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HAL Authorization

1 **Numerical and experimental investigation on the realization of target flow**
2 **distribution among parallel mini-channels**

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8 **Abstract**

9 Fluid flow maldistribution is considered as one of the main causes of performance
10 deterioration in various energy and process systems, especially when parallel micro- or
11 mini-channel fluidic networks are involved. For a specific purpose, the optimal flow
12 distribution is not necessarily uniform. However, specific non-uniform distributions are
13 somewhat more difficult to achieve than uniform ones. The insertion of a geometrically
14 optimized baffle has been numerically confirmed as an effective solution to this issue, but
15 experimental validation is still lacking which is indispensable for bridging the gap between
16 theory and practice.

17 This paper presents a numerical and experimental investigation on the realization of
18 target flow distribution among parallel mini-channels, using the optimized baffle insertion
19 method. A 15-channel fluidic network integrated with the distributor and the collector is
20 fabricated and tested. Various perforated baffles are optimized and fabricated corresponding
21 to different target distributions (uniform, ascending and descending). PIV technique is used
22 for the flow distribution measurement while CFD simulations are also performed for
23 comparison. CFD results and PIV data show that different target distributions could be
24 successfully achieved by the optimized baffle insertion method. The robustness of the
25 optimized baffle for uniform distribution is also evaluated and discussed to provide some
26 guidelines for future applications.

28 **Keywords:** Parallel mini-channels; Flow distribution; PIV; CFD; Perforated baffle

30

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1 **1 Introduction**

2 Fluid flow maldistribution is considered as one of the main causes of performance
3 deterioration in various energy and process systems, such as heat exchangers (e.g., Lalot et al.,
4 1999; Fan et al., 2008; Tarlet et al., 2014), fluidized beds (e.g., Ouyang et al., 1995; Ong et al.,
5 2009), chemical reactors (e.g., Saber et al., 2010; Guo et al., 2013, 2014), solar receivers (e.g.,
6 Fan and Furbo, 2008; Salomé et al., 2013; Wei et al., 2015a) and heat sinks for cooling (e.g.,
7 Sehgal et al., 2011; Siva et al., 2014). Nowadays, increasing attention has been devoted to
8 miniaturized fluidic networks in which the flow distribution among parallel micro- or
9 mini-channels should be properly controlled for enhanced heat and mass transfer and safety
10 reasons (Luo, 2013).

11 In the majority of the existing literature, flow maldistribution is synonymous with
12 “non-uniform flow distribution”, implying that uniform shape is assumed, or considered to be
13 the optimal distribution among parallel channels. Various methods have been proposed to
14 improve the fluid flow uniformity, as summarized in Rebrov et al. (2011) and Luo et al.
15 (2015). Through continuous efforts of academic or industrial researches, uniform fluid flow
16 distribution has become a more or less realistic goal. However, recent studies (e.g., Milman et
17 al., 2012; Boerema et al., 2013; Wei et al., 2015a) clearly show that the optimal flow
18 distribution may not necessarily be uniform, but usually non-uniform corresponding to a
19 defined objective function and constraints for optimization. The extension of the term “flow
20 maldistribution” from “non-uniform distribution” to “non-optimal distribution” (Wet et al.,
21 2015b) raises higher requirements for the design and optimization of flow distribution
22 devices which are beyond the capabilities of conventional empirical propositions or
23 trial-and-error attempts.

24 In our previous study (Wei et al., 2015b), a Computational Fluid Dynamics (CFD)-based
25 evolutionary algorithm has been developed with the aim of realizing the target flow
26 distribution among parallel channels. The basic idea is to install a thin perforated baffle at the
27 distributing manifold and to optimize the size and distribution of orifices, in order to reach
28 the target flow-rate in every downstream channel. The effectiveness of the proposed
29 evolutionary algorithm has been tested by several 2D examples with different fluidic network
30 geometries (axisymmetric or nonaxisymmetric) and different target curves (uniform,
31 ascending, descending, or step-like). Numerical results show that the optimized flow
32 distributions reached are in good agreement with the target curves. As the first attempt on the
33 realization of target flow distribution, the optimized baffle insertion method has been
34 numerically confirmed as a practical solution to this issue. However, the proposed method
35 depends strongly on the accurate simulations of fluid flow so that experimental validation of
36 CFD models as well as the proposed algorithm is indispensable for bridging the gap between
37 theory and practice. This involves the simulation and optimization of 3D objects, their
38 fabrication and experimental characterizations which are still lacking.

39

1 The current study aims at presenting an experimental validation of the optimized baffle
2 insertion method for the realization of target flow distribution among parallel mini-channels.
3 For this purpose, different perforated baffles are designed, optimized, fabricated and installed
4 in a 15-channel fluidic network to test their capability of realizing different target
5 distributions (uniform or non-uniform). In parallel, 3D CFD simulations are also performed,
6 providing a comparison with the experimental results.

7 The experimental technique used in this study is based on flow visualization using
8 Particle Image Velocimetry (PIV) technique. Through recording the movement of seeding
9 particles illuminated by the pulsed sheet laser, the fluid flow velocity profiles can be obtained.
10 Compared to conventional flow-rate measurement techniques, such as Hot Wire Anemometry
11 (HWA) or Pitot tube, PIV as a non-intrusive method will not disturb the fluid flow
12 streamlines. Another advantage of PIV is the whole-field (or multiple points) measurement
13 which is unique compared with other non-intrusive single point measurement techniques,
14 such as Laser-Doppler Velocimetry (LDV) and Doppler Ultrasonic Velocimetry (DUV). A lot
15 of successful applications of PIV for fluid flow measurement have been reported in the
16 literature, including single phase (air or water) (e.g., Meinhart et al., 1999; Wen et al., 2006)
17 or multi-phase flow (e.g., Kiger and Pan, 2000; Lindken and Merzkirch, 2002), laminar or
18 turbulent flow (e.g., Sheng et al., 2000; Westerweel et al., 2013) and coupled thermo-fluid
19 characteristics (e.g., Carlomagno and Ianiro, 2014). Therefore, it is considered as a reliable
20 and accurate technique for flow-rate measurement.

21 In the rest of this paper, we shall first introduce the 15-channel fluidic network device
22 fabricated for study and optimized perforated baffles used for different operation conditions.
23 Then the experimental set-up and measuring procedure will be presented, as well as the
24 numerical parameters for CFD simulations. After, the numerical and experimental results of
25 several cases for different target distribution curves will be presented, compared and
26 discussed. The effective range of the optimized baffle when the working condition varies
27 from the design value will also be evaluated and discussed to provide some guidelines for
28 future applications. Finally, main conclusions and perspectives will be summarized.

