CFD-based Study of Velocity Distribution among Multiple Parallel Microchannels

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***Abstract*—A three-dimensional computational fluid dynamics (CFD) model was used to calculate the velocity distribution among multiple parallel microchannels with triangle manifolds. The influences of structural parameters on velocity distribution among microchannels were analyzed. The simulation results showed that the velocity distribution became more uniform with larger microchannel length, depth or smaller width. Larger horizontal ordinate, longitudinal ordinate and radius of inlet/outlet, smaller lengths of bottom and side of symmetrical manifolds could favor obtaining narrow velocity distribution among microchannels. Symmetrical manifold structure could achieve more uniform velocity distribution among microchannels than that asymmetrical manifold structure.**

***Index Terms*—computational fluid dynamics, velocity distribution, parallel microchannel, manifold**

I. INTRODUCTION

Considerable progress of micro-fabrication techniques over the last decade has enabled microchannel reactors to be widely applied in multiple fields[1-4]. The two fundamentally different constructions of microreactors are monolithic construction and laminated-sheet structure[5]. The latter is considered as one of the preferred microreactor constructions, in which multiple sheets patterned with a large number of equal parallel microchannels are stacked and then bonded together to form a unit, as shown in Fig.1. The microchannels fabricated in the sheets generally have the characteristic dimensions on the order of hundreds of microns, resulting to a much larger surface area-to-volume ratio than that of conventional macroscopic reactors.

Equal fluid velocities in the microchannels are beneficial for improving the heat and mass transfer efficiency as well as achieving high selectivities and conversions. Although manifolds are usually incorporated to enhance the flow uniformity[8-10], it is difficult to obtain equal velocity distribution among multiple parallel microchannels. The structural parameters of manifolds and microchannels play an important role on the velocity distribution, however, current geometrical design largely depends on the rule of thumb. It is important, therefore, to design reactor geometries to achieve relatively narrow velocity distribution among microchannels.

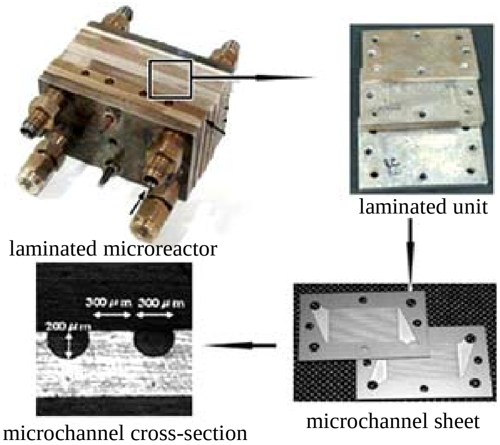

Figure1.Structure of laminated microchannel reactors[6-7]

Some researches were focused on the modeling and simulation of flow or velocity distribution among multiple parallel manifolds. Commenge et al.[11] developed an approximate pressure drop model to examine the features of fluid flow through microchannel reactors. Amador et al.[12] applied an electrical resistance network model to study the differences of flow distribution among microchannels with two manifold structures. Tonomura et al.[13] proposed a CFD-based optimization method for the design of plate-fin microchannel devices with rectangular manifolds.

In our previous works, we studied the characteristics of velocity distribution among non-uniform cross-section microchannels[14], parallel microchannels with complex manifold geometries[15] and asymmetrical manifolds[16] by a physical model. On the basis of these research findings, the objective of the present work is to further summarize the characteristics of velocity distribution among multiple parallel microchannels with triangle manifolds by using a three-dimensional computational fluid dynamics(CFD) model. The influences of structural parameters on velocity distribution among microchannels are analyzed by an evaluating parameter for the uniformity degree of velocity distribution.

II. MODEL DESCRIPTION

As shown in Fig.1, the microchannel sheet usually consists of an inlet, an outlet, multiple parallel

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microchannels and two triangle manifolds, one is inlet manifold, the other is outlet manifold. In addition, the direction of fluid is perpendicular to the inlet and outlet. In order to investigate the characteristics of flow patterns inside the microchannel plate, the flow zone of fluid is extracted from the plate as a research object, as shown in Fig.2. To study the effects of aspect-ratio of microchannel on the velocity distribution, the microchannel with rectangular cross-section is selected here.

