between the two types of acoustic wave.

SAW is an acoustic wave of nm-scale amplitude and oscillates in the MHz range. SAW based microfluidics is one of the most advance technologies. It can be exploited to drive actions such as mixing liquid, pumping and jetting [15]. Conventional interdigitated transducer (IDT) structure employed in SAW has the arrangement of several electrodes connected in a coupling mode. Formation of IDT on the piezoelectric substrates can be realized through lithography techniques. When an alternating input signal is applied to the electrode, it forms an electric field, thus affecting the surface acoustic wave due to the impact of piezoelectric coupling. The surface acoustic propagate away from interdigitated electrode waves acts as a mechanical actuator to induce mechanical response in the environment. Modifications on the electrode design from linear to annular cause the resulting surface acoustic energy to be converged at the center of the device. This will result in a maximum displacement magnitude and causes a high flow of velocity to be induced. The formation of this focused acoustic wave energy on the piezoelectric is important for many applications including pumping and particle removal.

F-SAW device typically consists of an annular interdigital transducer (AIDT) deposited on top of a piezoelectric substrate, lithium niobate-cement composite materials for high temperature transducers and arrays [16]. Lithium niobate is a PZT material with piezoelectric ceramic and polymer elements. Therefore, the novel properties of the composites are more enhanced than single components; they have large piezoelectricity, strong strength, low density and are easier to be fabricated into large area films or much more complicated forms [17]. When a RF signal is applied to an AIDT, surface acoustic waves are generated and propagate constructively by following the shape of AIDT on the substrate's surface. F-SAW devices can be operated at high frequencies (25-500 MHz) and high sensitivity (Hz g^{-1}) [18]. Amplitude of wave increases under the influence of focused wave energy and generates a larger disturbance force. The acoustic streaming or strong internal flow occurs when the wave is focused into the liquid and enhances the mixing speed of two droplets. Figure 1 shows the mechanism of focused-surface acoustic wave into liquid.

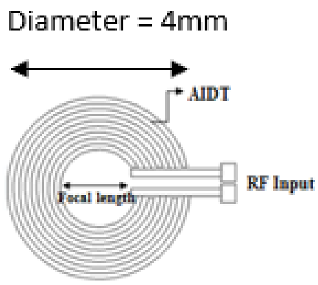


Fig. 1. Mechanism of F-SAW into liquids

Study of the flow characteristics of VFE-2 blunt edged delta wing profiles at high angle of attack [19]. Vortex is formed on the upper surface of the delta wing. The primary vortex is developed at certain chordwise location and progresses upstream with angle of attack; however, there are no data in VFE-2 suggesting that the vortex progresses with increasing angle of attack up to the apex region. Hence, experiment done by Hamizi and Khan proved that the response and state of the vortices at high angles of attack are important since variation in the vortex lift will very much influence the forces [20].

3. Experimental Setup and Method

First experimental setup was conducted using two mixing techniques; diffusion and F-SAW device. Materials used to demonstrate the mixing performance and efficiency were two different liquid colors namely blue and yellow. Mixing properties are identified as shown in Table 1.

Table 1
Mixing properties

Mixing method	Power (dBm)	Dye droplet (µl)	
		Yellow	Blue
Diffusion		0.5	0.5
		1.5	1.5
		2.5	2.5
F-SAW	10	0.5	0.5
	15	0.5	0.5
	20	0.5	0.5
		1.5	1.5
		2.5	2.5

3.1 Diffusion Mixing

A 0.5 µl droplet of yellow and blue dye was injected on a glass plate. The progression of the diffusion mixing was observed with the help of digital microscope. This process was repeated for every volume tabulated in Table 1. The angle of attack was limited to α = 23° with Reynolds number of 2×10^6.

3.2 F-SAW Device

The AIDT have a focal length of 500µm and electrode width of 30µm. The frequency operation of 50MHz and input power of 20dBm were generated by a function generator. The signal was subsequently fed directly to the AIDT to generate F-SAW. A 0.5µl droplet of blue and dye was injected on the substrate. The progression of F-SAW mixing was observed using digital microscope. This process was repeated for every volume tabulated in Table 1. Various powers for the total volume of 1µl droplet were recorded.

