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A novel design for passive micromixer based on Cantor fractal structure

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Abstract

This paper presents a simple and convenient rectangular fractal micromixer, called imitate Cantor structure (ICS). According to the principle of enhancing chaotic advection and folding fluid, it can produce better mixing performance. We study this new structure that a geometry microchannel is designed with reference to the Cantor structure. Simulations is researched using multi-physics field simulation software COMSOL 5.2a based on finite element theory. This paper will compare with fractal obstacle number, fractal obstacle series, fractal obstacle height, fractal obstacle spacing, as well as at various flow velocities. The results indicate that as the flow velocity increase, the mixing performance shows a V-type trend. Through observation of fluid flow in microchannel, we clearly see the chaos vortex promotes the mixing of the fluid. After multiple comparisons, we select the best structure to form the ICS micromixer.

1 Introduction

In recent years, microfluidic technology has induced increasing attention. The mixing of fluid is important in many microfluidic systems such as lab-on-a-chip and micro-total analysis systems. In a broader sense, common applications include sample preparation analysis, biomedical engineering and chemical engineering. Rapid and effective mixing are crucial in many microfluidic systems such as biochemical reactions (Jeon and Shin 2009; Chau et al. 2003; Lu et al. 2002; Whitesides 2006). As an important component, micromixer acts the role of mixing two or more species for analysis in bioengineering and chemical engineering. According to works reported by many researchers, micromixers can be divided into two categories: active and passive micromixers (Chen and Li 2017). Active micromixer need a variety of fields, for example, a magnetic field, an electric field, or the like is required. The flow in the channel is perturbed by liquid flow (Oddy et al. 2001; Niu et al. 2006; Sritharan et al. 2006). Manufacturing active micromixer is complex, not suitable for mass production. However, the passive

micromixer is not usually complex, just need to design microchannel structure to change the mixing efficiency.

In recent years, many scholars have carried on many studies of passive micromixer. Multifarious research and design methods of passives micromixer are applied by scholars. Their aim is to improve the mixture mixing efficiency. Hong et al. (2001) designed an innovative in-plane passive micromixer by the "Coanda effect" and simulation. Bhagat et al. (2007) reported, designed, simulated, fabricated a planar passive microfluidic mixer capable of mixing at low Reynolds numbers. Tofteberg et al. (2010) designed a passive micromixer of lamination in a planar channel system. Chen and Shen (2017) through the numerical analysis designed two types of E-shape micromixers, and designed a novel passive micromixer by applying an optimization algorithm to the zigzag microchannel (Chen and Li 2017). In this paper, a new passive micromixer based on T-type microchannel is designed with reference to the Cantor structure, and several key factors influencing the mixing efficiency are tested by numerical simulation. This paper presents a simple and convenient imitate Cantor structure (ICS) micromixer. We will study this new structure through finite element theory, from fractal obstacle number, fractal obstacle series, fractal obstacle height, fractal obstacle spacing, as well as at various flow velocities to compare. After the comparing, we can obtain the optimal microchannel structure to form the ICS micromixer.

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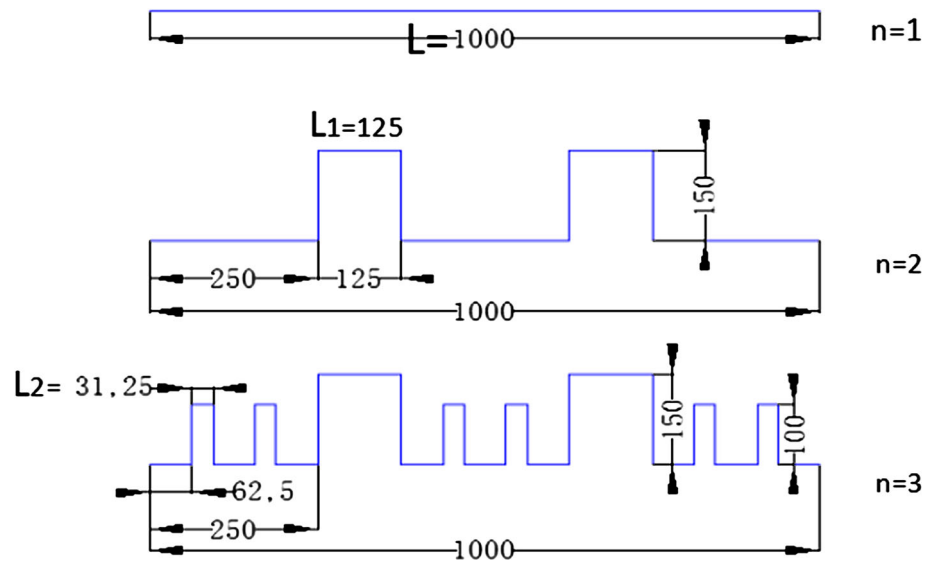Fig. 1 The fractal obstacle geometric structure formed by imitating of the Cantor structure (unit: μm)

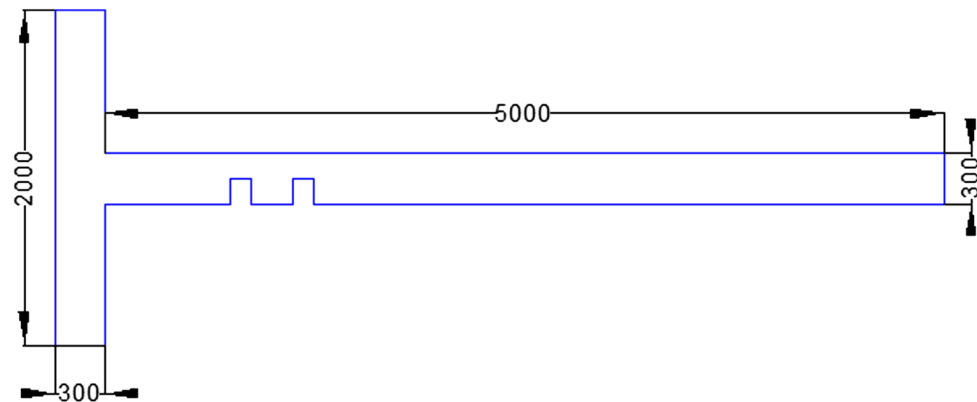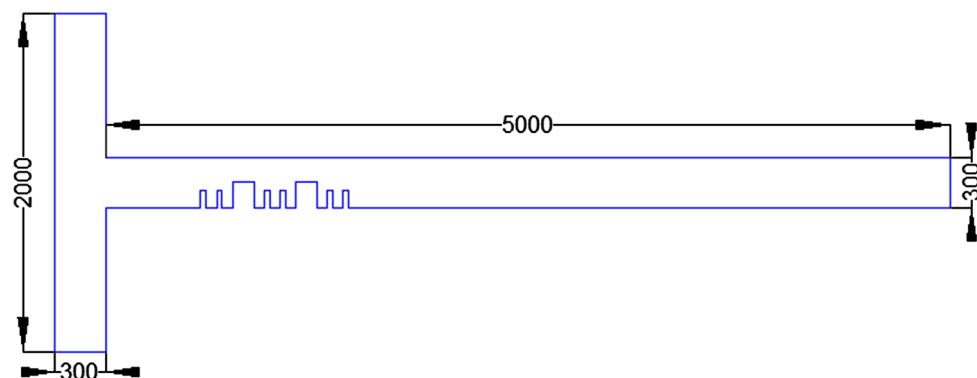Fig. 2 A primary fractal obstacle microchannel (unit: μm)