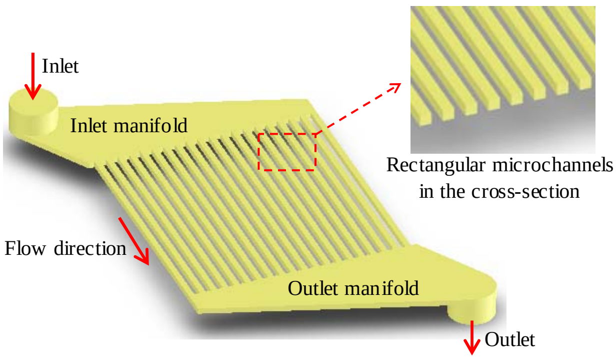

Figure2. The model built for the analysis of velocity distribution among microchannels with triangle manifolds

The inlet manifold and outlet manifold is generally centrosymmetric, however, it is not clear that whether the symmetrical geometry favors in obtaining uniform velocity distribution. In the following section, the effects of symmetry of two manifolds on the velocity distribution are investigated. Therefore, the structural parameters of microchannels and manifolds are firstly defined to facilitate understand of the shape change. As presented in Fig.3, the microchannel length, width, depth, interval and number are defined as L_c, W_c, E, W_s and N, respectively. The channels are numbered up from 1st to N th along the direction of O_1A.

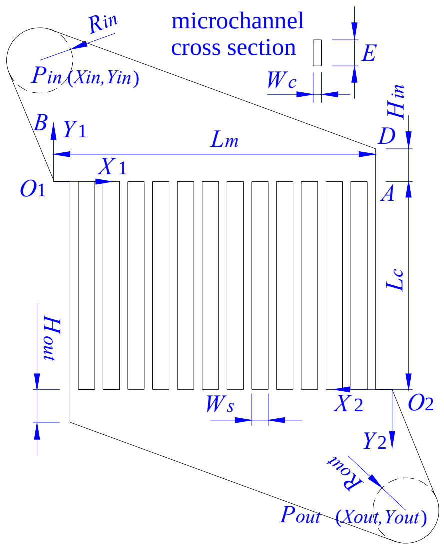

Figure 3. Parameters definition

During the design of manifolds, take the inlet manifold for example, the lengths of bottom L_m and side H_{in} are firstly determined, and then the position and magnitude of the inlet P_{in} are chosen, two tangent lines to the P_{in} through O_1 and D are respectively made, which yields the final manifold shape. Therefore, the position of inlet or outlet governs the manifold shape. Two coordinate systems are established to determine the relative position of manifold and inlet or outlet, respectively.

As for the inlet manifold, O_1 is chosen as the origin of the coordinate system. The bottommost line O_1A of manifold is selected as the axis X_1 and right as positive, while the vertical plumb O_1B perpendicular to O_1A as axis Y_1 and up as positive. O_2 is selected as the origin of the coordinate system for the outlet manifold, and the establishment of axis X_2 and Y_2 is similar to that of the axis X_1 and Y_1. But the direction of X_2 and Y_2 are left and down as positive, respectively. The coordinate of inlet P_{in} and outlet P_{out} in respective system are defined as (X_{in}, Y_{in}) and (X_{out}, Y_{out}). The radius of inlet and outlet are defined as R_{in} and R_{out}, respectively.

In this work, a specific case of 20-microchannel model with centrosymmetric manifolds was illustrated in Table 1. The microchannel distribution was assumed to be uniform, therefore W_s was determined by L_m when W_c was determined in advance. This model was seemed as the basic one, and then one or two of structural parameters was independently adjusted while fixing other variables for studying the effects of each structural parameter on the velocity distribution. In addition, the comparison of velocity distribution among microchannels with symmetrical and asymmetrical manifolds was studied. The investigated structural parameters were listed in rightmost volume of Table 1. The microchannel number N was maintained invariant to reduce calculation times.