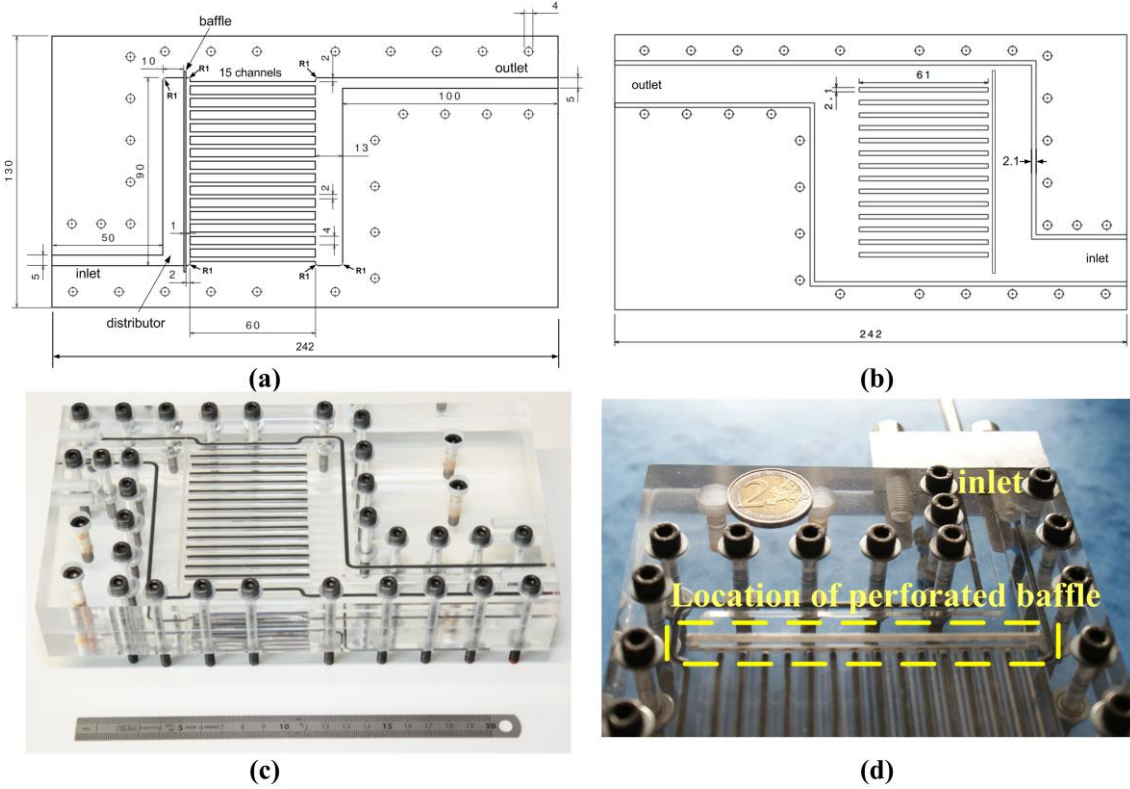
29 **2. Fluidic network device and optimized baffles**

30 In this section, the 15-channel fluidic network with the distributor and the collector will
31 be briefly introduced. The target distribution curves and optimized baffles will be presented
32 as well.

33 *2.1 15-channel device*

34 A mini-channel fluidic network consisting of 15 parallel channels, a distributor and a
35 collector is used for study, as shown in Fig. 1. The overall dimension of fluidic network is
36 242 mm in length and 90 mm in width. For the convenience of fabrication, the entire fluidic
37 network has the identical depth ($e=2$ mm). The inlet and outlet tubes located in diagonal
38 position have the same width of 5 mm, but different lengths (50 mm for inlet tube and 100

1 mm for outlet tube). The length of the distributing manifold is 13 mm and the width is 90 mm. In the distributing manifold, a groove with the thickness of 1 mm and the width of 96 mm is reserved for the installation of a perforated baffle. Identical dimensions are used for the collecting manifold (length of 13 mm and width of 90 mm) but without baffle groove.



5
6 **Figure 1: Geometry and dimensions of 15-channel fluidic network (unit: mm): (a) Parallelepiped A; (b) Parallelepiped B;**
7 **(c) Photo view after assembling; (d) Zoom on the inlet distributor and the location of the perforated baffle. Adapted from**
8 **Boutin et al. (2016).**

9 There are fifteen parallel straight channels having identical width of 2 mm, length of 60
10 mm and depth of 2 mm. They are evenly spaced at 4 mm between the axis of one channel and
11 another. For the convenience of description, they are indexed by k from 1 to M from the inlet
12 side to the outlet side. The mass flow-rate in k th channel is notated as m_k and the flow-rate
13 ratio σ is introduced for each channel as follows:

14
$$\sigma_k = \frac{m_k}{\bar{m}} \quad (1)$$

15 where \bar{m} is the average mass flow-rate among 15 channels given by:

16
$$\bar{m} = \frac{\sum_{k=1}^M m_k}{M} \quad (2)$$

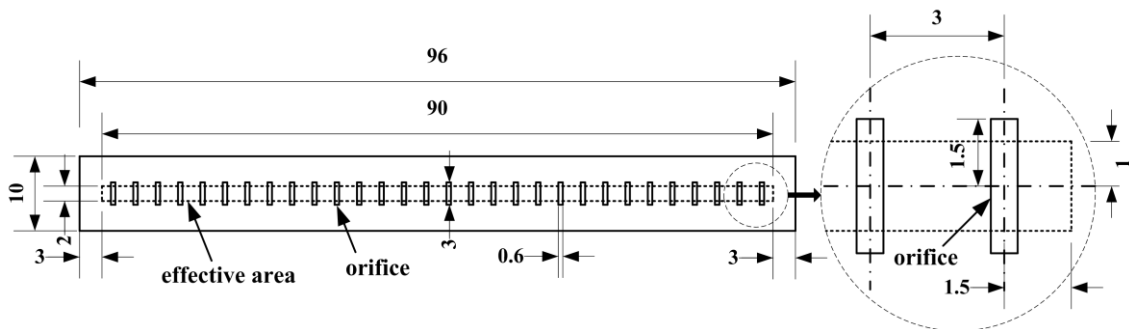
17 Note that it is a real 3D object with all parallel channels located in the same plane, suitable
18 for experimental tests of fluid flow distribution properties using visualization technique.

1 The device was fabricated in the laboratory LTN, France by digitally-assisted carving the
 2 network on the surface of a PMMA rectangular parallelepiped (A), as shown in Fig. 1(a). Six
 3 edge fillets (noted by R1 in Fig. 1(a)) having the same radius of 1 mm can be observed at
 4 different corners of the fluidic network due to fabrication process. Another PMMA
 5 rectangular parallelepiped (B) was also carved to form the enclosed fluidic network, as shown
 6 in Fig. 1(b). Note that the depths of the groove reserved for the baffle are 6 mm in rectangular
 7 parallelepiped A, and 4 mm in rectangular parallelepiped B to form the effective area of the
 8 baffle (the area that may be touched or passed through by the fluid flow). A number of
 9 grooves were reserved around the network or between neighboring parallel channels, and
 10 filled with rubble strips to prevent the water leakage. Moreover, 29 bolts were used for
 11 further sealing. The photo view of the 15-channel device after assembling is shown in Fig.
 12 1(c) and the location of baffle is indicated in Fig. 1(d).

13 2.2 Target distribution curves and optimized baffles

14 To validate the effectiveness of the optimized baffle insertion method, different target
 15 distribution curves are proposed to be realized, including a uniform curve, an ascending curve
 16 and a descending curve. The geometric dimensions of the optimized baffles are obtained
 17 accordingly using the CFD-based evolutionary algorithm developed in Wei et al. (2015b).

18 The thickness of the perforated baffle is 1 mm and the distance between the middle of the
 19 baffle and the inlets of parallel channels is 2.5 mm. For the convenience of installation, the
 20 baffle has a width of 96 mm and a height of 10 mm (as well as the groove for baffle), which
 21 is a bit larger than the cross-section of inlet distributing manifold. Likewise, the height of
 22 orifices is 3 mm, which is also larger than the thickness of the fluidic network ($e=2$ mm).
 23 However, the effective area of baffle is kept at $90 \text{ mm} \times 2 \text{ mm}$. 30 orifices are distributed
 24 equally on the effective area of baffle, with an identical spacing of 3 mm. For the
 25 convenience of description, they are indexed from 1 to 30 from the inlet side to the outlet side.
 26 For the initial uniform baffle subject to optimization (shown in Fig. 2), the orifices have
 27 identical width of 0.6 mm, the global porosity thus being 20%. Since the thickness of the
 28 entire network is fixed at 2 mm, the only variable for optimization is the width of orifice.
 29 Note that some of the parameters used here are determined or selected based on the
 30 parametric study presented in Luo et al. (2015) and Wei et al. (2015b).



