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Design and analysis of liquid mixing in a novel serpentine trapezoidal micromixer

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---ABSTRACT---

Micromixers are most essential components of µTAS (micro Total Analysis System) for carrying biochemical and biomedical analyses. Serpentine type passive micromixers are one of the simplest and effective mixing devices employed in various applications. They incur low cost of manufacturing, easier fabrication and integration. Among serpentine micromixers (curved, zig-zag and square wave), it is reported that square-wave type micromixer showed better mixing characteristics. In our previous study, it is found that square wave micromixer with convergent and divergent horizontal sections (sqw-cd) performed significantly better mixing. However, this design of micromixer (sqw-cd) is associated with considerably higher pressure drops. In the present study a novel design of serpentine trapezoidal micromixer has been proposed. The performance of mixing in serpentine trapezoidal (trap) micromixer is estimated for Re of 2 to 100. The results indicate higher quality of mixing with trap micromixer as compared to conventional square-wave micromixer (sqw) for Re above 20. The effective secondary flow phenomenon in trap mixer above Re of 20 compared to sqw mixer has improved the efficiency of mixing. But the performance of mixing in trap mixer remained low as compared to sqw-cd mixer in the Re range of 2 to 100. However, the pressure drop in trap mixer is substantially low as compared to sqw-cd mixer and sqw mixer. Therefore, it is observed that for the expense of same pressure drop, shorter mixing lengths can be obtained with a trap mixer as compared to sqw-cd mixer or sqw mixer.

KEYWORDS;- *Mixing quality, Passive micromixer, Square-wave mixer, Trapezoidal mixer*

I. INTRODUCTION

The reduced dimensions of micromixers substantially improved mass transfer efficiency and resulted in various advantages of very low reagent consumption, process safety in case of explosive reactions, straight-forward integration with other miniaturized components, portability and rapid mixing. Micromixers are utilized in various applications in the field of bio-medical and bio-chemical engineering [1] for protein folding studies, DNA micro-arrays, enzyme assays, drug screening, cell culturing, cell lysis and circulating tumour cell detection. In chemical engineering, they are utilized in applications such as organic synthesis, crystallization, polymerization, and extraction and chemical reaction kinetic studies. Nowadays they are also widely employed as microreactors for the synthesis of biodiesel [2]. Micromixers are two types viz., active and passive micromixers. Active micromixers employ an external energy source like ultrasonic[3], acoustic wave [4], magneto-hydrodynamic [5] or electro-kinetic instabilities [6]. Passive micromixers do not employ external energy source but require only pressure head to force sample and reagent inside micromixer. The flow of samples in passive mixer channel structures itself can induce stretching, folding, splitting and recombining or chaotic advection in order to achieve mixing [7]. The passive type micromixers are preferred for many applications as they are easier to fabricate and integrate, and also incur low cost of manufacturing.

Among various types of passive micromixers such as staggered herringbone mixers [8], split-and-recombine mixers [9], three-dimensional mixers [10] and Tesla mixers [11], serpentine micromixers are most simple structured and planar mixing devices. Hossain et al [12] studied three types of passive mixers viz., serpentine square, zig-zag and curved wave mixers. It is found that below a *Reynolds number* of 15, mixing is governed by molecular diffusion whereas above a *Re* of 15, chaotic advection is initiated in all three mixers. The degree of transverse directional movement is higher in the case of square wave micromixers and therefore an efficient mixing is obtained with square wave micromixer as compared to other two mixers. Nonino et al [13] also evaluated mixing performance of three different micromixers, zig-zag, and square and curved wave micromixers in the *Re* range of 5 to 150. It is found that square wave micromixer shows better mixing and superior to other mixer configurations. Kuo et al [14] carried out experiments to optimize a square wave micromixer for blood-plasma mixing. They found that an optimum structure of square wave mixer with varying width through length can deliver better mixing as compared to constant width square wave micromixer.

It is concluded that serpentine square wave designs [12-14] are simple and effective planar micromixers. To further enhance the performance of mixing at the expense of lower pressure drops, serpentine trapezoidal micromixer is proposed in the present study. Therefore, the mixing quality is evaluated for *Re* of 2 to 100 in four different configurations viz., square wave mixer without convergent and divergent sections (sqw mixer) and with convergent and divergent sections (sqw-cd mixer) and serpentine trapezoidal (trap) mixer with full length and reduced length and has been compared with each other.

II. METHODOLOGY

Mathematical Modeling

The governing equations of the fluid flow in micromixer are

$$\nabla \cdot V = 0 \tag{1}$$

$$V \cdot \nabla V = -\frac{1}{\rho}\nabla P + v\nabla^2 V \tag{2}$$

where, '*V*' denotes velocity vector, 'ρ' denotes density, '*p*' denotes pressure, and '*v*' denotes kinematic viscosity of the fluid.

