CFD and experimental analyses of flow distribution uniformity in minichannel reactors with a bifurcation structure manifold

X R Zhuang¹, X H Xu¹,², L Li¹, X Xin¹ and W F Xu¹

¹School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen 518055, Guangdong Province, China

E-mail: xuxinhai@hit.edu.cn

Abstract. This study investigated the flow distribution uniformity and pressure drop in minichannel reactors with a bifurcation structure inlet manifold and different type outlet manifolds. The numerical model was established and validated by experimental results. In order to analyze the effects of structural parameters on the flow distribution uniformity of the manifold, the bifurcation inlet manifold was first designed based on the principle of minimum entropy generation. The results showed that longer channel length of bifurcation in the inlet manifold allowed the flow to be fully developed and equally split into several flows. Then, with an identical bifurcation inlet manifold, the influences of outlet manifold with structures of bifurcation, triangle and rectangle, as well as the parallel minichannel length on the flow uniformity of minichannel reactors were also built and investigated. The results showed that the rectangular structure outlet manifold simplified the structure of minichannel reactors and reduced the parasitic power consumption. The flow uniformity of minichannel reactor increased as the parallel minichannel length increased and the impact was more significant at high inlet flow rate than at low inlet flow rate.

1. Introduction

With the development of microfabrication technology, microchannels and minichannels have been widely used in reactors. Compared to conventional reactors, small channel reactors present advantages with respect to high surface-to-volume ratio, high heat and mass transfer characteristics, high reaction efficiency, rapid response time, and small reactor volume [1,2]. The distribution of reactant flow in parallel channels plays an important role on the performance of small channel reactors. Uniform flow distribution is generally conducive to higher heat and mass transfer performance, better temperature control, and lower pressure drop, which can effectively improve the efficiency of small channel reactors [3,4]. Reactant flow distribution is significantly influenced by the manifold structure and parallel channels dimensions. Thus, the geometrical design of manifolds and parallel channels is an important issue in small channel reactors.

In recent years, optimal design of the manifold structure for uniform flow distribution in small channel reactors has attracted much attention. Most studies [5-8] focused on the Z-type microchannel reactors with the triangular structure for both inlet and outlet manifolds (shown in figure 1(a)) which are less uniform but more compact. Mei et al [4] presented an innovative A-type microchannel reactor with one inlet and two outlets, and the manifold structures also belonged to the triangle type. They found that the flow distribution in microchannels of the innovative reactor was much more uniform
than that of the conventional Z-type microchannel reactor. Except for the triangular manifold structure, Liu et al. [3,9,10] proposed a novel minichannel reactor using the bifurcation structure manifold as shown in figure 1(b). Numerical and experimental analyses presented that the flow channel length versus width in the straight section of the bifurcation manifold had significant effect on the flow distribution uniformity. And the circular-shape bifurcation was beneficial to the flow distribution uniformity at a relatively low pressure loss. Moreover, the bifurcation structure manifolds (shown in figure 1(b)) can offer advantages of more uniform flow distribution, higher heat transfer capabilities and lower parasitic power consumption [11]. In this paper, a minichannel reactor with bifurcation inlet manifold and rectangular outlet manifold was proposed and analyzed. Firstly, the bifurcation inlet manifold was designed based on the principle of minimum entropy generation, and the effects of the structural parameters on the flow distribution uniformity were discussed. Then, the influence of outlet manifold with structures of bifurcation, triangle and rectangle on the flow uniformity was investigated. The parallel minichannel length on the flow uniformity of minichannel reactors was also studied.