Table 1 The basic and investigated structural parameters of microchannel model

	Variables	Basic model	Investigated parameters
Microchannel structural parameters	N	20	-
	L_c(mm)	20	10;20;30;40;50
	W_c (μm)	500	100;200;300;400;500
	E (μm)	500	100;200;300;400;500
Manifold structural parameters	X_{in} /X_{out} (mm)	-2	-4;-2;-1;0;2
	Y_{in} /Y_{out} (mm)	7	5;6;7;8;;10
	R_{in}/R_{out} (mm)	2	0.5;1;2;2.5;3
	H_{in}/H_{out} (mm)	2	1;2;3;4;5
	L_m (mm)	20	14;16;20;22;30

III. CFD SET-UP AND ANALYSIS

In order to get the quantitative indications of the flow behaviors in the multiple parallel microchannels, numerical simulations were performed with a commercially available CFD software FLUENT, which specialized in solving fluid dynamics problems in complex geometries. The geometry of microchannel model as presented in Table 1 was created using Solidworks or Pro-Engineering software and then imported into GAMBIT pre-processor, which was used to create the meshing of volumes and the specification of boundary conditions.

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The model was meshed by hexahedral cells, as depicted in Fig.4. The flow pattern was assumed to be laminar in the microchannels. The governing equations were Navier-Stokes equation with non-slip boundary condition and energy equation. In addition, negligible gravity was used to evaluate the flow characteristics.

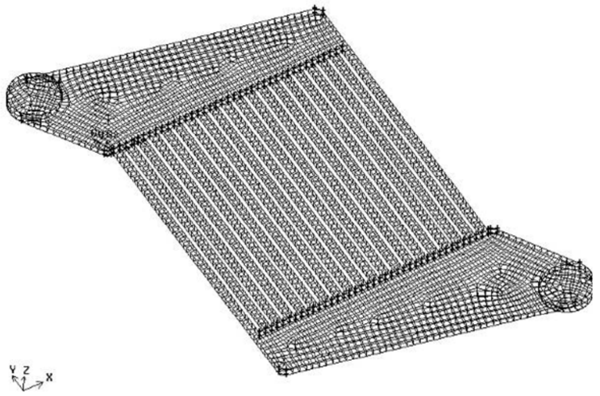

Figure 4. The model meshed by hexahedral cells

The liquid water(density as 998.2 kg·m^{-3} and kinetic viscosity as 1.003×10^{-3} kg·m^{-1}·s^{-1}) under 300K were selected as the fluid. The boundary conditions used were the velocity value in the Z direction of the inlet and the freedom outlet flow. The entrance velocity of fluid was preset to 1mm/s. The outlet pressure condition was set to zero and the solid boundaries were stationary.

An estimating parameter σ_U% as defined below is used to analyze the degree of velocity distribution among microchannels. The magnitude of σ_U% indicates the distributing degree of velocity among microchannels. Smaller σ_U% suggests more uniform velocity distribution.

$$\sigma_U\% = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{U_c(i)}{U_m}-1\right)^2}\times100 \qquad (1)$$

Where $U_c(i)$ is the velocity value of each microchannel, U_m is the mean value of microchannel velocities, as defined below.

$$U_m = \frac{1}{N}\sum_{i=1}^{N}U_c(i)\,(i=1,\,2,\,\ldots,\,N) \qquad (2)$$

IV. Results And Discussion

A. Effects of Microchannel Structural Parameters

Fig.5 showed how the microchannel structural parameters affected the velocity distribution among microchannels. According to Fig.5(a), the velocity distributions were asymmetrical with smaller L_c, and the values of velocities in the microchannels far away from the inlet were larger than that in the microchannels near the inlet. The velocity distribution would be symmetrical when the singular losses in the channels were ignored[11]. The singular losses due to expansion/contraction or change of velocity direction could be possible reasons leading to the deviation of velocity distribution. However, the velocity distribution seemed to be much more symmetrical and uniform with increasing L_c. That was because pressure drop became much larger in longer channels[13].