The governing equation for mass transport is given by

$$(V \cdot \nabla)c = D\nabla^2 c \tag{3}$$

where, '*c*' denotes concentration and '*D*' denotes coefficient of diffusion.

The mixing quality 'α' is

$$\alpha = 1 - \sqrt{\frac{\sigma_M^2}{\sigma_{\max}^2}} \tag{4}$$

where, $\sigma_{\max}^2$ is the maximum variance of concentration and σ_M^2 is the variance of concentration on a cross-section which is

$$\sigma_M^2 = \frac{1}{n}\sum_{i=1}^{n}(c_i - \bar{c}_M)^2 \tag{5}$$

where, $\bar{C}_M$ is the mean value of concentration of *n* elements of mesh in a cross-section. The value of mixing quality 'α' is 'zero' for no mixing and 'one' for complete mixing.

Numerical Modeling

The schematics of serpentine sqw mixer, sqw-cd mixer and trap micromixers are shown in figures 1a, 1b and 1c respecteively. The total length of all mixers is taken as 3400 µm whereas height of channels is considered as 100 µm. The grid in whole domain of all three types of micromixers is generated with hexahedral elements. Hexahedral mesh results in more accuracy and less computational time as compared to tetrahedral elements due to the alignment of hexahedral elements in the flow direction.

(a) (b)

(c)

Fig 1: Schematics of (a) sqw mixer (b) sqw-cd mixer (c) trap mixer

ANSYS Fluent, is employed for solving the fluid flow and mass transfer in three different mixer configurations. Samples are nameed as species '*a*' and '*b*', and assigned the liquid water properties at 20°C (ρ = 998.2 kg/m^3, μ = 0.001 Pas and D = 2 x 10^{-9} m^2/s) for all the simulations. The concentration in terms of the mass fraction for the boundary condition is set to one for species 'a' and set to zero for species 'b' at the left inlet and vice versa at the right inlet. The outlet pressure of all micromixers are assigned with atmospheric pressure. The boundary conditions are provided in Table 1. No-slip boundary condition is applied at walls.

Case	Velocity at left inlet (m/s)	Velocity at right inlet (m/s)	*Reynolds* number
I	0.02	0.02	2
II	0.05	0.05	5
III	0.1	0.1	10
IV	0.2	0.2	20
V	0.3	0.3	30
VI	0.65	0.65	65
VII	1	1	100

Table 1: Boundary conditions used in numerical simulations

III. RESULTS AND DISCUSSION

Grid Independence Test

Figure 2 shows the change of velocity profiles at the centreline of outlet of trap mixer (*Re* = 30). The minimum deviation is observed between 1207753 elements and 853500 elements. Therefore, the 853500 hexahedral elements grid is selected.

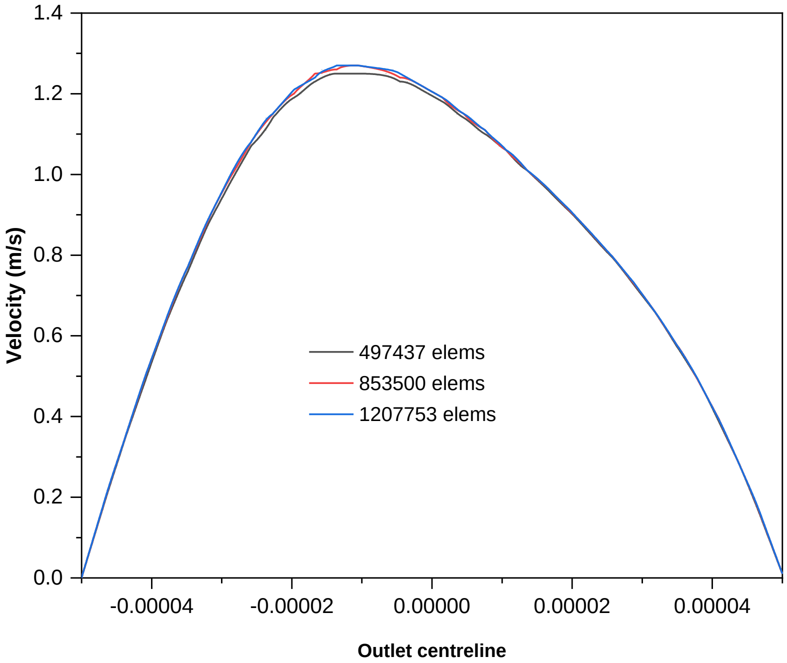


Fig 2: Change in velocity profiles with different grids of trap mixer

Mixing performance of different serpentine mixers

The mixing performance of different serpentine mixers viz., sqw mixer, sqw-cd mixer and trap mixer is estimated for *Re* of 2 to 100 as shown in Fig. 3. It is observed that at lower flow rates (2 < *Re* < 10), due to laminar regime, mixing is diffusion dominant and it is proportional to residence time. Therefore with increase in *Re* mixing quality decreases. However for *Re* > 10, mixing relies on both diffusion and convection. Therefore with increase in *Re* in this regime convective effects dominate and mixing increases. The mixing performance of trap mixer is mainly focused in the current study and has been discussed in detail.