2. Manifold structure design

Schematic of a four-stage bifurcation structure manifold is shown in figure 2. All the channels have the same depth of 2 mm for ease fabrication and the width of the channels in the fourth-stage is set to be 1 mm. According to the minimum entropy generation criterion proposed by Bejan [12-14], the ratio of the equivalent diameter of channels between the next stage \( D_{\text{eq},n+1} \) and the upper stage \( D_{\text{eq},n} \) of bifurcation needs to satisfy the following equation for laminar flow:

\[
\frac{D_{\text{eq},n+1}}{D_{\text{eq},n}} = 2^{-1/3}
\]

As the cross-section of flow channels is rectangle in this study, the equivalent diameter of each channel can be calculated as follows:

\[
D_{\text{eq},n} = \frac{2H_nW_n}{H_n + W_n}
\]

Where \( H_n \) is the depth of a channel in the \( n \)th stage; \( W_n \) is the width of a channel in the \( n \)th stage; \( n=1, 2, 3, \ldots \ldots \), and the number of flow channels after \( n \)-bifurcations will be \( 2^n \) at each level. Thus, \( W_n \) and
$D_{eq,n}$ of the four-stage bifurcation structure manifold are summarized in table 1.

| Stage | $W_n$ (mm) | $D_{eq,n}$ (mm) |
|-------|-----------|-----------------|
| 1     | 4.17      | 2.70            |
| 2     | 2.29      | 2.14            |
| 3     | 1.46      | 1.69            |

The length of channels in each stage of the bifurcation structure should be long enough for the flow to develop a symmetric velocity profile in order to get equally distribution in the next stage of the bifurcation. However, the length of channels is also limited due to the constraint of packaging size in practical applications. In the present study, the length of channels in each stage was assumed to be:

$$L_n = C \cdot D_{eq,n}$$  \hspace{1cm} (3)

Where $C$ is a constant coefficient. It can be deduced that the four-stage bifurcation structure is determined, once the distance of adjacent channels in the fourth-stage, $d$, and the coefficient $C$ are selected.

3. Numerical modeling

In order to investigate the effects of $d$ and $C$ on flow distribution uniformity in minichannels, the inlet manifold structure was first established and studied. Then, based on the determined inlet manifold structure, the influences of the outlet manifold structure and the length of parallel minichannels on the flow uniformity of whole minichannel reactor were further investigated.

The analyses of the flow distribution performance in the inlet manifolds and minichannel reactors were carried out using commercial software ANSYS FLUENT. Water at room temperature was considered as the fluid in the simulation. For the investigated conditions of low flow rates and low Reynolds numbers, the flow was considered as incompressible, laminar and steady state with constant properties in the flow channels. The boundary conditions applied for the analyses were non-slip at the channel walls, prescribed mass flow rate at the inlet, and pressure specified as atmospheric at the outlet. QUICK scheme was used for the discretization of the convection terms in the governing equations. The SIMPLE algorithm has been adopted to solve the coupling of the pressure filed and the velocity field. The convergence criteria for both continuity and momentum equations were set as $10^{-6}$. The studied Reynolds number at the inlet ranges between 85 and 890, the Reynolds number decreases as the flow passing from the inlet through channels in each stage of the bifurcation structure manifold. Thus, the flow should be laminar in the flow channels for all studied cases [9, 15].

To facilitate the analyses, two characteristics are adopted which are dimensionless flow rate, $M_i$, and uniformity index, $U$, defined as follows:

$$M_i = \frac{m_i}{m_{ave}}$$  \hspace{1cm} (4)

$$U = 1 - \left[ \frac{1}{2^n} \sum_{i=1}^{n} (M_i - 1)^2 \right]^{1/2}$$  \hspace{1cm} (5)

Where $m_i$ is the flow rate in the $i$th channel; $m_{ave}$ is the average flow rate in the $2^n$ channels; $i=1, 2, \ldots, 2^n$. $U$ is used to indicate the flow uniformity in the channels.

A grid independence study was conducted to select an appropriate grid number for low computation cost and high accuracy of the results. The effect of grid number is characterized by relative difference of mass flow rate (RDM) calculated as follows:
\[ RDM = \frac{\sum_{i=1}^{N} |m_i - m_i'|}{16m_i} \]  

Where \( m_i \) is the flow rate in the \( i \)th channel calculated based on the extra-fine grid, and \( m_i' \) is the flow rate in the \( i \)th channel calculated based on the coarse, medium, or fine grids.