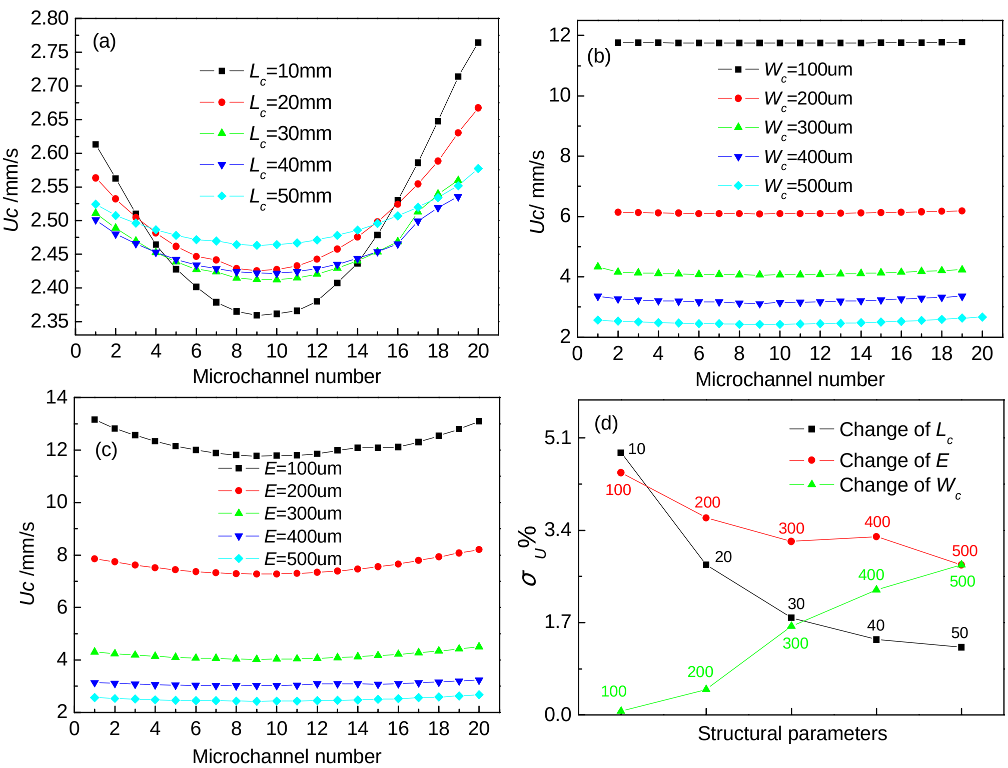

Figure 5. Influence of microchannel structural parameters on the velocity distribution among microchannels

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On the other hand, the change of W_c or E showed much effects on the velocity values than that of L_c, as shown in Fig.5(b) and (c). The velocity values varied between 2.35mm/s and 2.8mm/s when L_c changed from 10mm to 50mm, while it increased from the 2mm/s to 14mm/s when W_c or E decreased from 500μm to 100μm. The velocity value was inversed to the channel width or depth when the flow Q was constant, which was defined as below. Since the effect due to the change of flow in each microchannel was much smaller than that of the change of W_c or E, relatively large change of the velocity values was produced.

$$U_c = \frac{Q}{W_c E} \tag{3}$$

From Fig.5(b) and (c), it could found that the velocity distribution among microchannels appeared symmetrical. The centrosymmetry of the microchannel model could be the cause of symmetrical velocity distribution[11]. However, it was hard to determine the uniformity degree of velocity distribution due to the large change of velocity values. It could only be estimated by the change of σ_U%, as shown in Fig.5(d). Obviously, the velocity distribution became more uniform with larger microchannel depth or smaller width. Therefore, microchannel with high aspect-ratio rectangular cross-section could favor in obtaining narrow velocity distribution among microchannels.