Mixing performance of trapezoidal mixer at different Re

At low *Re* (*Re* < 20), the mixing performance of trap mixer is very low as compared to sqw or sqw-cd mixers (Fig. 3). The repeating units in trap mixer are very less as compared to other mixers which reduce the residence time of samples and thereby decrease mixing. With increase in *Re* (*Re* > 20), the mixing quality of trap mixer with full length (L = 3400 µm) showed a considerable increment in comparison with conventional square-wave mixer. However, the reduced length (L = 2735 µm) trap mixer also performed better than square-wave mixer for *Re* > 20. Even though the number of repeating units is less in trap mixer, increase in inertial forces at higher *Re* and the backward inclined channels of trap mixer caused more stretching and vortices (Fig. 4c) as well as sustained the secondary flows for an extended period of time in the channels as compared to sqw mixer (Fig. 4a) or sqw-cd mixer (Fig. 4b).

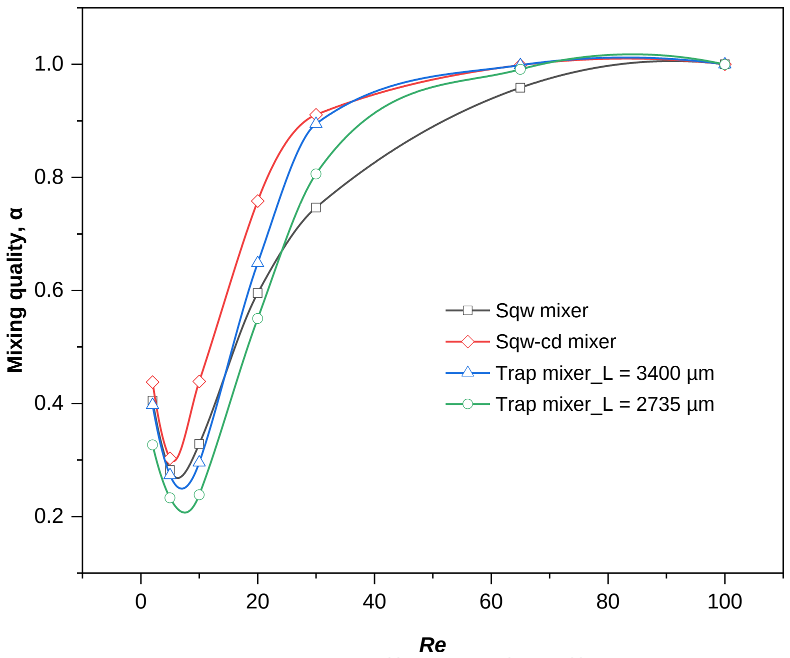
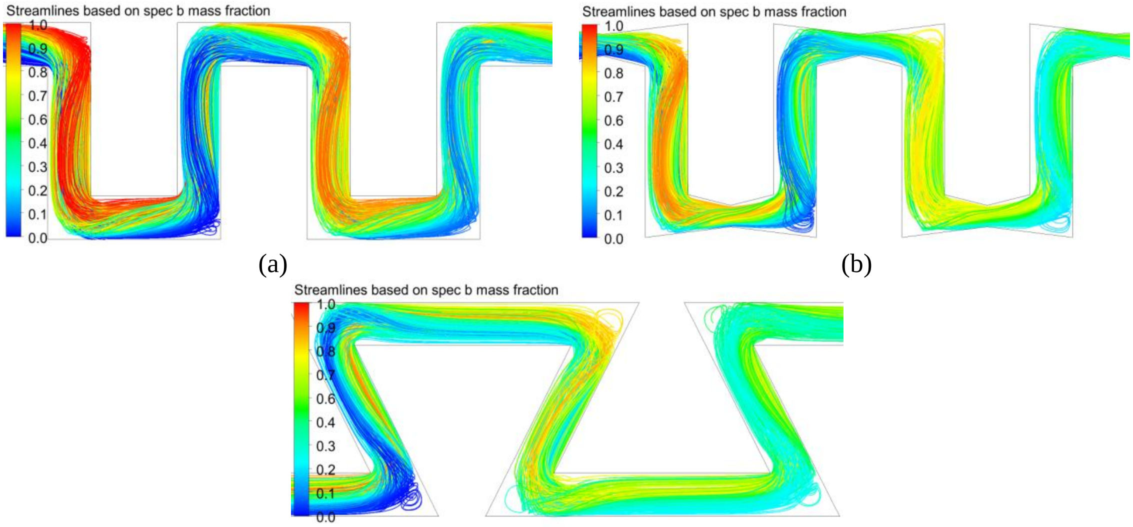