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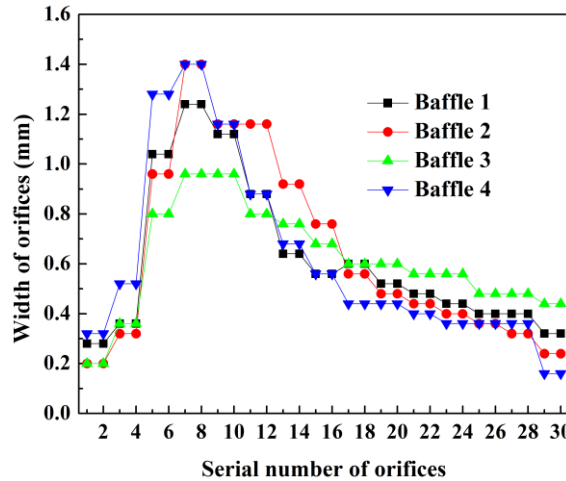
Figure 2: Geometry and dimensions of the uniform baffle with identical width of orifices (unit: mm).

1 In this study, four perforated baffles are optimized under two different inlet total fluid
 2 flow-rate conditions, i.e. high inlet flow-rate ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$) and low inlet flow-rate
 3 ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$), for representing both the turbulent and laminar flow patterns. The
 4 corresponding Re numbers in the inlet tube are 8500 and 850, respectively. The mean Re
 5 numbers in the parallel channels (Re_{ch}) are 1000 for $Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$ and 100 for $Q_{in}=0.18$
 6 $\text{L}\cdot\text{min}^{-1}$. The corresponding inlet flow-rate under which the perforated baffle is optimized is
 7 named as the baffle's design flow-rate. Baffles 1 and 2 are used for realizing uniform flow
 8 distribution among 15 parallel channels respectively under low or high inlet flow-rate
 9 condition ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=1000$). Baffles 3 and 4 are optimized for respectively
 10 achieving ascending or descending flow distribution under low inlet flow-rate ($Q_{in}=0.18$
 11 $\text{L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$). Baffle 5 is the uniform initial baffle with identical width of orifices
 12 whereas Baffle 6 is named as "empty baffle" for representing the configuration of distributing
 13 manifold without baffle insertion. The baffle number, the corresponding target curve, the
 14 design inlet flow-rate and detailed dimensions of the orifices are summarized in Table 1 and
 15 Fig. 3. Note that m'_k is the target value of mass flow-rate in k th channel.

16 **Table 1: Target curves and design flow-rates for different perforated baffles**

No. Baffle	Target curve	Design flow-rate
1	uniform $m'_k = \bar{m} \quad (k = 1, 2, \dots, 15) \quad (3)$	$Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$
2	uniform $m'_k = \bar{m} \quad (k = 1, 2, \dots, 15) \quad (3)$	$Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=1000$
3	ascending $m'_k = (0.025k + 0.8)\bar{m} \quad (k = 1, 2, \dots, 15) \quad (4)$	$Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$
4	descending $m'_k = (1.2 - 0.025k)\bar{m} \quad (k = 1, 2, \dots, 15) \quad (5)$	$Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$
5	Initial uniform baffle	-
6	Empty baffle	-

17



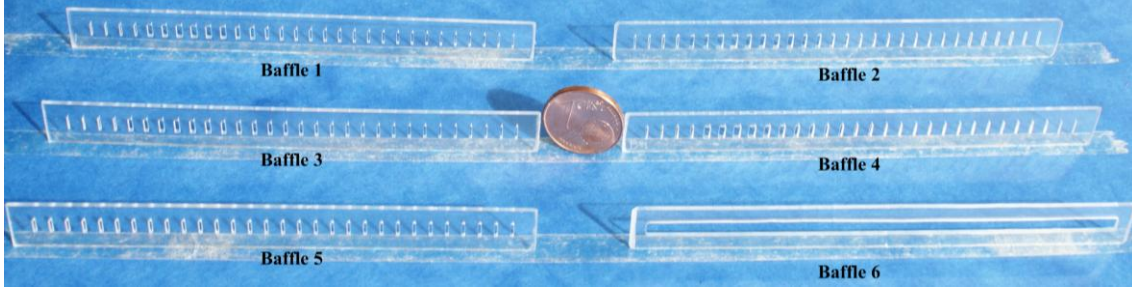
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19

Figure 3: Width distribution of orifices on the baffles.

20 The perforated baffles, as shown in Fig. 4, were also fabricated in the laboratory LTN by
 21 carving the orifices on thin PMMA slices, using a digital drilling machine. Theoretically,
 22 more precise optimization results lead to better approaching of target curves, but also set

1 higher requirements on computational abilities and fabrication precisions. For this study, the
 2 in-house fabrication tolerance is 0.01 mm and the minimum width of orifice is 0.16 mm,
 3 implying a possible deviation between the numerically optimized distribution and the target
 4 curve. To minimize this intrinsic maldistribution, more precise fabrication technologies
 5 should be introduced, with smaller fabrication tolerances.



6
7 **Figure 4: Photography of baffles used in this study.**

8 The degree of closeness between the target curve and the optimized flow distribution
 9 curve obtained by CFD-based evolutionary algorithm or by PIV measurement is quantified
 10 globally by the maldistribution factor (MF) and locally by the maximum deviation
 11 θ_{\max} defined as follows:

$$12 \quad MF = \sqrt{\frac{1}{M-1} \sum_{k=1}^M \left(\frac{m_k - m'_k}{\bar{m}} \right)^2} \quad (6)$$

$$13 \quad \theta_{\max} = \max \left(k = 1, 2, \dots, 15 \left\| \frac{m_k - m'_k}{m'_k} \right\| \right) \times 100\% \quad (7)$$

14 **3 Experimental setup and CFD simulation parameters**

15 *3.1 Experimental setup*

16 Figure 5 shows a schematic diagram of the experimental set-up built in the laboratory
 17 LTN. It is composed of fluid circuit and PIV measurement facility. Pure water was used in
 18 this study as the working fluid. In the fluid circuit, water was pumped from a 300 L water
 19 tank, then passed through the test section (15-channel fluidic network), and finally returned
 20 back to the water tank to form a closed loop. A precision pump (VWR, REGLO-Z,
 21 instrumental error less than 0.1%) was installed in the circuit with a measurement range of
 22 32-3200 mL·min⁻¹ and the output mass flow-rate was controlled directly based on its own
 23 readings. Fresh water was introduced to clean the 15-channel device after each series of tests
 24 and a filter was used to avoid the discharge of sewage.