**Table 2.** Grid independence study for the inlet manifold structure with \( d=1 \) mm and \( C=2 \).

| Grid number | Coarse   | Medium  | Fine    | Extra-fine |
|-------------|---------|---------|---------|------------|
| RDM (%)     | 181500  | 465240  | 1991070 | 4138635    |

The grid sensitivity study was conducted for the inlet manifold structure with \( d=1 \) mm and \( C=2 \). The grid number varies from 181,500 to 4,138,635 at the coarse, medium, fine and extra-fine meshing cases. The inlet flow rate was set at 150 mL/min. Table 2 summarizes the corresponding results of RDM for the four meshing cases. It can be seen that the deviation between fine and extra-fine grids are almost negligible. Thus, the fine grid number is adequate to get accurate numerical results and has been adopted for all further studies.

### 4. Experimental setup and numerical validation

An experimental system was set up to measure the flow distribution uniformity for the manifold as shown in figure 3. De-ionized water from the glass reservoir is pumped into the manifold at a constant flow rate controlled by the peristaltic pump. When the flow is in steady state, the outlet water from each minichannel is collected separately by graduated cylinders for a certain time period. Thereafter, the mass of water collected in each graduated cylinder is measured by a Mettler-Toledo analytical balance with the precision of 0.1 mg. In order to ensure the repeatability of the measured data, the experiments have been repeated at least five times on different days under the same operating conditions.

![Figure 3. Picture of the experimental setup for flow distribution measurement.](image)

![Figure 4. Picture of the fabricated three-stage bifurcation structure manifold.](image)

A bifurcation structure manifold was machined and fabricated following the dimensions described in Section 2 with \( d=1 \) mm and \( C=2 \). As the flow channel dimensions at the fourth stage are too small, it is impossible to insert rubber tubes at the outlets of each minichannel without leakage in the experiment. Therefore, a three-stage bifurcation structure manifold using the dimensions corresponding to the first three stages of the four-stage bifurcation manifold was tested. The manifold was fabricated on Plexiglas plates using CNC machining to ensure high accuracy, and bolts and nuts were used to cover a top plate on the manifold for compression sealing, shown in figure 4. High pressure N\(_2\) gas was used to purge through the manifolds immersed in water to test the sealing performance. Then, a series of experimental measurements with the inlet flow rate ranging between 60-160 mL/min were conducted. The experimental data were compared with the numerical results for...
numerical validation in figure 5. It can be seen that numerical predictions agree well with the experimental results for the dimensionless flow rate. And the agreement between experimental and numerical results of uniformity index is satisfactory with the deviation less than 3%. Thus, the reliability of the numerical simulation method is verified. The following investigations of the influences of structural parameters on the flow uniformity of microchannel reactors will fully rely on the numerical computations.

![Figure 5](image)

**Figure 5.** Experimental and numerical results for the three-stage bifurcation structure manifold. (a) Dimensionless flow rate and (b) uniformity index.

### 5. Results and discussion

#### 5.1. Manifold inlet structure

Figure 6 shows the dimensionless flow rate distribution and velocity contour for a four-stage bifurcation structure inlet manifold with \( d=1 \) mm and \( C=1 \). It can be found that the flow rate distribution pattern is symmetric on the centre axis between channels 8 and 9. And the flow rates in the side minichannels are relatively higher than that of in the middle channels. It might be because of the non-fully developed flow and the centrifugal effect. According to Kays and Crawford [16], the hydrodynamic entry length of a laminar flow should be larger than \( 0.05ReD_{eq} \), while the channel length in the inlet manifold is not long enough due to size restriction. On the other hand, the velocity profile in the channels after the first-stage bifurcation skews to the outer side channels due to the effect of centrifugal force, and the centrifugal force intensifies the uneven distribution at the second to the fourth-stage bifurcation as shown in figure 6(b). Since longer channels allow the flow to develop symmetric velocity profiles and the parameters of \( d \) and \( C \) affect the length of channels in each stage of bifurcation, influences of the two parameters on the flow distribution uniformity of the inlet manifold were thereafter examined.