3.3 Y-Junction Channel

The second experimental setup was carried out to examine the same type of mixing as in the first experiment, which were active and passive, to investigate diffusion and F-SAW mixing integrating enclosed space. The microfluidic system consisted of a Y-channel with two 1mm diameter inlet branches at the same angle to each other merging into a 4mm diameter circular-shaped chamber. Minimum surface area of circular channel exposed to the liquid reduces the friction between wall surface and liquid, hence requiring less energy to pump the water for a given flow rate. The Y-channel was designed and drawn using Coral Draw software followed by photolithography method to PDMS (Figure 2), which was then being poured onto the mold and baked for 1 hour.

Fig. 2. Y-channel PDMS in a container was baked in the oven for 1 hour before the tubing was made

Tubing was made at both branches using 1mm inner diameter puncher and PTFE tube connected at both inlets. A syringe pump controller (TS-2A Syringe Pump Controller Longer Pump) injected blue and yellow commercial water-diluted food colors into each branch of the Y-branch (See Figure 3).

(a) (b)

Fig. 3. (a) Syringe pump used to control the flow rate of both passive and active mixing. (b) RF generator used in active mixing to supply signal to device

From the end of the main channel, the mixing fluid was extracted. The experiments explored the effects of various fluid flow rates pumped at 3µl / min, 5µl / min and 10µl / min by the syringe pump while considering the stability of the microfluidic system as a whole (Figure 4). Using a mobile Samsung J7 Pro camera, fluid flow profiles were captured. Since vibration can cause small amounts of blurring, care was taken when recording images. While conducting experiments, the microfluidic device was tightly taped to a work desk using a cellophane tape to prevent blurring of the recorded images. It is worth mentioning that lighting might be varied between various experiments, hence led to different color contrast in the recorded images.

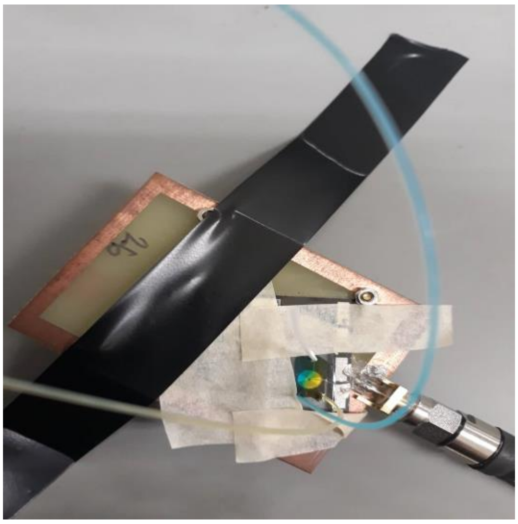


Fig. 4. A close-up top view of active mixing of the F-SAW device. Different dye colors were injected at both inlets to observe the time taken for mixing to occur

4. Result and Discussion

Micromixing snapshots by diffusion and F-SAW mixing with different volume were taken as shown in Figure 5 and Figure 6. From the Figure 5, it can be observed that the droplets have spread into liquid. This process utilized space and required longer time upon completion.

In Figure 6, F-SAW showed a constructive propagation of wave mixing following the shape of AIDT. From the center of droplet area, the internal flow of counter clockwise direction was observed. This process utilized low power yet produced faster response time for mixing completion compared to those of passive mixing.

From the first set of experiment, F-SAW mixing recorded shorter period of time than diffusion mixing at various total volumes of droplet. F-SAW and diffusion mixing recorded 38s and 240s of time for 1 µl droplet. As the volume of droplet increases, the time taken to complete mixing also increased for F-SAW and diffusion mixing.

Time taken to color changes was decreased with the increase in input power on F-SAW mixing as shown in Figure 7(b). Color changes from yellow and blue to green took shorter time as input power increases. Input power is an important performance parameter. Results analysis showed that maximum power has higher mixing efficiency of 84% for 1 µl droplet than minimum power. Therefore, the stronger of acoustic energy, the more efficient the mixing.

From the result as shown in Figure 8, mixing efficiency for F-SAW device was measured by manipulating the volume of droplets. F-SAW mixing showed an efficiency of 91-84% for 1-5µl droplets mix. F-SAW mixing was proven more reliable and efficient compared to passive diffusion mixing technique. Mixing efficiency was seen higher as volume of droplets increases. Therefore, large volume of droplets can be used in F-SAW mixer.