B. Effects of Manifold Structural Parameters

Fig.6 presented the influences of symmetrical manifold structural parameters on the velocity distribution. According to the established coordinate system presented in Fig.3, symmetrical manifold here implied that the structural parameters of inlet manifold and outlet manifold were equal to each other. In response to the simulation results, it found that the velocity distribution appeared somewhat symmetrical regardless of which parameter. The maximum value appeared the furthest channel from the inlet while the minimum value always in one of the middle microchannels, such as No.9, 10 and 11.

The velocity values changed from 2.3 to 2.7mm/s with the change of $X_{in}(X_{out})$, $Y_{in}(Y_{out})$ or $H_{in}(H_{out})$ whereas they varied much when $R_{in}(R_{out})$ or L_m changed. Since the entrance velocity was preset to 1mm/s and maintained invariant, the flow in the inlet changed with the change of R_{in}, leading to large variation of velocity value in each microchannel. As for the change of L_m, the most probable reasons responsible for the change of velocity values lay in two aspects, one was the corresponding change of microchannel interval W_s in order to assure the uniformity of microchannel distribution. The other was the change of manifold shape. These reasons also resulted to great change of uniform degree of velocity distribution by the change of L_m, as shown in Fig.6(f). The value of σ_U% increased from 0.35 to 12 when L_m changed from 14 to 30. Fig.6(f) also presented the values of σ_U% by other different manifold structural parameters. The values of σ_U% varied a little with the change of other parameters. In addition, it was found that the velocity distribution became more uniform with larger $X_{in}(X_{out})$, $Y_{in}(Y_{out})$, $R_{in}(R_{out})$ or smaller H_{in}/H_{out}, L_m. For special, the manifold changed to approximate right triangle when $X_{in}=X_{out}=2$. Fig.6(f) indicated that the velocity distribution among microchannels with right triangle manifolds was more uniform than that of the corresponding one with oblique angled manifolds, here referred to $X_{in}=X_{out}=-4$, -2,-1 and 0.

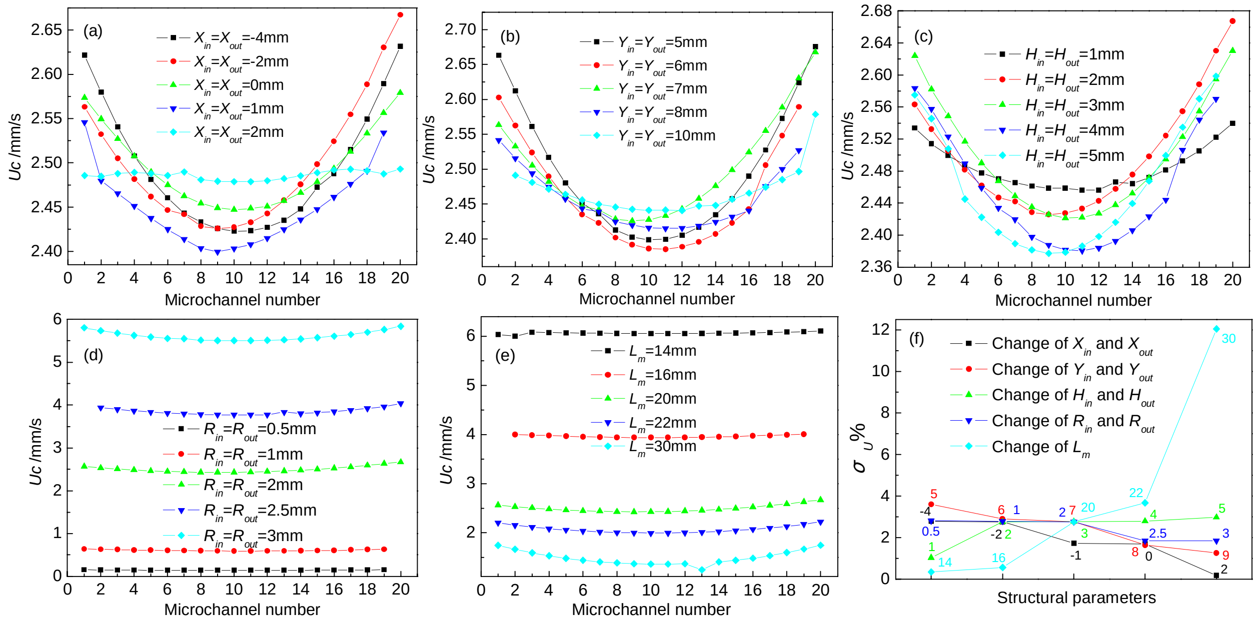

Figure 6. Influence of symmetrical manifold structural parameters on the velocity distribution