25

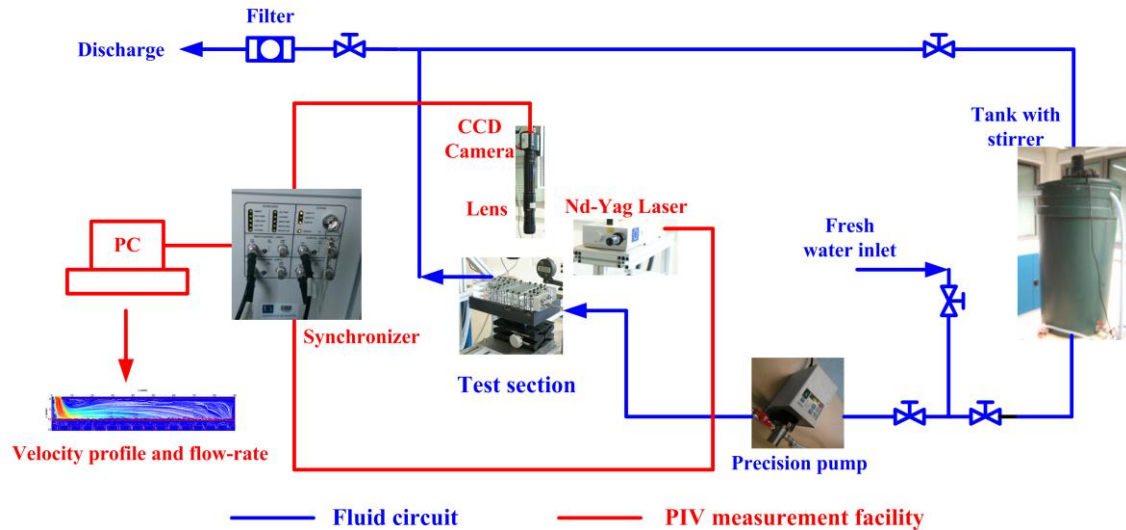
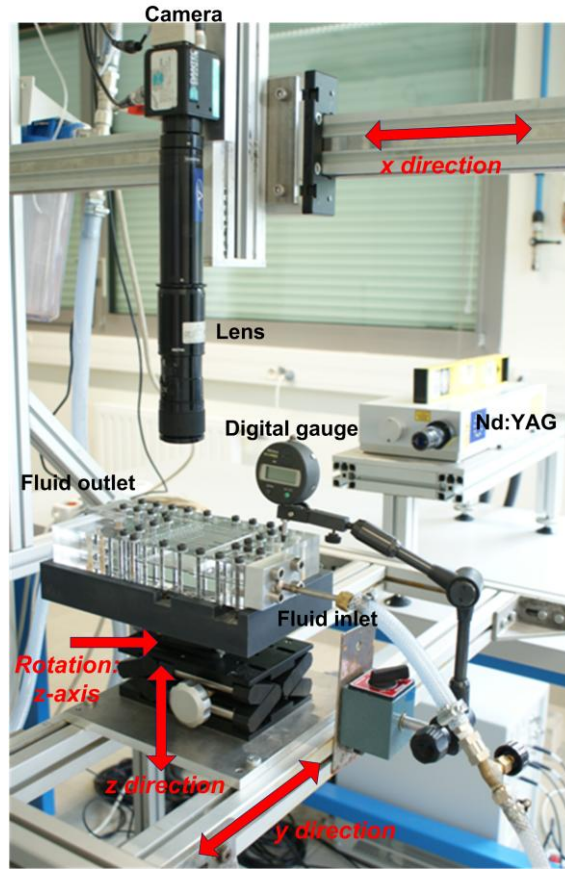


Figure 5: Schematic diagram of the experimental setup built for this study.

Standard 2D-2C PIV facility used in this study consists of illumination unit, image record unit, synchronous controlling unit and data processing unit. The light source used was Nd-Yag laser (Litron Incorporation, DualPower 65-15 DANTEC laser). The pulse energy was 65 mJ with the duration of 4 ns. The light wavelength was 532 nm and the diameter of light beam was 6.5 mm. The pulse frequency is 5 Hz, indicating that the fluid flow was recorded five times per second. The light scattered from the particles was collected by a CCD camera (DANTEC, FlowSense) with 2048×2048 pixels. An additional macro LAVISION lens was used to yield a magnification of about 230 pixel·mm⁻¹, corresponding to the view field of about 8.9 mm×8.9 mm. A synchronizer (DANTEC, 80N77) was used to guarantee that the laser and the CCD camera work synchronously. A commercial software FlowManager (v3.41) was used to control the PIV system and to process the data by 2-frame cross-correlation and Fast Fourier Transforms (FFTs). In the current study, the size of the PIV interrogation window was fixed at 16×16 pixels considering a compromise between the measurement accuracy and the computational time. The spatial resolution of PIV for this study is about 0.19 mm, determined by 2.8 times of the size of interrogation window (Foucaut et al., 2004). Polyamid Seeding Particles (PSP-5) supplied by DANTEC Company were used as seeding in our study with good chemical stability and environmental friendliness. The particle density is 1030 kg·m⁻³ and the diameter of particles ranges from 1 μm to 10 μm with the average of 5 μm.

Figure 6 shows the workbench specially designed and built which permits the subtle movements of the test-section. The camera can be moved in *x* direction whereas the platform to fix the test-section is moveable in *y* and *z* directions. The movements in *x* and *y* directions were realized using steel orbits while the movement of the platform along *z* direction was realized using a precise lift and a digital gauge with an accuracy of 0.01 mm. The focus of the lens must be adjusted for each vertical plane due to different scattered light optical paths, leading to different magnification ratios which must be taken into account in the

1 post-processing. The platform can also be rotated around z -axis to ensure a fine overlap
2 between the walls of channels and the boundaries of the PIV interrogation windows.



3 **Figure 6: Experimental workbench for subtle movements of the test-section.**

4 *3.2 Measurement procedure and uncertainty*

5 To obtain the flow distribution properties among parallel channels, the flow-rate in every
6 individual channel should be measured when the total inlet flow-rate is stable. To do that, the
7 cross-section of each channel was divided into 9 planes along z direction for measuring the
8 velocity profiles using 2D-2C PIV technique, with a stepping distance of 0.25 mm. It should
9 be noted that the laser source was fixed so that the device should be moved vertically along z
10 direction for different measuring planes, using the adjustable workbench described above.
11 Due to the limitation of the test view of PIV, at most two channels can be measured together
12 each time. For a total of 15 channels, the fluidic network should be moved along y direction
13 and then eight successive measurements should be repetitively performed.

14 In our pre-test, two numbers of instantaneous frames, 200 and 375, were used for each
15 plane to test the image independence. The maximum deviation is less than 0.1% (Boutin et al.,
16 2016). Therefore, 200 pairs of frames for each plane were enough to save the experiment and
17 post-processing time. In order to analyze the uncertainty of the 2D-2C PIV technique, the
18 results of total mass flow-rate obtained by PIV in this study are compared to the display of
19 high precise pump. The maximum possible deviation is 5.1% which will be indicated as the

1 error bar for PIV results in the following figures, implying that the PIV technique is relatively
2 accurate for flow-rate distribution measurements among parallel channels. More details on
3 the PIV measurement procedure may be found in our earlier work (Boutin et al., 2016).

4 *3.3 CFD simulation parameters*

5 To compare with the PIV measurements, 3D CFD simulations were performed to
6 calculate the flow-rate distribution among 15 parallel channels, using the same geometrical
7 characteristics as the fabricated device and the same working fluid of pure water with density
8 of $998.2 \text{ kg}\cdot\text{m}^{-3}$ and viscosity of $1.003\times 10^{-3} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$. The inlet mass flow-rate was set to be
9 constant according to different operational conditions. The operational pressure was fixed at
10 101325 Pa. Simulations were performed under steady state, incompressible and isothermal
11 condition without heat transfer. The gravity effect at $-z$ direction was also taken into account.
12 In fact, the optimized perforated baffles in Section 2.2 were obtained with the same
13 simulation parameters.