![Figure 6](image)

**Figure 6.** Numerical results for a four-stage bifurcation structure inlet manifold with \( d=1 \) mm and \( C=1 \). (a) Dimensionless flow rate distribution and (b) velocity contour.
The effect of $d$ on the flow distribution uniformity and pressure drop of the inlet manifold at four inlet flow rates with $C=1$ is shown in figure 7. It can be seen that the flow distribution uniformity increases with the increasing $d$, and the impact is more significant at low inlet flow rate. The pressure drop also increases with the increasing $d$, and the influence enhances as the inlet flow rate increases. As the length of channels in each stage of bifurcation increases with the increase of $d$, the pressure drop raises and the flow velocity decreases along the channel. A fully-developed flow is easier to establish at lower flow velocity in the same channel length resulting in more even flow distribution after the bifurcations. Moreover, the increasing pressure drop consumes more parasitic power, and the overall size of the inlet manifold becomes larger when $d$ increases. Therefore, $d$ should be as short as possible for the inlet manifold when the flow distribution uniformity is satisfied for applications.

![Figure 7](image7.png)

**Figure 7.** Effect of $d$ for the inlet manifold at four inlet flow rates with $C=1$. (a) Flow distribution uniformity and (b) pressure drop.

The effect of $C$ on the flow distribution uniformity and pressure drop of the inlet manifold at six inlet flow rates with $d=1$ mm is shown in figure 8. It indicates that the flow distribution uniformity increases as $C$ increases, because a larger $C$ results in a longer channel length. And the influence becomes less evident when $C$ enlarges to a certain extent. Furthermore, the pressure drop also increases with the increasing $C$, and the effect enhances as the inlet flow rate increases which leads to a larger parasitic power consumption.

![Figure 8](image8.png)

**Figure 8.** Effect of $C$ for the inlet manifold at six inlet flow rates with $d=1$ mm. (a) Flow distribution uniformity and (b) pressure drop.

5.2. **Manifold outlet structure**

In order to investigate effect of the outlet manifold structure on the flow uniformity of minichannel reactors, the inlet bifurcation structure manifold with $d=1$ mm and $C=2$ as well as the parallel channel length of 100 mm were used. Three outlet manifolds with different structures of bifurcation, triangle and rectangle which have the same $L_o$ were studied as shown in figure 9. The results in figure 10 show...
that the flow uniformity in minichannels with the triangular outlet structure manifold is slight lower than the other two outlet structure manifolds. The outlet manifold structures of bifurcation and rectangle have similar flow uniformity. It suggests that the outlet manifold structure has much less significant effect on the flow uniformity of minichannel reactors than the inlet manifold structure. In addition, pressure drop of the rectangular structure outlet manifold is the smallest one among those three outlet manifold structures. Thus, the rectangular structure outlet manifold can be selected to simplify the structure of minichannel reactors which also reduces the parasitic power consumption and manufacturing cost.

![Figure 9](image)

**Figure 9.** Drawings of three outlet manifold structures with identical bifurcation structure inlet manifold and parallel channel length. (a) Bifurcation, (b) triangle and (c) rectangle.

![Figure 10](image)

**Figure 10.** Effect of the outlet manifold structure for the minichannel reactors using identical bifurcation structure inlet manifold and parallel minichannel length. (a) Flow distribution uniformity and (b) pressure drop.

5.3. Parallel minichannel length

For purpose of studying effect of the parallel minichannel length $L$ on the flow uniformity of minichannel reactors, the inlet and outlet manifold structures in figure 9(c) were used. And the results are presented in figure 11. It indicates that the flow uniformity increases as the parallel minichannel length increases. However, the flow uniformity becomes less dependent on the parallel minichannel length when it is long enough for the flow to be fully-developed. Comparing with the low inlet flow rate, the parallel minichannel length has more impact on the flow uniformity at high inlet flow rate.
Figure 11. Effect of the parallel minichannel length on the flow uniformity of minichannel reactors.