Fig. 3 A quadratic fractal obstacle microchannel (unit: μm)

2 Geometric model design

According to the Cantor fractal set structure, we design a simple fractal geometry model and called it ICS (Wang et al. 2009; Warren and Krajcinovic 1995; Warren et al. 1996). Based on the Cantor structure, we divide the ICS into two kinds: primary fractal obstacle and quadratic fractal obstacle geometric model (Fig. 1). This simple ICS generation process is as follows:

1. In the initial step, specify a straight line with a fixed length of L = 1000 μm.
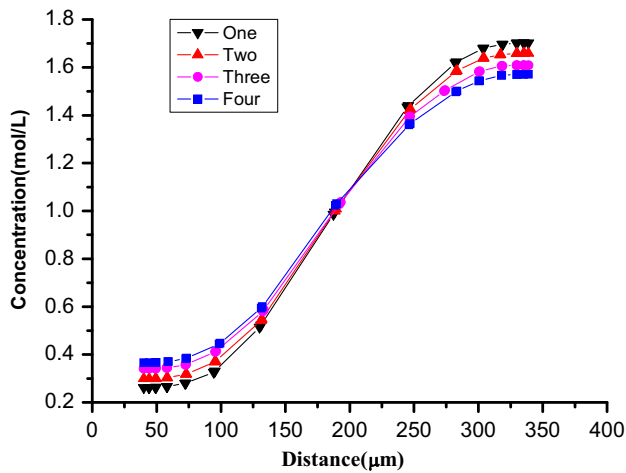
Fig. 4 Comparison of four primary fractal obstacles mixing efficiency at microchannel outlet

2. In the second step, the microchannel model begins at a height of 300 μm. Straight line divided into eight equal parts $L_1 = \frac{1}{8}L$, $L_1 = 125$ μm. Start height is defined as 150 μm, get the first fractal obstacle as shown in Fig. 1.

3. In the third step, the remaining lines are segmented in the same proportion $L_2 = \frac{1}{8}L_1$, $L_2 = 31.25$ μm,the

primary fractal obstacle will be divided into quadratic fractal obstacle.

By combining ICS and microchannel, the ICS micromixer is designed. Figure 1 shows the imitate Cantor structure.

Figure 2 shows combination of a primary fractal obstacle and T type microchannel. Figure 3 shows a combination of quadratic fractal obstacle and T type microchannel.

In this paper, we will study this new structure, from fractal obstacle number, fractal obstacle series, fractal obstacle height, fractal obstacle spacing, as well as at various flow velocities to compare. After comparing, we can obtain the best structure which can form the ICS micromixer.

3 Governing equations

In this research, the mixing performance of micromixer is analyzed using COMSOL Multiphysics 5.2a. This commercial code solves steady continuity. The Navier–Stokes equations and the continue equations are usually used to describe the dynamic properties of velocity and pressure
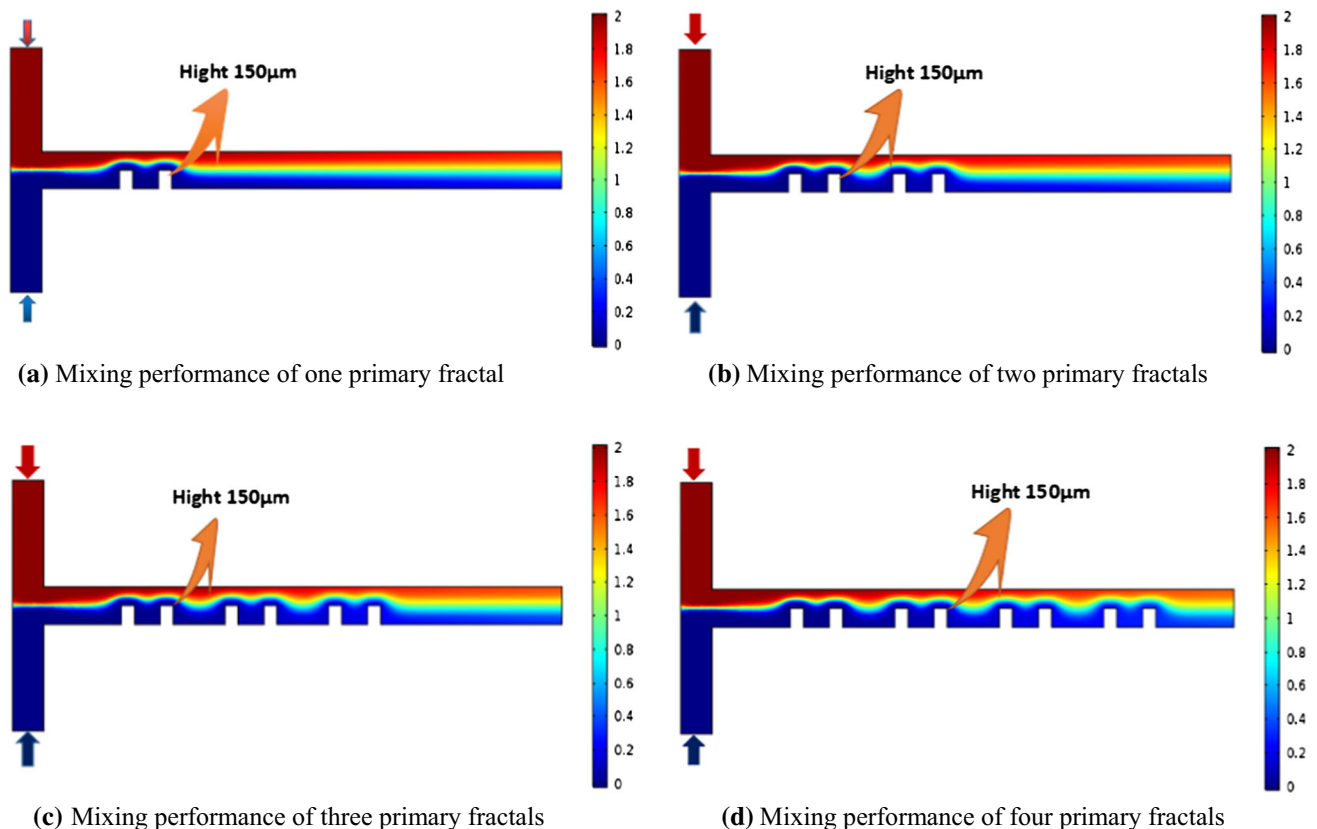