14 Navier-Stokes equations were solved by a commercial code ANSYS FLUENT (version
15 12.1.4), using COUPLED method for pressure-velocity coupling, and second-order upwind
16 differential scheme for discretization of momentum and standard method for pressure.
17 Laminar or standard $k-\varepsilon$ model was respectively used to simulate the laminar or turbulent
18 flow. Constant mass flow-rate at inlet surface was given and the boundary condition of outlet
19 was set as pressure-outlet with zero static pressure. Adiabatic wall condition was applied and
20 no slip occurred at the wall. The solution was considered to be converged when 1) sums of
21 the normalized residuals for control equations were all less than 1×10^{-6} ; and 2) the mass
22 flow-rate at each channel was constant from one iteration to the next (less than 0.5%
23 variation).

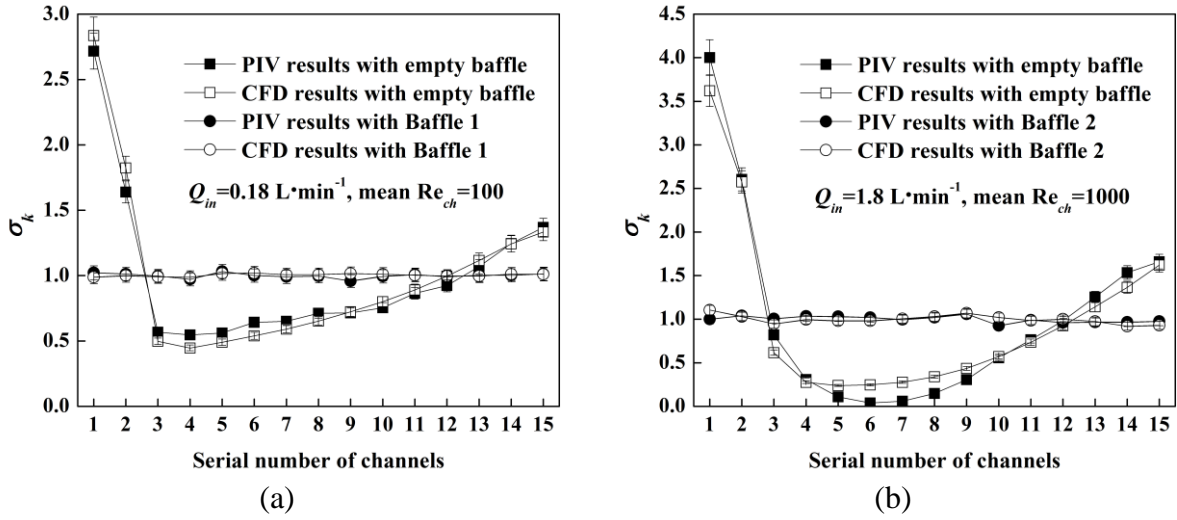
24 In the study, structured mesh was generated using software ICEM (version 12.1) to build
25 up the geometry model, including about 1.42 million elements in total. A grid independence
26 study was performed with a refined mesh with about 5.49 million elements in total. The
27 maximum difference of the mass flow-rate in each channel is less than 4.9% so that the
28 normal mesh was used as a compromise between the calculation time and the precision while
29 the value of 4.9% was indicated as error bars for CFD results in the following figures.

30 **4 Results and discussion**

31 *4.1 Realization of uniform distribution*

32 Two different inlet total fluid flow-rates (Q_{in}) were tested for uniform flow distribution,
33 i.e. low inlet flow-rate of $0.18 \text{ L}\cdot\text{min}^{-1}$ and high inlet flow-rate of $1.8 \text{ L}\cdot\text{min}^{-1}$. The numerical
34 (CFD, indicated by hollow symbols hereafter) and experimental (PIV, indicated by solid
35 symbols hereafter) results on fluid flow distribution among the 15 parallel channels are
36 shown in Fig. 7. Note that "empty baffle" (Baffle 6) is used as the reference case in this test.

1 The target curve for uniform distribution ($m'_k = \bar{m}$) is explicit (horizontal line at $\sigma_k=1.0$) so
 2 that it is not shown in Fig. 7.



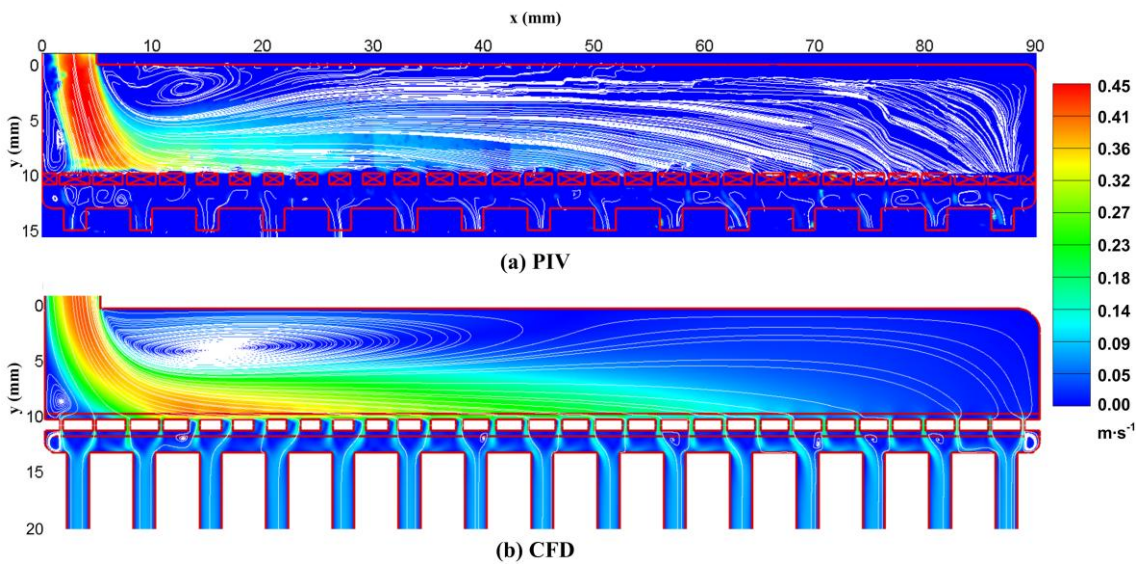
3 **Figure 7: Realization of uniform fluid flow distribution under different inlet flow-rate conditions: (a) $Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$,**
 4 **mean $\text{Re}_{ch}=100$; (b) $Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$, mean $\text{Re}_{ch}=1000$.**

5 Under low inlet flow-rate condition ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$; $\text{mean Re}_{ch}=100$) with empty
 6 baffle, the values of flow-rate are relatively high ($\sigma_k > 1.5$) in channel 1 and 2 facing to the
 7 inlet tube and then decrease rapidly to the lowest in channel 4, as shown in Fig. 7(a). After
 8 that, a slow increase of flow-rate appears till the channel 15 which is the farthest channel
 9 from the inlet tube. The flow distribution in the parallel channels is obviously non-uniform,
 10 with the σ_k values ranging from 0.55 to 2.72 (PIV results). Meanwhile, CFD and PIV results
 11 are in good agreement, implying that under low flow-rate condition, the laminar model is
 12 capable of correctly simulating the fluid flow. With the insertion of the optimized baffle 1, the
 13 fluid flow distribution among parallel channels is greatly homogenized and tends toward
 14 uniform, indicated by a small variation of σ_k values (both CFD and PIV) around 1.0. The
 15 maximum deviation θ_{\max} among 15 channels is lower than 5.0% and the corresponding MF
 16 value is smaller than 0.02.