Fig 3: Change in mixing quality with different *Re* for different serpentine mixers



(a) (b) (c)

Fig 4: Streamline contours at a *Re* of 30 in the case of (a) sqw mixer (b) sqw-cd mixer (c) trap mixer

Pressure drop and mixing quality comparison of different mixers

The comparison of pressure drop and mixing performance of different serpentine mixers is plotted as shown in Fig. 5. It is observed trap mixer with full length (L = 3400 µm) is performing considerably better than all other mixer configurations for *Re* above 5. A nearly equivalent mixing performance is also witnessed by trap mixer with reduced length (L = 2735 µm). Particularly, trap mixer with full length (L = 3400 µm) is very efficient than other serpentine mixers in the pressure drop range of 10 to 35 kPa. Trap mixer with reduced length

(L = 2735 µm) is efficient in the pressure drop range of 5 to 60 kPa compared to sqw mixer. Therefore with serpentine trap mixer a better mixing can be obtained at the expense of smaller pressure drops along with a shorter length of mixing channel.

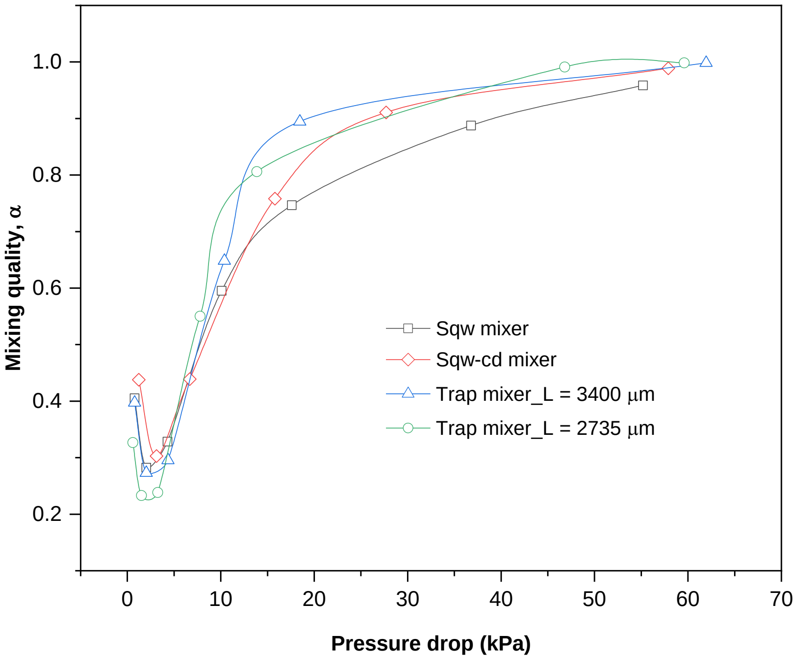


Fig 5: Change in mixing quality with pressure drop in different serpentine mixers

IV. CONCLUSION

The mixing performance of three different serpentine mixers viz., square wave (sqw mixer), square wave with convergent and divergent sections (sqw-cd mixer) and trapezoidal (trap mixer) is evaluated for *Re* of 2 to 100 mainly focusing on trap mixer. The laminar regime of diffusive mixing and less number of repeating units has resulted in lower mixing performance of trap mixer at low *Re* (*Re* < 20) compared to sqw or sqw-cd mixers. For *Re* above 20, the mixing performance of trap mixer with full length (3400 µm) is significantly higher than sqw mixer and nearly equivalent to sqw-cd mixer. Trap mixer with reduced length (L = 2735 µm) has also shown considerably higher mixing performance compared to sqw mixer while it is lower compared to sqw-cd mixer or trap mixer with full length. The better mixing obtained by trap mixer in comparison with conventional sqw mixer for higher *Re* (*Re* > 20) owes to the backward orientation of channels which increased stretching and vortex formation as well as sustaining the secondary flows for an extended period of time in the channels. From the pressure drop and mixing quality comparison, it is observed that trap mixer with full length (L = 3400 µm) is very efficient than other serpentine mixers in the pressure drop range of 10 to 35 kPa whereas trap mixer with reduced length (L = 2735 µm) is efficient in the pressure drop range of 5 to 60 kPa compared to sqw mixer. Therefore, serpentine trapezoidal mixer (trap mixer) is the most efficient alternative to conventional sqw mixer in the pressure drop range of 5 to 60 kPa which also allows shorter lengths of mixing channel with a higher mixing quality.

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