This study also demonstrates the mixing mechanisms for an enclosed microfluidic channel Y-junction where different fluid flow rates transported through the Y-junction microfluidic channel were studied. The flow rates manipulated for passive and active mixing in Y-channel microfluidic system were3µl/min, 5µl/min and 10µl/min. Micrometers dimensions for Y-channel tubing were80µm in height and 4mm chamber diameter of region of interest. Enclosed Y-channel was used in this study to identify the concept by integrating F-SAW in active mixing. This will induce shear stress on the interfacial surface that helps the mixing process; adopting an active mixer's structure while maintaining the system as a whole. This experiment also proved that mixing acts differently for two conditions; open and enclosed channels.

Results of mixing in Y-junction channel (passive and active mixing) show mixing profiles for the different flow rate conditions are shown below. Mixing profiles in Figure 9 shows different flow rates for passive mixing in Y-junction channel. When the flow rates were lower than 3µl / min at t=0min, little to no mixing was observed since molecular diffusion was only insufficient to promote mixing but after some time at t=3.42min, green color was observed. This differs from the case of higher flow rate of 5µl/min where self-mixing was observed based on the intensity of green color formed as early as 2.26min. When the flow rate was set higher at 10µl/min, shorter time was taken for the mixing to occur as the yellow and blue dye colors change to green as early as 1.23min with the intensity of green color that increased when t=3min.

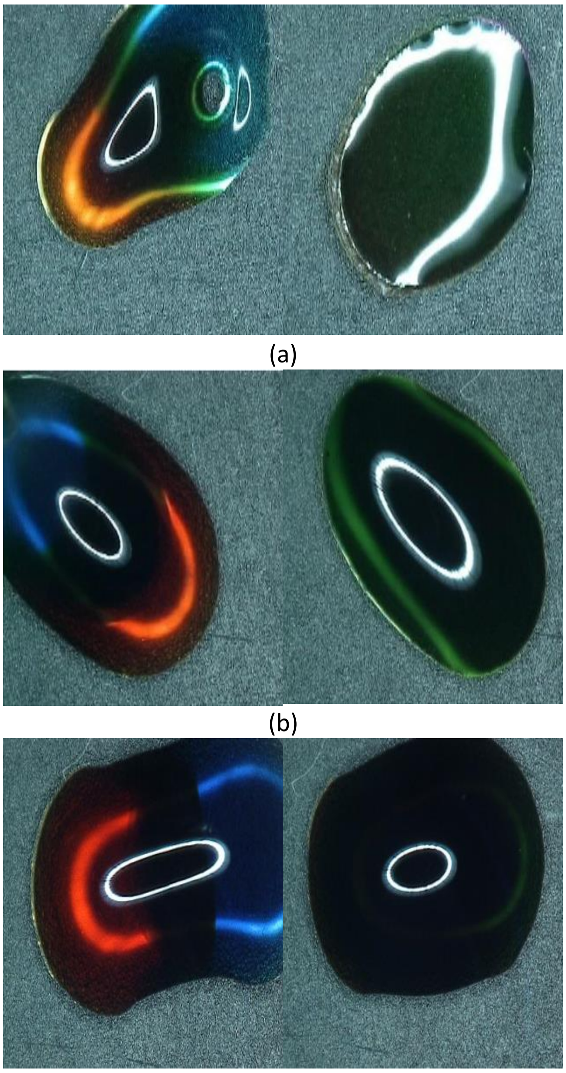
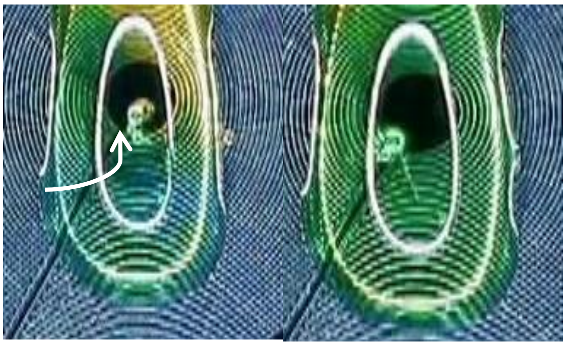
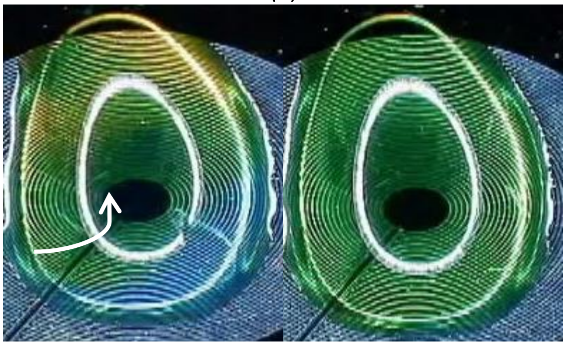