17 Figure 7(b) shows the CFD and PIV results on flow distribution under high inlet
 18 flow-rate condition ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$; $\text{mean Re}_{ch}=1000$). With the insertion of empty baffle, a
 19 similar distribution curve may be observed compared to that under low-rate condition, the σ_k
 20 values ranging from 0.04 to 4.00 (PIV results). CFD results are also in good agreement with
 21 the PIV results for the general tendency, especially noticeable discrepancies for channels 5-9,
 22 implying the potential difficulties in simulation caused by turbulence and vortex flows. Even
 23 so, the insertion of the optimized baffle 2 serves as an optimized flow homogenizer to
 24 improve the distribution uniformity, indicated by the decreased MF value from 1.100 to 0.041
 25 (PIV results). For each channel, the maximum deviation θ_{\max} also decreases from 299.9% to
 26 8.0% (PIV result). For the case of optimized baffle, CFD results show better agreement with
 27 PIV results, indicated by almost flat distribution curves at $\sigma_k=1.0$.

1 To better validate the CFD simulations by PIV measurement, an examination on the fluid
 2 flow streamlines in the distributing manifold was carried out. Due to the limitation of view
 3 field, the inlet distributing manifold was divided into seven independent parts which were
 4 successively recorded by the CCD camera and then processed and connected so as to
 5 reconstruct the fluid flow streamlines in the whole distributing manifold, except for a narrow
 6 bar area which is not transparent due to the existence of the baffle. PIV and CFD results
 7 under low inlet flow-rate conditions ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$) with optimized
 8 baffle 1 are presented in Fig. 8. Corresponding flow streamlines obtained with empty baffle
 9 can be found in Fig. 7 of Boutin et al. (2016).

10 Under low inlet flow-rate condition, both the flow streamlines in the distributing
 11 manifold obtained by PIV and CFD methods seem smooth and regular. A vortex next to the
 12 inlet tube may be easily observed both on PIV and CFD images, with similar location and
 13 size. This also explains the good agreement between PIV and CFD results on flow-rate
 14 distribution among parallel channels. Due to the optimized dimensions of orifices on the
 15 baffle, the fluid flow downstream the baffle is changed significantly so that a relatively
 16 uniform fluid flow distribution is achieved.

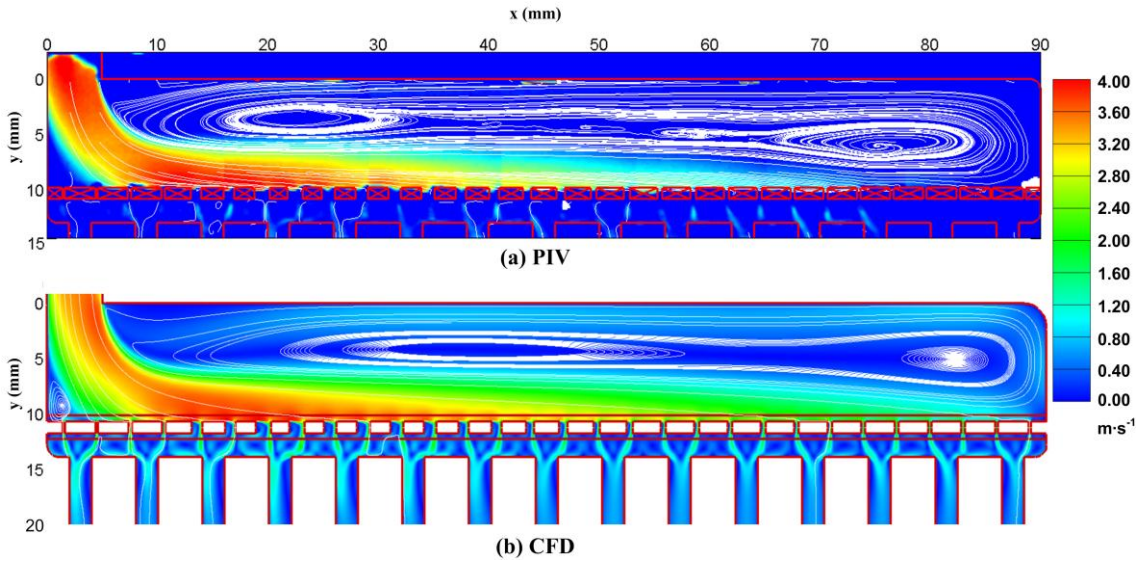


17
 18 **Figure 8: Streamlines in the distributing manifold under low inlet flow-rate condition ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=100$)**
 19 **with optimized baffle: (a) PIV measurement; (b) CFD simulation.**

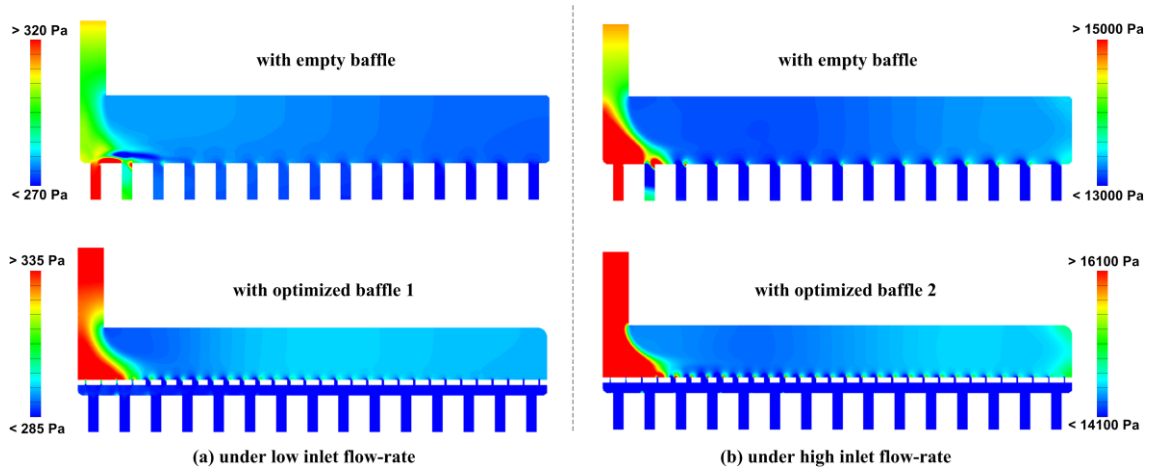
20 Figures 9 shows the streamlines in the distributing manifold with optimized baffle 2
 21 under high inlet flow-rate condition ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=1000$). Corresponding flow
 22 streamlines obtained with empty baffle can be found in Fig. 8 of Boutin et al. (2016). The
 23 flow profiles become irregular, indicated by the existence of more and larger vortices and
 24 recirculation flows. The difference of flow profiles under low and high inlet flow-rate
 25 conditions can be explained qualitatively based on the pressure distribution in the distributing
 26 manifold, as shown in Fig. 10. Under low inlet flow-rate, the pressure decreases gradually
 27 from inlet side to outlet side. On the contrary, a relative low-pressure area can be observed in
 28 the middle of the distributing manifold under high inlet flow-rate, implying a backflow from
 29 outlet side to inlet side which that generates obvious vortices. The inserted perforated baffle

1 mainly influences the downstream pressure distribution to regulate the fluid flow-rates in
 2 parallel channels.

