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Fluid mixing in a microchannel with longitudinal vortex generators

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HIGHLIGHTS

- Fluid mixing in a T-shaped microchannel with winglet pairs was investigated.
- Divergent winglet pairs may generate longitudinal vortices to enhance mixing.
- Gaps formed by winglets and the channel sidewall may induce fast mixing.
- Taguchi method is applied to find out a better combination of geometrical parameters.
- Both simulation and experiment results show interface distortion due to winglets.

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ABSTRACT

A heat transfer enhancement technique based on longitudinal vortex generators (LVGs) has been well established for large-scale heat exchangers. Motivated by the success of the LVGs, this paper is intended as an investigation of micromixers based on the T-shaped channel with rectangular winglet pairs (RWPs) mounted on the bottom of the main channel. The RWPs stay with an angle of attack to the main flow direction and generate longitudinal vortices to enhance fluid mixing. The effects of geometrical parameters on the performance of micromixers with micro-scale LVGs are investigated by numerical simulations and the Taguchi method. The validity of numerical simulations is examined by comparing the numerical and experimental results. The results obtained for a wide range of Reynolds numbers show that the mixing efficiency of the micromixer with divergent RWPs is greater than that of the micromixer without RWPs for convection-dominant cases as well as diffusion-dominant cases. A static Taguchi analysis shows that the relative effectiveness of the geometrical parameters can be ranked as: asymmetry index > angle of attack > winglet height > winglet spacing. Based on the relative influence of the geometric parameters, we can obtain an optimal parameter group on the parameter selected range.

1. Introduction

The micromixer is an important component in the microfluidic systems which have wide applications for biomedical analysis and chemical synthesis [1–3]. The small Reynolds number appearing in most microfluidic systems is related to laminar flow. Here, the Reynolds number is defined as $Re = \bar{u}d_h\ \nu^{-1}$ with $\bar{u}$, d_h and ν denoting the characteristic value of flow velocity, the hydraulic diameter of the main channel and the kinematic viscosity of the fluid, respectively. Thus, the mixing between different species relies heavily on mass diffusion. To enhance the mixing performance effectively, various methods have been reported in the last two decades [1–3]. A micromixer can be classified either a passive or an active type depending on its working mechanism. Active micromixers generally require *external* power *sources* for mixing enhancement and usually yield good mixing. However, their fabrication cost is high and integration with other devices is not easy. Therefore, passive micromixers are widely developed. An efficient technique for mixing enhancement is to insert obstacles into the microchannel or to build baffles on the walls of the microchannel to induce lateral flow [4–6]. Various microchannel structures such as bending, curved and/or converging-diverging channel which induces lateral advection in the flow [6–11] and other designs such as channel confluence, lamination, hydrodynamic focusing and impinging [11–16] have been developed to enhance the mixing of fluids in passive micromixers. Stroock et al. [17] have showed that chaotic mixing can be achieved in a straight microchannel with patterned grooves on the channel bottom at low *Re*. Besides, there are two passive micromixers having geometries similar to conventional mixers, including those based on a series of rigid elements that form intersecting channels to split, rearrange and combine the component streams and those constructed by right-handed and left-handed short-helix elements arranged alternately, have been fabricated by Bertsch et al. [18]. They have shown that the micromixers analogous to those large-scale mixers can yield good mixing efficiency.

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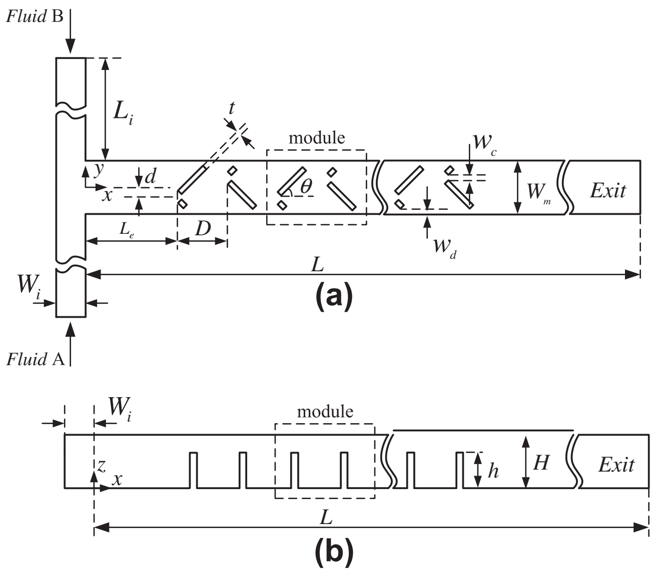

Fig. 1. Schematic diagram of the microchannel with divergent RWPs: (a) top view and (b) side view.