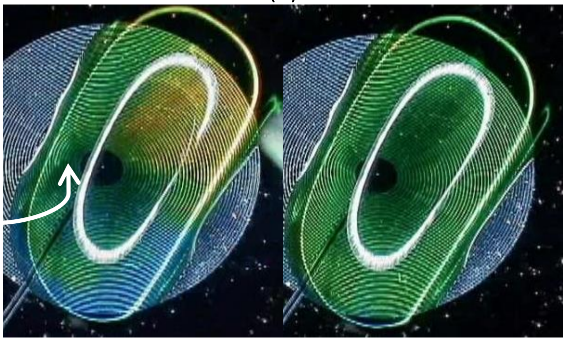
Fig. 5. Complete diffusion mixing a) 1µl at t=240s, b) 3µl at t=300s and c) 5µl at t=420s



(a)

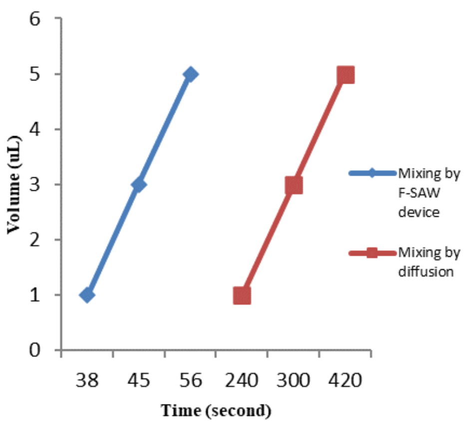


(b)

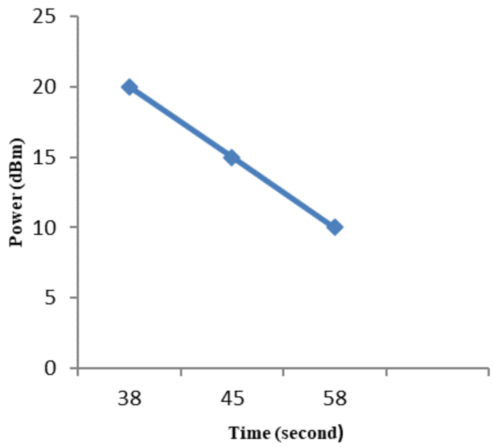


(c)

Fig. 6. Complete F-SAW mixing a) 1µl at t=38s b) 3µl at t=45s and c) 5µl at t=56s



(a)



(b)

Fig. 7. (a) Volume effects on diffusion and F-SAW mixing and (b) Input power effects on F-SAW mixing

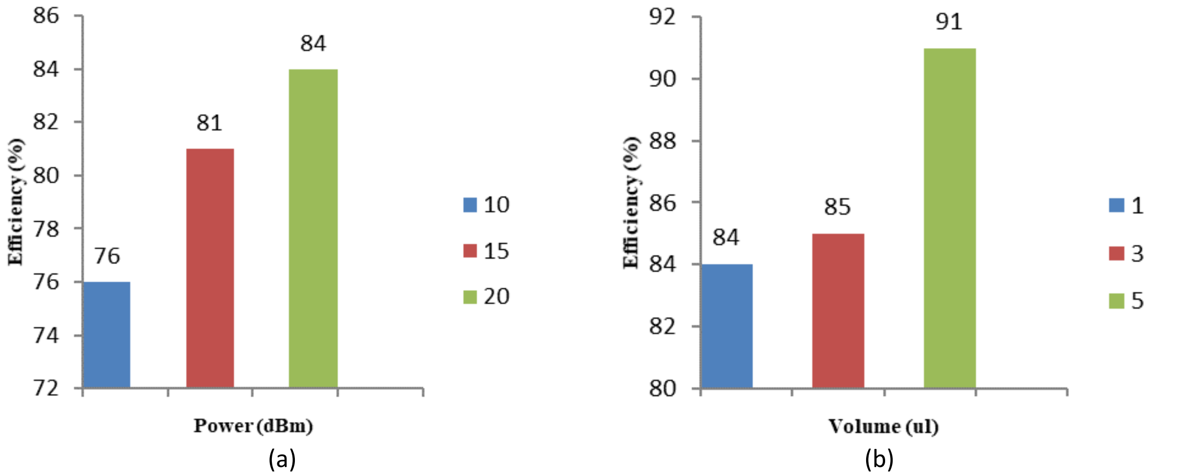


Fig. 8. (a) F-SAW device efficiency for 1μl droplet mixing and (b) Mixing efficiency of F-SAW device