Fig.7 presented the velocity distribution among microchannels with different structures of asymmetrical manifolds. As for all the parameters, only the change of R_{in} made great variation of velocity values in the microchannels due to the change of the flow, as shown in Fig.7(e).

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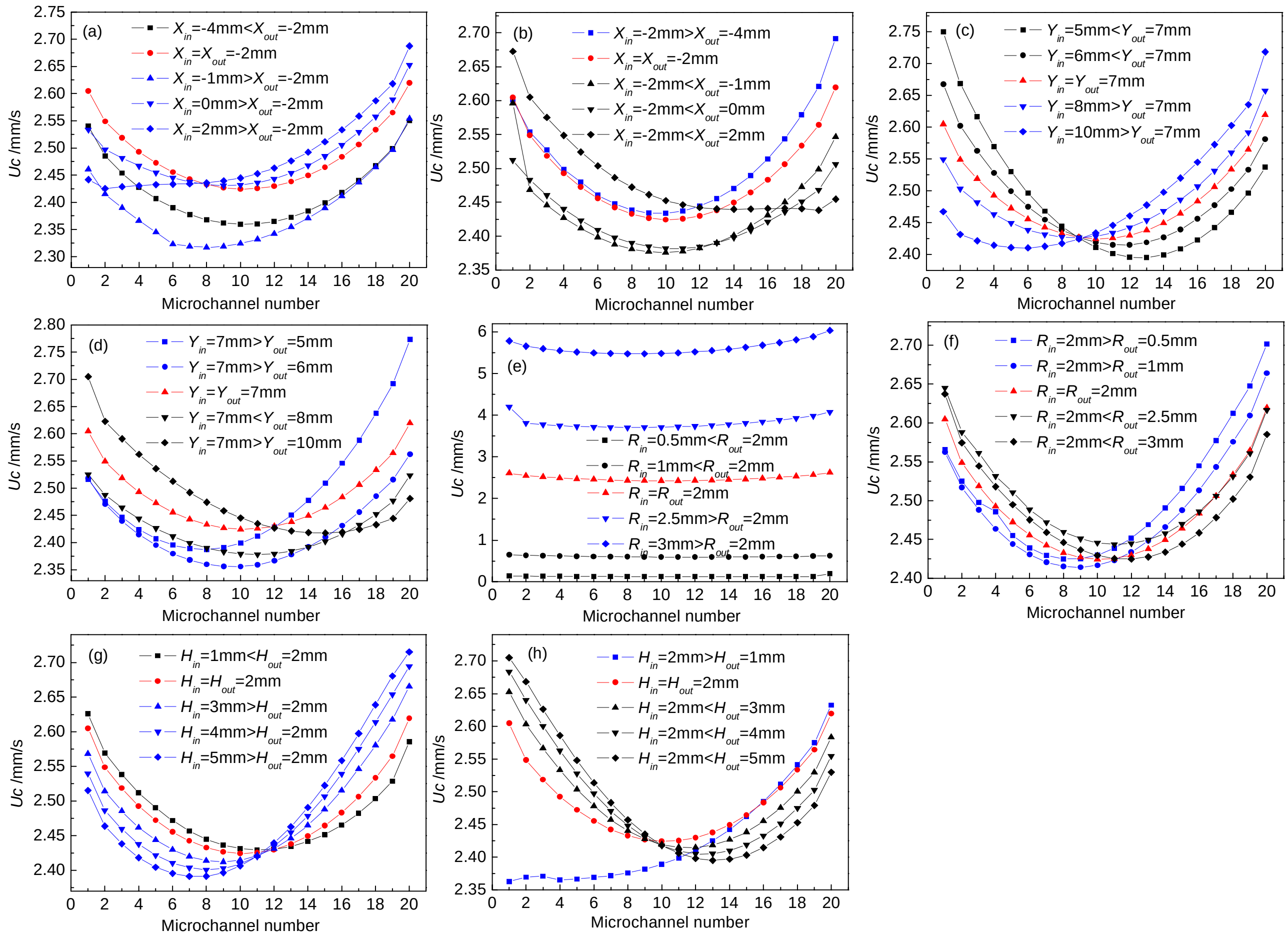