(a) Mixing performance of one primary fractal

(b) Mixing performance of two primary fractals

(c) Mixing performance of three primary fractals

(d) Mixing performance of four primary fractals

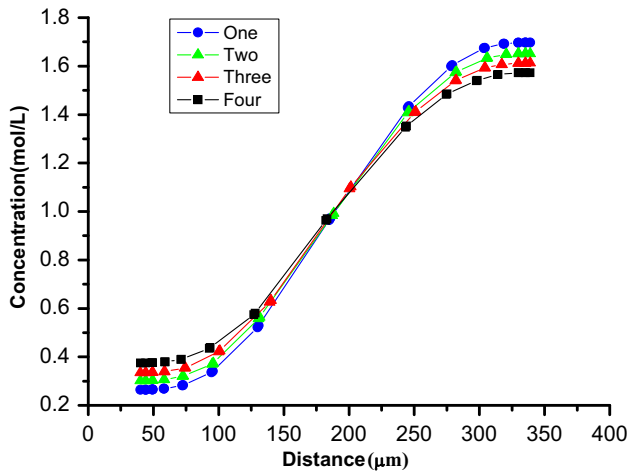Fig. 5 Mixing performance of primary fractal obstacle

Fig. 6 Comparison of four primary fractal obstacle mixing efficiency at microchannel outlet

for incompressible fluidic flows, the equations are expressed as follows (Park et al. 2005):

$$\rho \cdot \left(\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{t}} + (\boldsymbol{u} \cdot \nabla \boldsymbol{u}) \right) = \left(\boldsymbol{f} - \nabla p + \nabla^2 \boldsymbol{u} \right) \tag{1}$$

$$\nabla \cdot \boldsymbol{u} = 0, \tag{2}$$

where $\boldsymbol{u}$ is the velocity vector, $\boldsymbol{f}$ is the force, ρ is the density of the fluid, p is the pressure, t is the time.

The species transport in the system can be described by the diffusion-convection equation as shown in Eq. (3).

$$\frac{\partial \mathrm{c}}{\partial t} (V \cdot \nabla) C = D \nabla^2 C, \tag{3}$$

where C is concentration and D is diffusion constant of the species.

The variables for the species mixing studies are the flow velocity corresponding to the characteristic dimensionless number Re.

$$\mathrm{Re} = \frac{\rho u d}{\eta}, \tag{4}$$

where Re is Reynolds number, ρ is the fluid density, and d is the microchannel diameter in this paper. η is the viscosity coefficient of the fluid.

Mixing efficiency of the species can be calculated by the formula as follows:

$$M = 1 - \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left(\frac{C_i - \overline{C}}{\overline{C}} \right)^2}, \tag{5}$$

(a) Mixing performance of one quadratic fractal

(b) Mixing performance of two quadratic fractals

(c) Mixing performance of three quadratic fractals

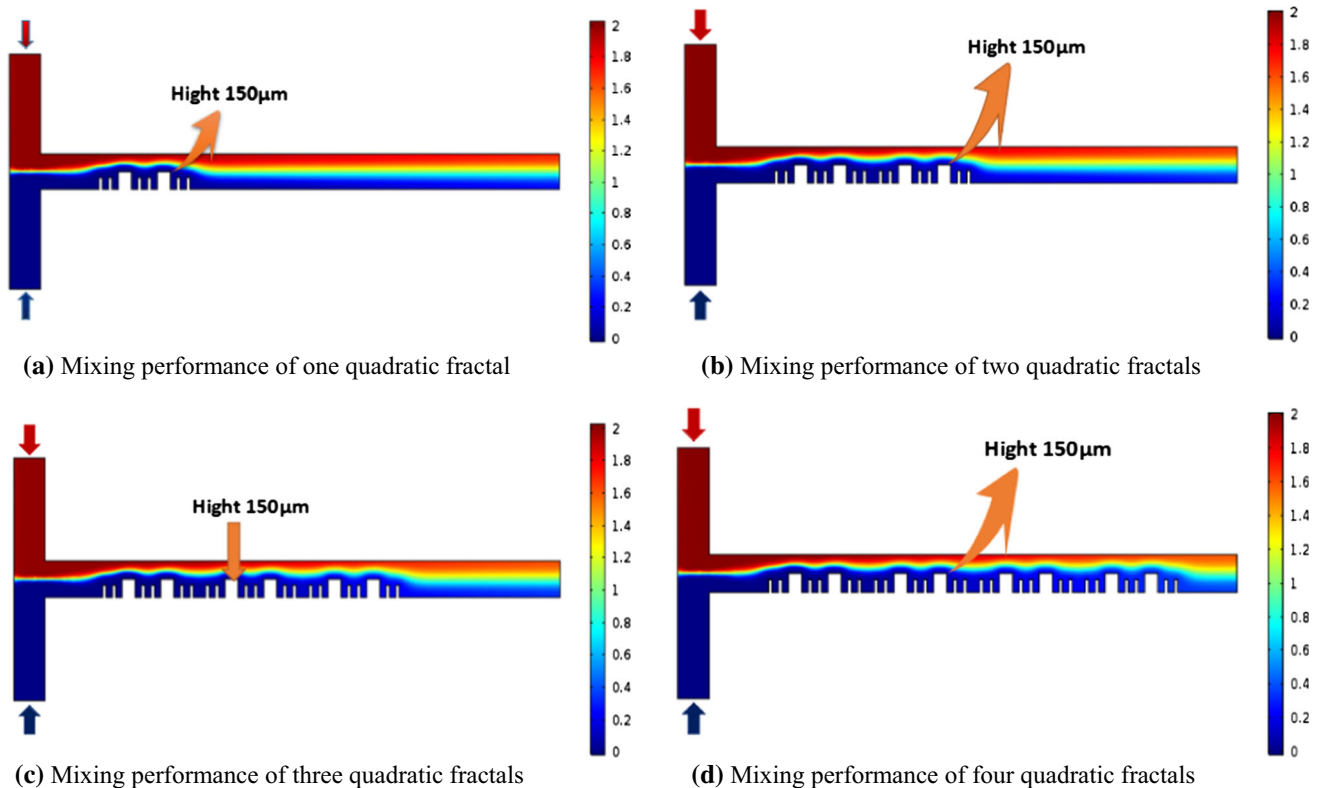**(d)** Mixing performance of four quadratic fractals