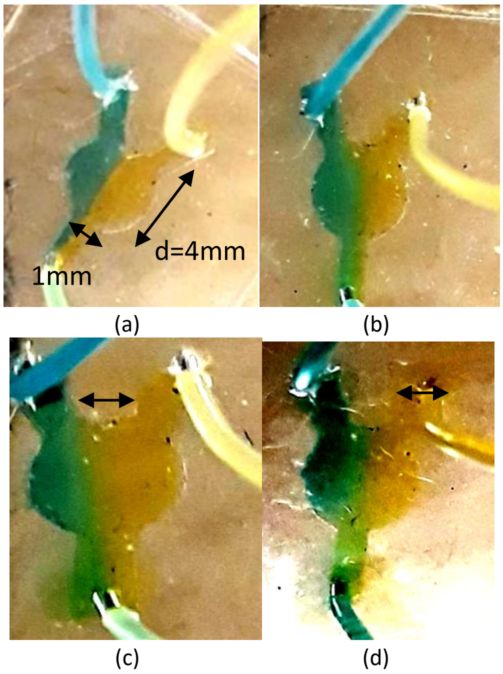
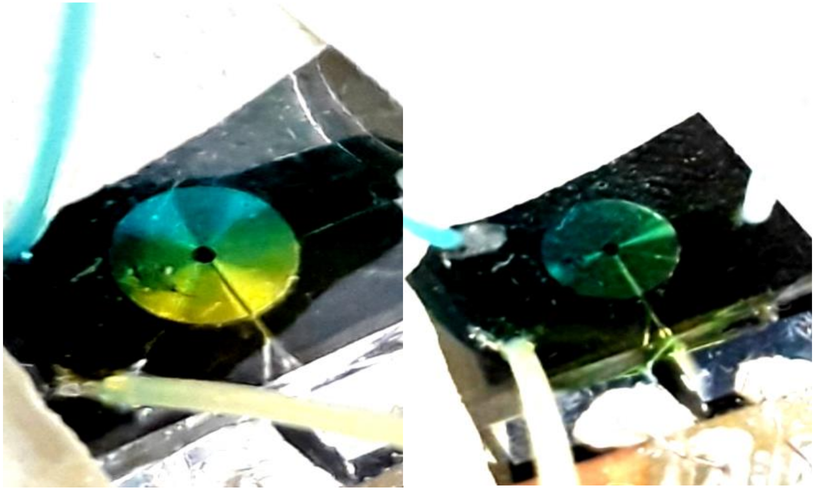


Fig. 9. (a) Flow rate of 3μl/min at time=0s, (b)Flow rate of 3μl/min at time=3.42min, (c) Flow rate of 5μl/min at t=2.26min, (d) Flow rate of 10μl/min at t=1.23min

In the first set of experiments, fluid was introduced in the two branches of the Y junction and removed at the base; no external disturbance was imposed. Therefore, any mixing that occurred was in passive nature. Images below show the fluid at a range of different flow rates through the junction. The flow rates used in this experiment were3μl / min, 5μl / min and 10μl / min. It is worth mentioning that the flow across the open junction did not involved any disturbances and was stable during the mixing. Secondly, it can be seen that the yellow and blue streams converged at the junction and continued to flow as separate streams into the chamber for the lower flow rate as shown in Figure 9(a),(b) and (c). For higher flow speeds, self-mixing happened as per Figure 9(a) and (b). Mixing was also observed to occur rapidly in (c) and (d) (in space). The mixing at the extraction end was not total as can be seen from image (d). Slower flow rates may occur at the output channel due to viscous forces since the outlet diameter was smaller than the channel width and fluid height at these locations, showing unmixed fluid. However, the output fluid in the glass was found to be mixed. Color intensity of fluid was observed in comparing the mixing distribution for different fluid flow rates.

Active mixing in Y-junction channel was carried out by integrating an F-SAW device placed beneath the Y-junction channel. F-SAW propagate wave and theoretically performed mixing for the two different color liquids. As per Figure 10(a), even at t=0min, green color mix can already be observed with mixing efficiency that was much higher for Y-channel active mixing compared to Y-channel passive mixing since it took shorter time to complete compared to Y-channel mixing without the introduction of F-SAW device. Higher flow rate was manipulated for the second set of experiments and the results are shown in Figure 11.