3 With the optimized baffle 2, the sizes of the vortices in y direction are relatively smaller
 4 because of the reduced available space in the distributing manifold upstream the baffle.
 5 Similar to the cases for low inlet flow-rate condition, the locations of the vortices upstream
 6 the baffle are not significantly changed with or without the insertion of baffle 2. Nevertheless,
 7 because of optimized sizes of orifices, the fluid flow downstream the baffle is also controlled
 8 to achieve uniform flow distribution, illustrating and confirming the effectiveness of the
 9 geometrically optimized baffle insertion method.



10
 11 **Figure 9: Streamlines in the distributing manifold under high inlet flow-rate condition ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=1000$)**
 12 **with optimized baffle: (a) PIV measurement; (b) CFD simulation.**



13
 14 **Figure 10: Pressure distributions in the distributing manifold.**

15 The values of MF and the maximum deviation for empty baffle 6 and for optimized
 16 baffles 1 and 2 under different inlet flow-rate conditions are summarized in Table 2. It can be
 17 observed that the flow distribution finally achieved is relatively more uniform under low
 18 flow-rate condition than under high flow-rate condition. The precise control of fluid flow

1 becomes much more difficult due to the turbulent flow and the existence of various vortices,
 2 leading to higher uncertainties in CFD simulations, in evolutionary algorithm and in PIV
 3 measurement. Nevertheless, satisfactory results can still be obtained ($MF < 0.05$, θ_{\max} about
 4 10%) under high flow-rate condition and we are pretty sure that more satisfying results may
 5 be achieved by employing advanced computational facilities and precise fabrication
 6 techniques. Meanwhile, the total pressure drops of the fluidic network increase respectively
 7 by 4.95% from 391.9 Pa (empty baffle) to 411.3 Pa (optimized baffle) under low inlet
 8 flow-rate, and by 17.2% from 16786.8 Pa (empty baffle) to 19673.0 Pa (optimized baffle)
 9 under high inlet flow-rate. Extra energy consumption is inevitable to change the initial fluid
 10 flow distribution toward the target curve.

11 **Table 2: Maldistribution factor (MF), maximum deviation (θ_{\max}) and total pressure drop of the fluidic network (Δp) for**
 12 **empty baffle 6 and for optimized baffles 1 and 2 under different inlet flow-rate conditions**

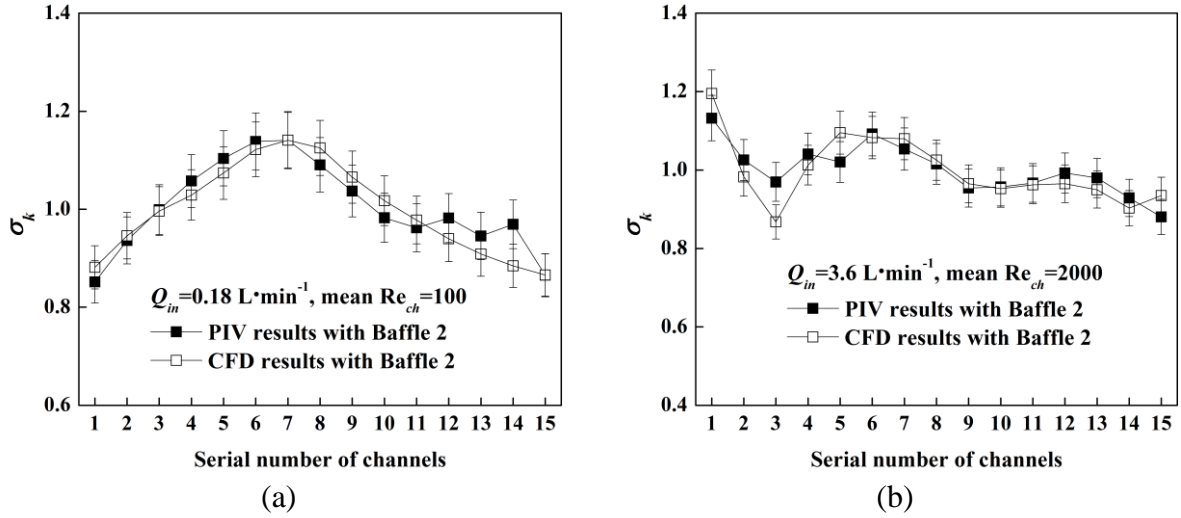
Operation condition	Parameter for maldistribution	Empty baffle		Optimized baffle for uniform distribution	
		CFD results	PIV results	CFD results	PIV results
$Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$ mean $Re_{ch}=100$	MF	0.637	0.577	0.011	0.019
	θ_{\max}	183.6%	172.2%	1.8%	4.7%
	Δp (Pa)	391.9	-	411.3	-
$Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$ mean $Re_{ch}=1000$	MF	0.973	1.100	0.049	0.041
	θ_{\max}	261.9%	299.9%	10.2%	8.0%
	Δp (Pa)	16786.8	-	19673.0	-

13 4.2 Effective range of optimized baffle - a robustness study

14 In the above sub-section, it has been demonstrated that under the design flow-rate
 15 conditions, the optimized baffles are really effective on the improvement of flow distribution
 16 uniformity. Generally, it is recommended that the optimized baffle should work under its
 17 design working condition and should be replaced by a new one when the operation condition
 18 changes. In real-world engineering however, the workload (inlet flow-rate) may be fluctuant
 19 so that the frequent replacement of baffle would become laborious, sometimes not
 20 cost-effective. Actually small deviations from target flow distribution may be acceptable
 21 when the tolerance on the distribution quality is relatively high. Therefore, it will be
 22 interesting and of practical significance to test the robustness of the optimized baffle when
 23 the inlet flow-rate deviates from its design value.

24 In this study, the optimized baffle 2 designed for uniform distribution ($Q_{in}=1.8 \text{ L}\cdot\text{min}^{-1}$;
 25 mean $Re_{ch}=1000$) was tested both numerically and experimentally under other two inlet
 26 flow-rate conditions, i.e. a lower flow-rate of $0.18 \text{ L}\cdot\text{min}^{-1}$ (mean $Re_{ch}=100$) and a higher
 27 flow-rate of $3.6 \text{ L}\cdot\text{min}^{-1}$ (mean $Re_{ch}=2000$). Note that for this higher flow-rate, a gear pump
 28 (MICROPUMP, O/CGC-M35.PVSF) with a measurement range of $1\text{-}5 \text{ L}\cdot\text{min}^{-1}$ and a flange
 29 flowmeter (KOBOLD, DPL-1P15GL443) are used. PIV and CFD results on the flow
 30 distribution among parallel channels obtained under different inlet flow-rate conditions are
 31 shown in Fig. 11. It can be obviously observed that the flow distribution becomes less

1 uniform when the inlet flow-rate deviates from the design value. More precisely, when the
 2 inlet flow-rate is reduced by a factor of 10 with respect to its design value ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$
 3 instead of $1.8 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=100$ instead of 1000), the flow distribution curve appears
 4 to be a parabolic shape, with the maximum in the middle channels (channels 6-7) and the
 5 minimum on both sides (channels 1 and 15). Contrarily when the inlet flow-rate is doubled
 6 ($Q_{in}=3.6 \text{ L}\cdot\text{min}^{-1}$ instead of $1.8 \text{ L}\cdot\text{min}^{-1}$; mean $Re_{ch}=2000$ instead of 1000), the actual
 7 distribution curve appears to be a multi-segment line fluctuating around $\sigma_k=1.0$.