Fig. 7 Mixing performance of different numbers of quadratic fractal obstacles
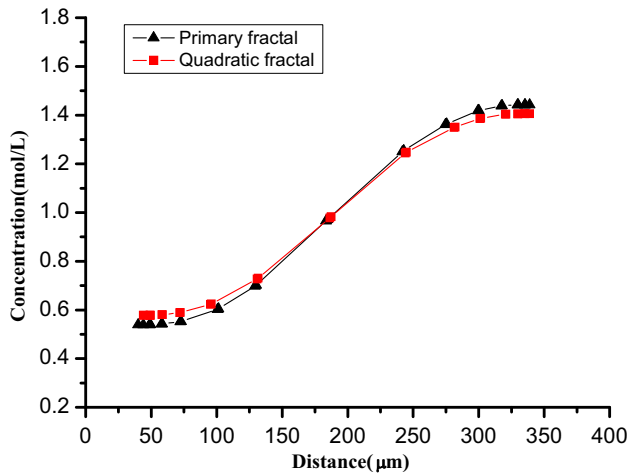
Fig. 8 Mixing concentration of four primary fractal obstacles and four quadratic fractal obstacles at microchannel

where M is the mixing efficiency of micromixer, N is the total number of sampling points, C_i and $\overline{C}$ are normalized concentration and mean concentration respectively.

In order to reach mixing phenomena, ink and deionized water at 25 °C is selected as the working fluids. The inlet 1 and inlet 2 are injected into two species with the concentration of 0 and 2 mol/L, respectively.

4 Result and discussion

4.1 The effect of fractal obstacle number on the micromixer efficiency

First of all, we carry on numerical simulation of ICS. Whether it is primary fractal obstacle or quadratic fractal obstacle, the number of fracture model in the microchannel is from 1 to 4, with a height of 150 μm and same location as distribution. The velocity of the fluid is 0.01 mm/s.

Figure 4 shows mixing concentration of 1–4 fractal obstacles. Figure 4 shows different numbers of primary fractal obstacle numerical simulation of concentration. Through the Fig. 5 we can observe the mixing performance of species. Because of increasing the number of fractal obstacles, the fluid folds several times in the microchannel. So the number of fractal obstacles are different, the mixing effects of species are also different.

It can be seen in Fig. 5 that the mixing efficiency increases with the number of primary fractal obstacle increasing. When the primary fractal obstacle number is four, mixing efficiency of the micromixer is best.

Figure 6 shows the mixing concentration of different fractal obstacles numbers. Figure 7 shows that the numerical simulation of the quadratic fractal obstacle and the primary fractal obstacle are carried out under the same conditions.

After analysis, it is found that the microchannel consisting of four quadratic fractal obstacle has best mixing performance. Therefore, it can be concluded by the numerical simulation that the number of fractal obstacles are more and more, the mixing performance is better and better in the microchannel.

4.2 The effect of geometric fractal obstacle series on efficiency

According to the comparison of the number of obstacles, when the number of primary fractal obstacle or quadratic fractal obstacle is four, the mixing effect is better than the others. So we can directly select the microchannel with four fractal obstacles to compare. The number of primary fractal obstacles and quadratic fractal obstacles in microchannel are four. The flow velocity of this group is 0.01 mm/s, the height of fractal obstacle is 150 μm. Fractal obstacle is up-down staggered distribution in microchannel. Figure 8 shows comparison of mixing concentration of the micromixer with four primary fractal obstacles and
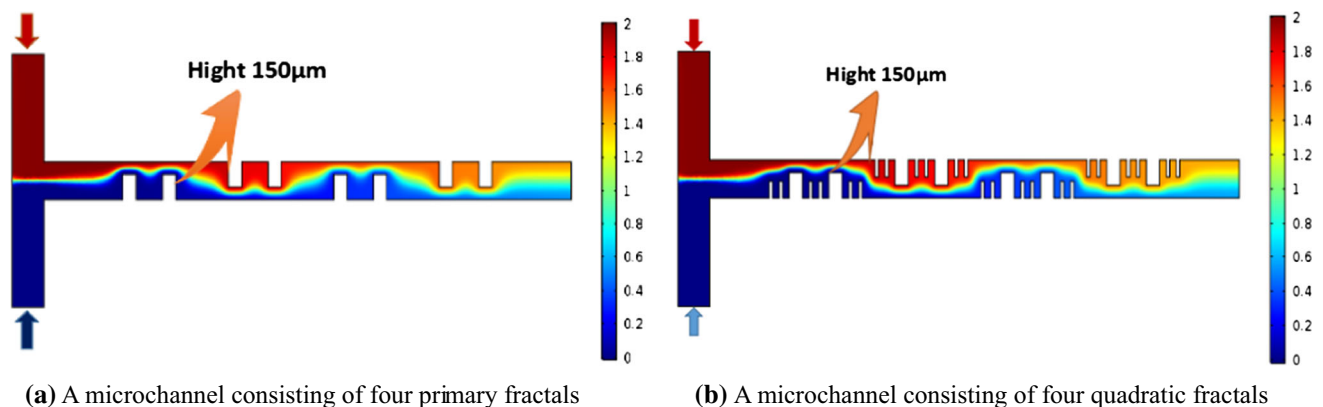

(a) A microchannel consisting of four primary fractals

(b) A microchannel consisting of four quadratic fractals

Fig. 9 Mixing performance of four primary fractal obstacles and four quadratic fractal obstacles
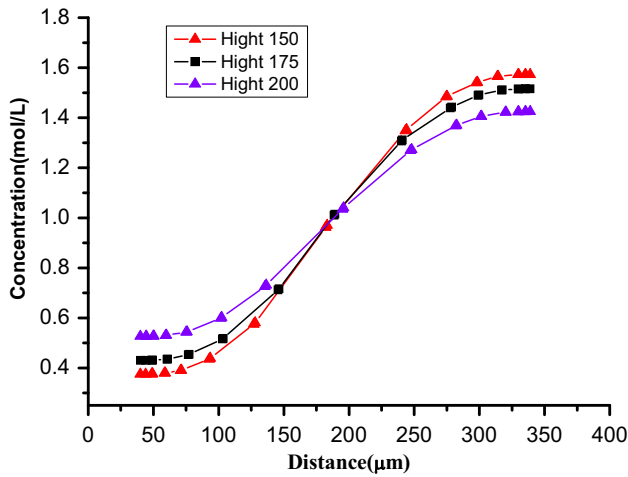
Fig. 10 The mixing concentration compare of three different heights at microchannel outlet

mixing concentration of the micromixer with four quadratic obstacles. Figure 9 shows the mixing performance of the microchannel with four fractal obstacles.

It is not difficult to find conclusions that the mixing efficiency of micromixer with quadratic fractal obstacle under the same condition is better than mixing efficiency of micromixer with primary fractal obstacle. So increasing the series of fractal obstacles in the microchannel can increase the mixing efficiency.