Figure 7. Influence of asymmetrical manifold structural parameters on the velocity distribution

According to the simulation results, an interesting conclusion could be summarized as follows: When the structural parameter of inlet manifold was larger than the corresponding one of outlet manifold(such as when $X_{in}>X_{out}$, $Y_{in}>Y_{out}$, $R_{in}>R_{out}$ or $H_{in}>H_{out}$), the velocity values in the microchannels far away from the inlet would be larger than that symmetrical one near the inlet. Moreover, the minimum value appeared in the middle channels near the inlet. However, smaller structural parameter of inlet manifold resulted in opposite laws of velocity distributions. When $X_{in}<X_{out}$, $Y_{in}<Y_{out}$, $R_{in}<R_{out}$ or $H_{in}< H_{out}$, the velocity values in the channels near the inlet were much larger that the symmetrical one far away from the inlet. The results were accord with the previous ones calculated by a physical model[13].

On the other hand, the velocity distribution among microchannels with symmetrical manifolds appeared much more symmetrical than that with asymmetrical manifolds. Table 2 presented the comparison of the values of σ_U% between the symmetrical and asymmetrical manifolds. The bold numbers in the table represented the same model, that is, the symmetrical manifold structure. It found that the minimum value of σ_U% appeared when the structural parameter of inlet manifold was equal to the corresponding parameter of outlet manifold. That was to say, the symmetrical manifold structure was favor in obtaining much more uniform velocity distribution among microchannels.

Table 2. The value of σ_U% for different structural parameters

		σ_U%			σ_U%
X_{in} /mm (X_{out}=-2mm)	-4	2.45	X_{out} /mm (X_{in} =-2mm)	-4	2.82
	-2	**2.38**		**-2**	**2.38**
	-1	2.67		-1	3.80
	0	2.41		0	3.96
	2	2.91		2	2.60
Y_{in} /mm (Y_{out}=7mm)	5	3.88	Y_{out} /mm (Y_{in}=7mm)	5	4.31
	6	2.90		6	3.60
	7	**2.38**		**7**	**2.38**
	8	2.55		8	4.06
	10	3.52		10	3.22
R_{in} /mm (R_{out}=2mm)	0.5	3.49	R_{out} /mm (R_{in}=2mm)	0.	3.23
	1	2.72		1	2.90
	2	**2.38**		**2**	**2.38**
	2.5	2.61		2.	2.36
	3	2.72		3	2.40
H_{in} /mm (H_{out}=2mm)	1	2.25	H_{out} /mm (H_{in}=2mm)	1	3.72
	2	**2.38**		**2**	**2.38**
	3	2.92		3	2.76
	4	3.57		4	3.34
	5	4.07		5	3.82

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V. CONCUSIONS

According to the simulation results of the proposed microchannel model, the conclusions could be summarized as follows:

(1)The velocity distribution became more uniform with larger microchannel length, depth or smaller width. Microchannel with high aspect-ratio rectangular cross-section could favor in obtaining narrow velocity distribution among microchannels.

(2)As for the symmetrical manifold structures, the velocity distribution becomes more uniform with larger horizontal ordinate, longitudinal ordinate and radius of inlet/outlet, smaller lengths of bottom and side of manifolds.

(3)Symmetrical manifold structure could achieve more uniform velocity distribution among microchannels than that asymmetrical manifold structure.

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