William L. N. Buglie[1]
Khairul Fikri Tamrin[1,*]
Nadeem Ahmed Sheikh[2]
Mohd Fairus Mohd Yasin[3]
Shahrol Mohamaddan[1,4]

Enhanced Fluid Mixing Using a Reversed Multistage Tesla Micromixer

A two-dimensonal Tesla micromixer is experimentally characterized at varying Reynolds numbers (*Re*) and valve stages with the aim to acquire sufficiently high mixing performance. To ease fabrication, a simplified Tesla valve design is adopted. Results show two distinctive regimes of low and high *Re*. In the low-*Re* regime, a steady incremental mixing was observed as the fluid passes by each valve, whereas an enhanced mixing was identified right in the first valve in the high-*Re* regime. This is predominantly due to the amplified opposing flow from the helix branch which promotes stronger chaotic advection in the main microchannel. Interestingly, the measured mixing performance was found comparable to that of three-dimensional passive micromixers reported in the literature.

Keywords: Microfluidics, Micromixer, Mixing index, Mixing performance, Reversed multistage Tesla micromixer

Received: January 25, 2022; *revised:* April 09, 2022; *accepted:* May 10, 2022

DOI: 10.1002/ceat.202200055

1 Introduction

In microfluidics, scaling down standard laboratories setups to the micrometer (µm) scale demonstrates a large volumetric reduction of the sample amount required for rapid and efficient analysis. This relies on efficient fluid mixing for high throughput. Microfluidic mixing is generally categorized into two main groups, namely, active and passive mixing [1–3]. In particular, an effective mixing in a passive micromixer can be accomplished by manipulating the pattern/structure of microchannels. Additionally, the integration with other microfluidic devices (micropumps, microreactors, etc.) is less complex [4].

A number of passive micromixers with complex three-dimensional (3D) microchannel patterns/designs have been studied in the past. Chen et al. [5] simulated a micromixer with cross-wise ridges placed inside the microchannel and compared the mixing performance with a conventional Y-micromixer. The result shows an increased mixing which can be attributed to a significant amount of split and recombination (SAR) helical flows produced by the embedded ridges. Shah et al. [6] designed a Y-micromixer with circle-split-and-recombination (YCSAR) elements to generate chaotic advection and Dean vortices. Xie et al. [7] studied a micromixer with semicircle mixing elements to stretch and perturb flow in the microchannel. Although the mixing mechanism was dominated by convection rather than diffusion, these complex 3D patterns are easier to simulate numerically than physically constructed due to space restriction and miniaturization issues that need to be addressed to achieve the required precision.

Several numerical studies have been conducted to evaluate key design features on flow characteristics of the Tesla valve in the reverse direction. Mohammadzadeh et al. [8] studied the performance of the Tesla valve as a function of diodicity (ratio of reversed pressure drop to the forward pressure drop) and discovered that the diodicity increases with higher Reynolds number. Qian et al. [9] also identified that the pressure drop within the valves rises with the flow rate in both forward and reverse flows, with the latter being the larger since the fluid flows mostly into the helix channel than the main channel. This agrees well with the findings by Porwal et al. [10] who further showed that heat transfer enhancement in reversed flow was attributed to the flow bifurcation and fluid stagnation. Furthermore, it has been numerically demonstrated that suitable embedment of obstacles in the shape of plates [11] and diamond [12] within the Tesla valve was capable of significantly enhancing the mixing performance.

Although there is a growing number of numerical studies reported in the literature concerning Tesla valves, the experi-

---

[1] William L. N. Buglie, Dr. Khairul Fikri Tamrin, Prof. Dr. Shahrol Mohamaddan
tkfikri@unimas.my
Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia.

[2] Prof. Dr. Nadeem Ahmed Sheikh
Department of Mechanical Engineering, Faculty of Engineering, International Islamic University, Islamabad, Pakistan.

[3] Dr. Mohd Fairus Mohd Yasin
High Speed Reacting Flow Laboratory, School of Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, Johor, Malaysia.

[4] Prof. Dr. Shahrol Mohamaddan
Department of Bioscience and Engineering, College of Systems Engineering and Science, Shibaura Institute of Technology, Saitama, Japan.