4.3 Effect of fractal obstacle height on mixing efficiency

According to the above conclusion, the microchannel consisting of four fractal obstacles has the best mixing performance. So this group we compare with quadratic fractal obstacle of different heights on the mixing efficiency. The velocity of the height group is 0.01 mm/s. Fractal obstacle distribution is all at the bottom. Height and spacing of fractal obstacle are respectively 150 and 125 μm. So this group of key comparative is height of obstacle, which height are 150, 175, 200 μm, respectively. Figure 10 shows the mixing concentration with different heights of fractal obstacles. Figure 11 shows the mixing performance of fractal obstacles with three different heights.

From Figs. 10 and 11, it can be seen that the quadratic fractal micromixer with 200 μm height obstacle has the
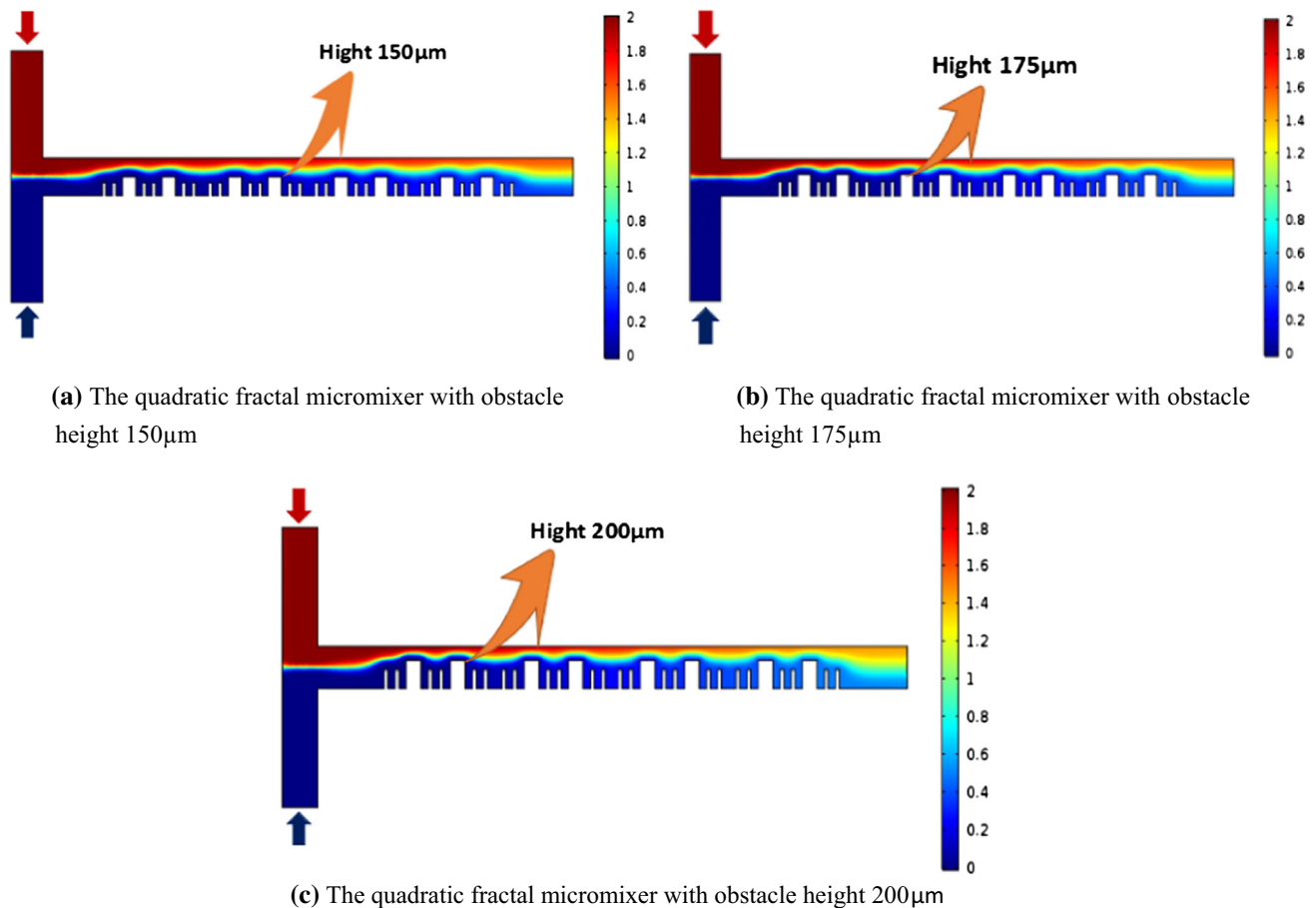

(a) The quadratic fractal micromixer with obstacle height 150μm

(b) The quadratic fractal micromixer with obstacle height 175μm

(c) The quadratic fractal micromixer with obstacle height 200μm

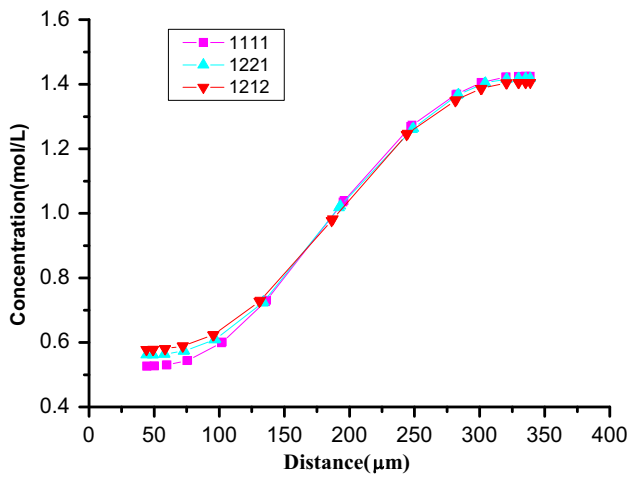**Fig. 11** Mixing performance of three different heights

Fig. 12 Mixing concentration of three different configurations at microchannel outlet

best mixing performance under the same condition. The quadratic fractal obstacle of height 200 μm is the best choice in this group. So increasing the height of fractal obstacles in the microchannel can significantly increase the mixing efficiency.

4.4 Effect of fractal obstacle position on mixing efficiency

Due to the distribution of the quadratic fractal obstacle in the microchannel can be configured eight different locations, we select three representative configurations of fractal obstacle to compare. Three different obstacle configurations are respectively all at the bottom (1111), down-up-up-down (1221), up-down on staggered (1212). The flow velocity of this group is also 0.01 mm/s, the height of fractal obstacle is 200 μm, and space distance is 125 μm. So this group of key comparison is fractal obstacle position in the microchannel. Figure 12 shows mixing concentrations of the micromixer with three different position configurations. Figure 13 shows the mixing performance of the micromixer at three different position configurations.