Table 1
Values of geometrical parameters.

No.	Parameter	Level		
		1	2	3
A	θ	22.5°	45°	90°
B	h	$0.5H$	$0.75H$	$0.875H$
C	d	$0.25W_m$	$0.167W_m$	$0W_m$
D	D	$1.75W_m$	$1.5W_m$	$1.25W_m$

A heat transfer enhancement technique based on longitudinal vortex generators (LVGs) has been well established for large-scale heat exchangers [19]. The longitudinal vortices (LVs) have their axes parallel to the main flow direction. The phenomenological similarity of convective heat and mass transfer suggests that the enhancement mechanism for heat transfer should basically also work for mass transfer. Nevertheless, there are only a few investigations considering the effects of longitudinal vortices on mass transfer or mixing in large-scale flows. Kaniewski et al. [20] presented a numerical study of mixing two laminar streams of different gases at $Re = 250$ in a large-scale rectangular channel by LVs generated by a pair of rectangular winglets. Ferrouillat et al. [21] applied numerical simulations with turbulence model to study heat transfer and mixing in a channel with vortex generators. The success of the downscaling mixers reported by Bertsch et al. [18] arouses our interest in the applicability of the LVGs to mass transfer enhancement in microchannels. Most of investigations done for heat transfer enhancement in channels with LVGs

Table 2
L_9 (3^4) orthogonal array.

Case	Parameter			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

examined the performance of large-scale LVGs. Fiebig [22] has examined the performance of LVGs in the rectangular channel on the order of mini-scale in the range of Re from 1000 to 50,000 and very recently Liu et al. [23] investigate the heat transfer enhancement of rectangular channels with LVGs at micro-scale in the range of Re from 150 to 1200. Kaniewski et al. point out that a LV needs to be generated with an axis between the two (frequently parallel) streams in mass transfer configurations [20]. This is different from the manipulation of the wall layer by LVGs for heat transfer enhancement in heat exchangers.

This paper is intended as an investigation of micromixers with geometries similar to the above devices with LVGs for heat or mass transfer enhancement. The vortex generators considered are pairs of rectangular winglets built on the microchannel bottom and staying with an angle of attack to the main flow direction. The LVs generated by the pressure difference at the front and back sides of the winglets persist downstream of the location of the winglets, and so enhance mixing of the fluids in the rectangular channel. Scaling down of the micromixers raises some new issues, among which the Re is much smaller than that considered in the literature above [19–23]. Moreover, the gap between the winglets or between one of the winglets and the channel sidewall may induce fast mixing between fluid streams, because the throttling by the gaps considerably decreases the mixing length [24]. Therefore, the use of downscaling LVGs to form micromixers still needs to be carefully evaluated for their applicability to micro-mixing.

The Taguchi method [25] is a powerful tool for experimental optimization. It has been used not only to reduce the number of experiments, but also to analysis the sensitivity of parameters for passive micromixers [26], to optimize geometric characteristics of a grooved micromixer [27] and to design an active micromixer [28]. In this work, we adopt numerical simulations and the Taguchi method to investigate the effects of geometrical parameters on the performance of micromixers with micro-scale LVGs. The validity of numerical simulations is examined by comparing the numerical and experimental results.

2. Micromixer design

The present design of micromixers is based on the T-shaped channel with rectangular winglet pairs (RWPs) mounted on the bottom of the straight main channel, as shown in Fig. 1. The winglets with height (h) protrude into the flow at an angle of attack (θ). The geometrical dimensions are expressed in terms of channel

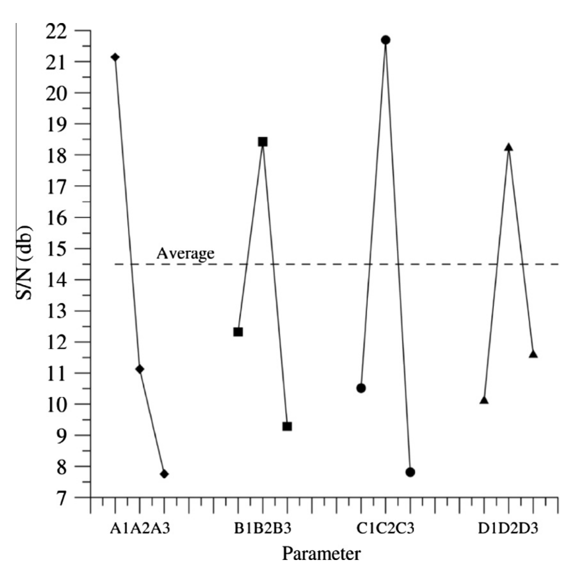

Fig. 2. Influence of design parameters (listed in Table 1) on signal to noise ratio.