6. Conclusions

CFD simulation was conducted in the present study to investigate the flow distribution uniformity in minichannel reactors. The numerical results were validated by experimental measured data. At first, the bifurcation manifold was designed based on the principle of minimum entropy generation. The effects of the adjacent distance of the channels in the fourth-stage ($d$) and the length coefficient of channels in each stage ($C$) on the flow distribution uniformity in the inlet manifold were analyzed. As longer channels allow the flow to be fully developed, the flow distribution uniformity increases with the increasing $d$ and $C$. Moreover, the impact of $d$ is more significant at low inlet flow rate, while the influence of $C$ becomes less evident when $C$ enlarges to a certain extent. The pressure drop also increases with the increasing $d$ and $C$, and the influences enhance as the inlet flow rate increases which consumes more parasitic power. Since the overall size of the inlet manifold becomes larger when $d$ and $C$ increase, they should be as short as possible when the flow distribution uniformity is satisfied for practical applications. With identical bifurcation inlet manifold and parallel minichannel length, the outlet manifold with structures of bifurcation, triangle and rectangle have similar flow uniformity of minichannel reactors. Moreover, pressure drop of the rectangular structure outlet manifold is the smallest among all the outlet manifolds. Therefore, a minichannel reactor with bifurcation inlet manifold and rectangular outlet manifold can obtain satisfied flow uniformity, reduced manufacturing cost and parasitic power consumption compared to other manifold designs. The flow uniformity of minichannel reactors increases as the parallel minchannel length increases. And comparing with the low inlet flow rate, the length of parallel channels has more impact on the flow uniformity at high inlet flow rate.

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References

[1] Commengé J M, Falk L, Corriou J P and Matlosz M 2002 Optimal design for flow uniformity in microchannel reactors AIChE J. 48 345-58

[2] Pan M, Tang Y, Pan L and Lu L 2008 Optimal design of complex manifold geometries for uniform flow distribution between microchannels Chem. Eng. J. 137 339-46

[3] Liu H, Li P, Lew J V and Juarez-Robles D 2012 Experimental study of the flow distribution uniformity in flow distributors having novel flow channel bifurcation structures Exp. Therm. Fluid Sci. 37 142-53

[4] Mei D, Liang L, Qian M and Lou X 2013 Modeling and analysis of flow distribution in an A-type microchannel reactor Int. J. Hydrogen Energy 38 15488-99
[5] Pan M, Tang Y, Yu H and Chen H 2009 Modeling of velocity distribution among microchannels with triangle manifolds *AIChE J.* **55** 1969-82
[6] Pan M, Wei X L, Zeng D and Tang Y 2010 Trend prediction in velocity distribution among microchannels based on the analysis of frictional resistances *Chem. Eng. J.* **164** 238-45
[7] Pioresi C, Fan Y and Luo L 2015 Numerical study on the improvement of flow distribution uniformity among parallel mini-channels *Chem. Eng. Process: Process Intensification* **95** 63-71
[8] Madane K and Kulkarni A A 2018 Pressure equalization approach for flow uniformity in microreactor with parallel channels *Chem. Eng. Sci.* **176** 96-106
[9] Liu H, Li P and Lew J V 2010 CFD study on flow distribution uniformity in fuel distributors having multiple structural bifurcations of flow channels *Int. J. Hydrogen Energy* **35** 9186-98
[10] Liu H and Li P 2013 Even distribution/dividing of single-phase fluids by symmetric bifurcation of flow channels *Int. J. Heat Fluid Fl.* **40** 165-79
[11] Chen Y and Cheng P 2002 Heat transfer and pressure drop in fractal tree-like microchannel nets *Int. J. Heat Mass Transfer* **45** 2643-48
[12] Bejan A 2006 *Advanced Engineering Thermodynamics* (New Jersey: John Wiley and Sons)
[13] Bejan A 1996 Entropy generation minimization: The new thermodynamics of finite-size devices and finite-time processes *J. Appl. Phys.* **79** 1191-218
[14] Bejan A and Lorente S 2006 Constructal theory of generation of configuration in nature and engineering *J. Appl. Phys.* **100** 041301
[15] White F M 2006 *Fluid Mechanics* 6th ed (New York: McGraw-Hill Science/Engineering/Math)
[16] Kays W M and Crawford M E 1993 *Convective Heat and Mass Transfer* (Princeton: McGraw-Hill)