Through the comparison of three mixing performance, it can be seen from Figs. 12 and 13 that the best mixing efficiency appears in the location of the staggered distribution (1212) in this group. The obstacles of staggered distribution (1212) in microchannel can promote fluid folding more, so the position of the obstacle in the microchannel can affect performance of the micromixer.
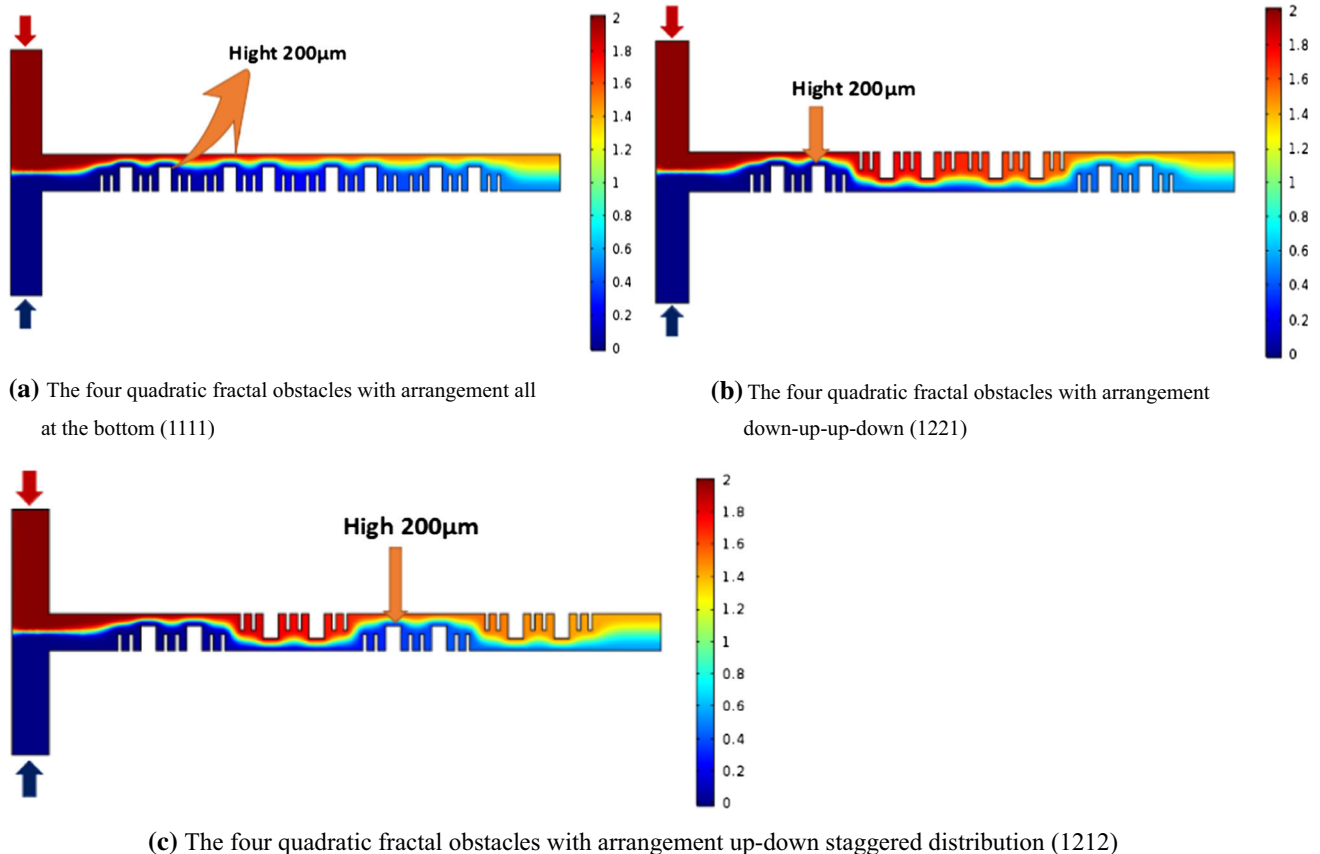

(a) The four quadratic fractal obstacles with arrangement all at the bottom (1111)

(b) The four quadratic fractal obstacles with arrangement down-up-up-down (1221)

(c) The four quadratic fractal obstacles with arrangement up-down staggered distribution (1212)

Fig. 13 Mixing performance of the micromixer with different position of fractal obstacle
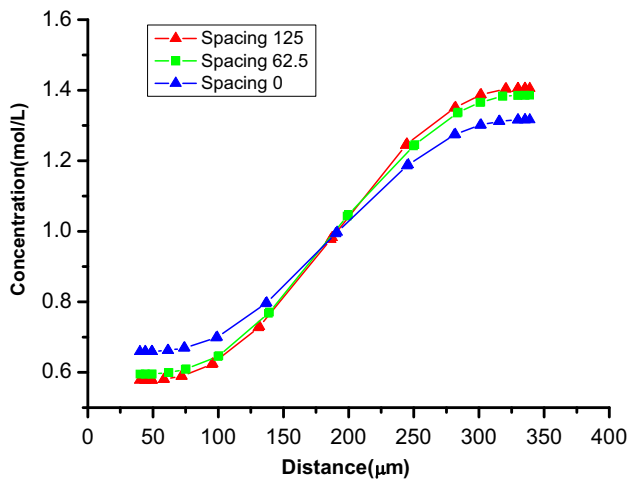
Fig. 14 Concentrations of three different spacings at microchannel outlet

4.5 The effect of fractal obstacle spacing on the mixing efficiency

According to the study above, the microchannel consisting of four staggered quadratic fractal obstacles with the height 200 μm has the best mixing efficiency. We are still compared under the results of the previous groups. This group mainly compares the influence of the spacing between fractal obstacles on the mixing efficiency. The three spacing of fractal obstacle are 125, 62.5, 0 μm, respectively. The flow velocity of the spacing group is 0.01 mm/s, the height of fractal obstacle is 200 μm, and the fractal obstacle position is staggered distribution in the microchannel. Figure 14 shows the mixing concentrations of the micromixer with different spacing between fractal obstacles. Figure 15 shows the mixing performance of the micromixer with different spacing between fractal obstacles.

Through numerical simulation, it can be found that the micromixer has best mixing efficiency when the spacing of fractal obstacles in microchannel is 0 μm. So decreasing the spacing of fractal obstacles in the microchannel can significantly increase the mixing efficiency.