(a) (b)

Fig. 10. (a) Flow rate of 3µl/min at t=0min and (b)Flow rate of 3µl/min at time=1.30min

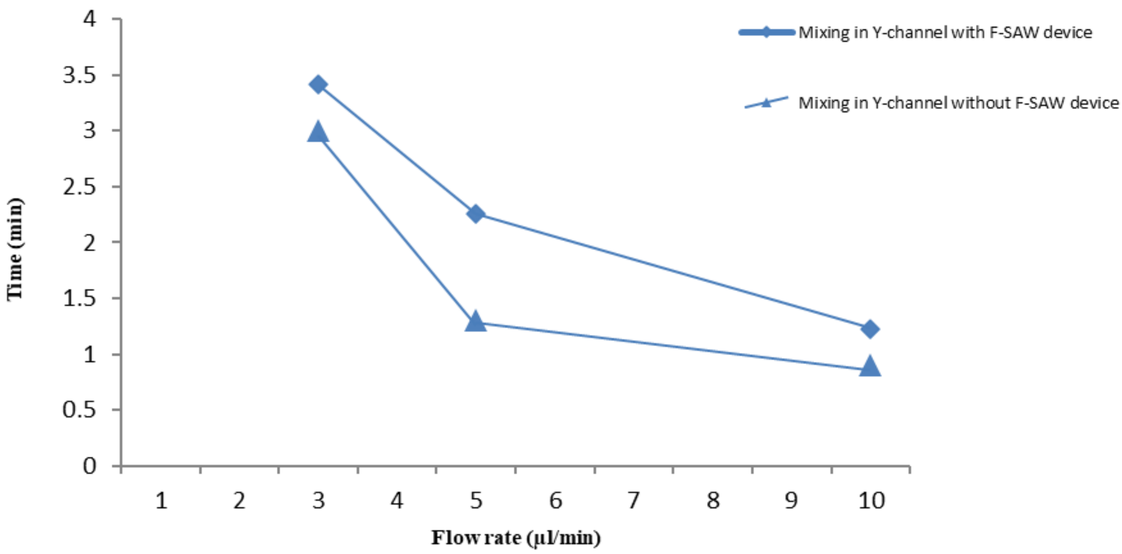


Fig. 11. Different effects of flow rate on time for mixing in Y-channel with F-SAW and without F-SAW device

Using the Stokes flow rule, microfluidic systems operated where viscous forces overwhelm inertial effects at low flow rates. Due to the laminar nature of the flow, blue and yellow liquid flowed according to the pressure gradient; thus, mixing within space occurred via molecular diffusion. Liquid color changes in the mixing chamber were resulted from the manipulation of different fluid flow speeds. Mixing time shorten as the process reaches a higher flow speed due to the different fluid velocities in the mixing region.

To compare both sets of experiment, nature of the channel was discussed where the fluid motion varied according to the nature of the channel. Random motions promoted stirring in the flow. Therefore, fluid freedom in the open channel enhanced the effect of perturbations compared to that of a closed system such as Y-channel as can be seen in experiments 1 and 2. As per case of enclosed system, fluid was bounded by solid on one surface and other surface disturbances by surface acoustic waves, which was explained by Figure 11 where the time taken for mixing in Y-channel with F-SAW was shorter than that without F-SAW.

5. Conclusion

In conclusion, the mixing of two droplets utilizing passive diffusion method and F-SAW device has been demonstrated. When fluid flowed in Y-channel, different mixing profiles were observed. In a passive mixing system, fluid flow rates played an important role in the mixing process as higher flow rates influence the mixing of fluid despite the propagation of acoustic wave in active mixing. While high flow rates can cause mixing in open channels, lower flow rates require an active intervention source to achieve this result. This can be provided by surface acoustic wave device that gives rapid mixing to the chaotic mixing. Therefore, mixing in open channels with and without interference can be shown as a phase in more complicated open fluidic networks as they are developed. Mixing process performed by F-SAW device produced fast response, thus being more efficient compared to passive method despite the condition of mixing in open or enclosed (Y-junction channel) environment. This low powered device has the efficiency of 91-84% for mixing 1-5 µl droplets. Mixing process using F-SAW device can be very useful for future biomedical and chemical analyses.

Acknowledgement
Authors would like to gratefully acknowledge the financial support by the Universiti Kebangsaan Malaysia (UKM) and the Ministry of Education of Malaysia through a grant project (code no: GGPM-2017-035).

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