(a) The quadratic fractal micromixer with spacing 125μm

(b) The quadratic fractal micromixer with spacing 62.5μm

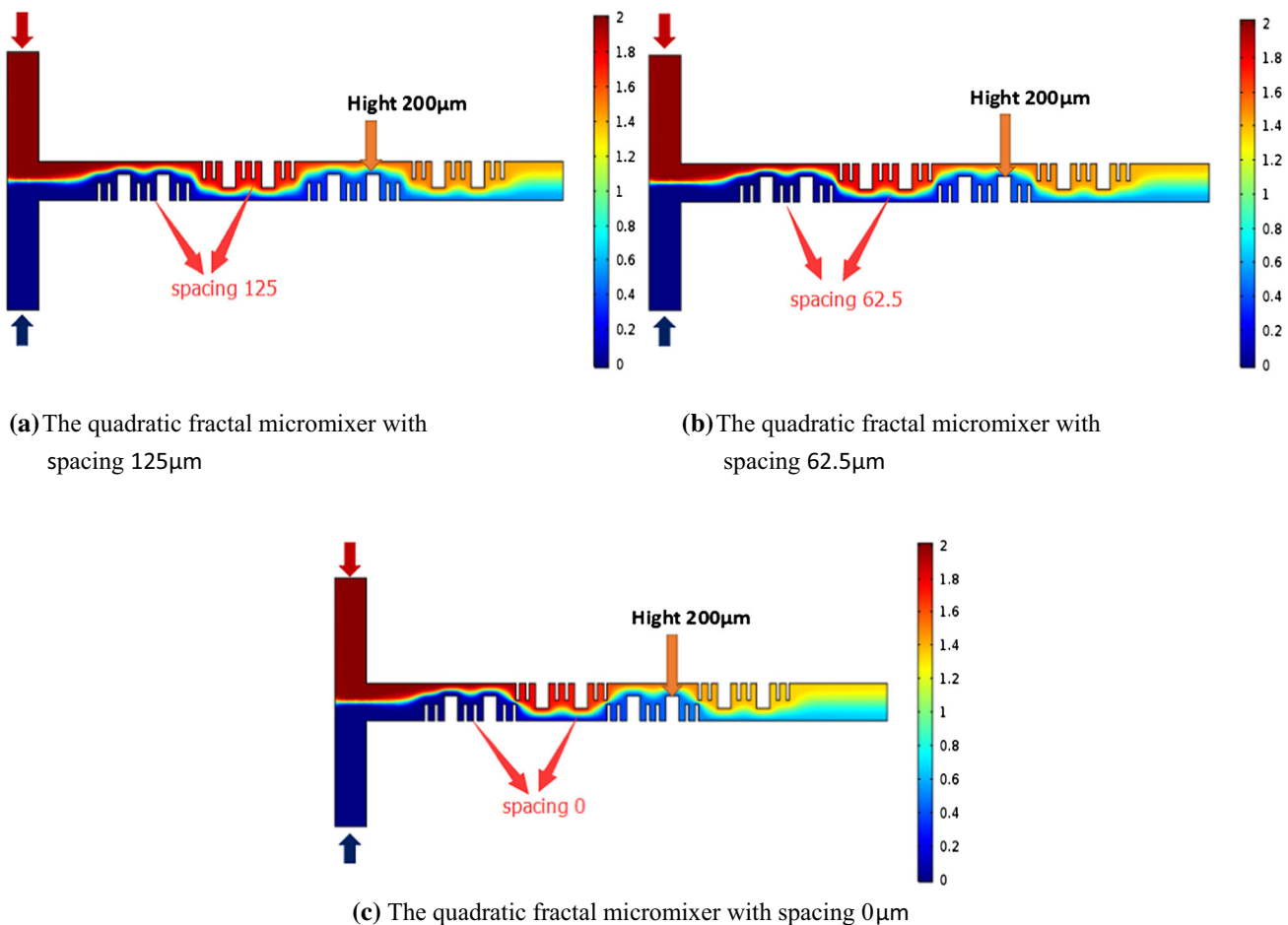**(c)** The quadratic fractal micromixer with spacing 0μm

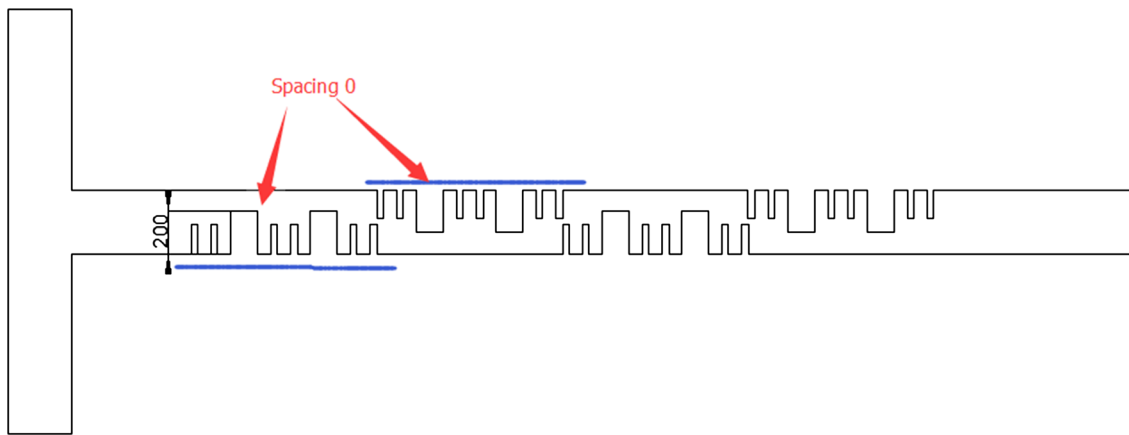**Fig. 15** Mixing efficiency of three different spacings

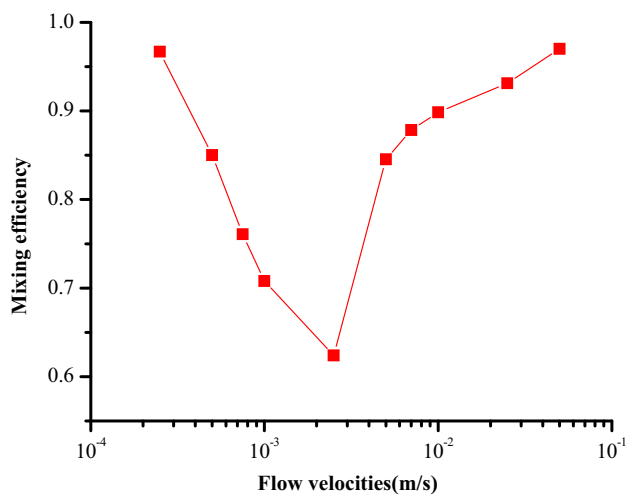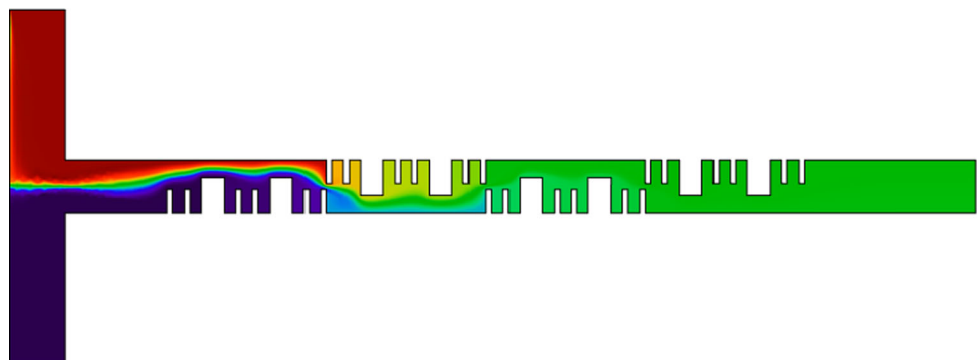**Fig. 16** The optimal microchannel called ICS microchannel (unit: μm)

Fig. 17 Mixing efficiency of the ICS micromixer at ten different flow velocities

4.6 Flow velocity effect on mixing efficiency

From the above results, we can obtain an optimal microchannel structure, which is composed of four quadratic fractal obstacles with height 200 μm, spacing 0 μm, and staggered distribution. Therefore, we get the best

microchannel, we call it ICS microchannel. Figure 16 shows the optimal microchannel, called ICS microchannel.

In order to obtain more appropriate velocities to achieve the better mixing performance. On the basis of this structure, we continue to compare the mixing efficiency at different flow velocities. Figure 17 shows mixing efficiency of the ICS micromixer at ten different velocities.

Through comparing with the mixing efficiency of the ICS micromixer at ten different flow velocities, it can be found form Fig. 17 that the mixing efficiency of the micromixer is V-type trend at flow velocity from small to large. The mixing efficiency decreased continuously at flow velocities of 2.5×10^{-4} to 2.5×10^{-3} m/s. And when the flow velocity is between 2.5×10^{-3} and 0.5 m/s, the mixing efficiency rises continuously. Figure 18 shows optimal mixing effect of the ICS micromixer. It can be seen from Fig. 18 that the species is completely mixed at certain flow velocity. ICS micromixer can promote fluid chaos and fold, so the species can get better mixing.

4.7 Comparison of vortex in the microchannel

After obtaining the optimal structure of the microchannel, we take three places A, B, and C to compare vortex which generated in the ICS microchannel. Figure 19 shows five

Fig. 18 Optimal mixing effect of ICS micromixer

Fig. 19 Vortices of comparison at different flow velocities

(a) u=0.00025m/s

(b) u=0.0075m/s

(c) u=0.001m/s

(d) u=0.005m/s

(e) u=0.05m/s

Fig. 20 ICS microchannel concentration streamlines
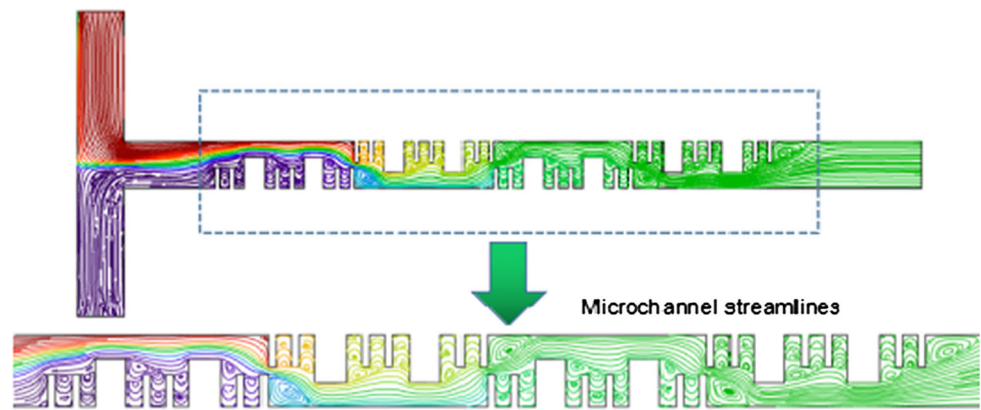
different flow velocities arrow diagram. The arrow indicates the velocity direction of the fluid. And the color indicates the mixing concentration.

Through the comparison of the Fig. 19, it can be seen that the ICS has lot of vortices. Especially there are many obvious small vortices in the fractal obstacle, and the increase of velocity can promote the generation of vortices in microchannel. It can be seen from Fig. 19e, when the flow velocity is 0.05 m/s, the fluid flows past the fractal obstacle, there is a larger vortex formation. There vortices do not appear in several other velocities. So the fluid reaches the best effect of mixing time faster than other velocities, and the flow distance is shorter. Therefore, this ICS micromixer in the flow velocity increase to a certain large can get more efficient mixing. Figure 20 shows concentration streamlines. We can see the mixing processes and mixing effects of two species when there flow through fractal obstacle barriers.

It is clear to see from Fig. 20 that the fluid forms distinct vortexes in the fractal obstacle. These vortices increase fluid chaos and fold, so the formation of vortices promotes mixing of the species. Therefore, this ICS achieves the purpose of increasing mixing effects.

5 Conclusion

In this paper, we design an ICS micromixer by referring to the Cantor fractal obstacle structure. The numerical simulation based on finite element theory is carried out in this research. Through numerical simulation, we can get some conclusions as follows. The more the number of fractal obstacles, the better the mixing effect. The mixing effect of micromixers consisting of four quadratic fractal obstacles is better than the mixing effect of micromixers consisting of the four primary fractal obstacles. Increasing height of fractal obstacle in the microchannel can better promote species mixing. Through comparison of the fractal obstacle of height 200 μm and the fractal obstacle of height

150 μm, the mixing efficiency is improved by about 20%. Different fractal obstacle positions in microchannel can also affect the mixing efficiency, and the microchannel with staggered fractal obstacles distribution (1212) has the best mixing effect. When the fractal obstacle spacing is 0 μm, the mixing efficiency is higher than the other spacing by 5–10%. By comparing the velocity arrow diagram, we can see that the formation of vortices promotes the mixing of species. When the velocity is maximum, the formation of large eddies can be clearly seen, which further promotes the mixing efficiency of the species. At a minimum velocity of 2.5×10^{-4} m/s, the mixing efficiency can reach 96.8%. When the flow velocity is less than 2×10^{-3} m/s, the mixing efficiency can reach more than 90%. The mixing efficiency is reduced at the flow velocities from 2.5×10^{-4} to 2.5×10^{-3} m/s. When the flow velocity is 2.5×10^{-3} m/s, the mixing efficiency is the minimum, about 62%. And when the flow velocity is more than 1×10^{-2} m/s, the mixing efficiency can also reach more than 90%. Furthermore, the best mixing efficiency can over 97%, and the design can easily be realized using a range of microfabrication techniques.

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