8 **Figure 11: Effective range tests for optimized baffle (design flow-rate of $1.8 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=1000$): (a) lower flow-rate**
 9 **($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=100$); (b) higher flow-rate ($Q_{in}=3.6 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=2000$).**

10 The MF and θ_{max} values for the optimized baffle 2 under different inlet flow-rate
 11 conditions are listed in Table 3. It may be observed that the optimized baffle works less
 12 effectively when the working condition deviates from its design value, indicated by larger
 13 values of MF and θ_{max} . When the inlet flow-rate is reduced by a factor of 10 ($Q_{in}=0.18$
 14 $\text{L}\cdot\text{min}^{-1}$), the MF value is smaller than 0.095 while the θ_{max} value is lower than 15%. When
 15 the inlet flow-rate is doubled ($Q_{in}=3.6 \text{ L}\cdot\text{min}^{-1}$), the MF value is smaller than 0.085 while the
 16 θ_{max} value is lower than 20%. Within a large variation range of inlet flow-rate (a factor of
 17 0.1-2.0 with respect to the design value), the maximum deviation will rise to $\pm 20\%$, which is
 18 the double of that under design value ($< \pm 10\%$). However, compared to the empty baffle case
 19 (with θ_{max} higher than 170% at least), *the distribution non-uniformity is still limited at a*
 20 *relatively low level* under our tested conditions by the insertion of a sub-optimal baffle.

21 **Table 3: Maldistribution factor (MF) and maximum deviation (θ_{max}) values for the same optimized perforated baffle under**
 22 **different flow-rate conditions**

Parameter for maldistribution	Baffle 2 ($Re_{ch}=1000$)		Baffle 2 ($Re_{ch}=100$)		Baffle 2 ($Re_{ch}=2000$)	
	CFD results	PIV results	CFD results	PIV results	CFD results	PIV results
MF	0.049	0.041	0.093	0.090	0.085	0.065
θ_{max}	10.2%	8.0%	14.1%	14.8%	19.6%	13.5%

23

24

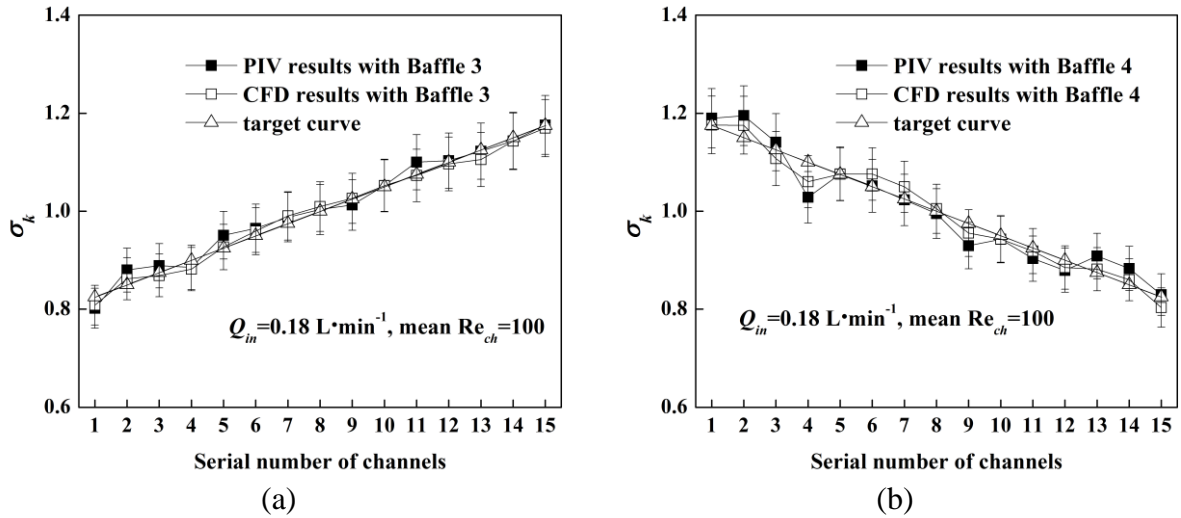
1 Results shown in Fig. 11 also confirm the reliability of CFD simulations by PIV
2 measurement. Generally speaking, the results obtained by PIV and CFD are in good
3 agreement with each other, forming similar curves under the tested working conditions. Due
4 to the potential simulation errors, or the uncertainty in PIV measurement, the flow-rates in
5 some individual channels may be slightly different (e.g., channel 14 in Fig. 11(a), and
6 channel 3 in Fig. 11(b)).

7 *4.3 Realization of non-uniform target flow distribution*

8 In our previous work (Wei et al., 2015b), we have numerically demonstrated the
9 realization of non-uniform target flow distribution by the insertion of an optimized perforated
10 baffle, which has never been achieved by other conventional methods to the best of our
11 knowledge. In this sub-section, we try to validate this distinguished feature of our method by
12 testing two representative non-uniform target curves, i.e. a linear ascending and a linear
13 descending curve. These target curves are mathematically described in Table 1 and indicated
14 by hollow triangular symbols (Δ) in the following figures. Corresponding perforated baffles 3
15 and 4 were optimized and fabricated, as shown in Table 1 and Fig. 4. These baffles were then
16 installed in the distributor section of the 15-channel fluidic network (Fig. 1) and PIV
17 measurements were performed under the inlet flow-rate $Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$. The results of
18 empty baffle 6 under the same working condition were also used as the reference case for
19 comparison.

20 Figure 12 and Table 4 present the CFD and PIV results for realizing the ascending or
21 descending curve, using the optimized baffle 3 or 4, respectively. It can be seen that the CFD
22 results are in good agreement with the PIV measurements, approaching quite well the target
23 curves. Compared to the empty baffle 6 case, the MF value is reduced from about 0.7 to
24 smaller than 0.02 for the ascending target curve, and from about 0.6 to about 0.03 for the
25 descending target curve, by using the optimized baffles. The θ_{\max} value also decreases from
26 about 240% to lower than 4% for the ascending target curve, and from about 140% to lower
27 than 7% for the descending target curve. Moreover, the extra pressure drops caused by the
28 inserted perforated baffles are about 5% for both cases. Based on the results obtained above,
29 it is experimentally validated that the CFD-based evolutionary algorithm developed in Wei et
30 al. (2015b) is capable of realizing some non-uniform target flow distributions among parallel
31 channels.

32 It should be noted that these target curves proposed and tested here are just simple
33 examples. By a logical extension of this point, we are quite confident that other shapes of
34 target distribution curves can also be approached by the insertion of optimized perforated
35 baffles. For some extreme operation situations (e.g., step-like target curve) however,
36 complementary methods (e.g., partition walls, second baffle, etc.) may be necessary and this
37 issue will be further investigated in our future work.



1 Figure 12: Realization of non-uniform target flow distribution using optimized perforated baffle ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$, mean
2 $Re_{ch}=100$): (a) ascending target curve; (b) descending target curve.

3

4 Table 4: Maldistribution factor (MF), maximum deviation (θ_{max}) and total pressure drop of the fluidic network (Δp) for
5 realizing non-uniform target flow distribution ($Q_{in}=0.18 \text{ L}\cdot\text{min}^{-1}$, mean $Re_{ch}=100$)

Parameter for maldistribution	Ascending target curve				Descending target curve			
	Empty baffle 6		Optimized baffle 3		Empty baffle 6		Optimized baffle 4	
	CFD results	PIV results	CFD results	PIV results	CFD results	PIV results	CFD results	PIV results
MF	0.665	0.619	0.011	0.016	0.628	0.576	0.019	0.030
θ_{max}	243.7%	201.4%	2.0%	3.5%	141.3%	111.6%	3.6%	6.5%
Δp (Pa)	391.9	-	409.1	-	391.9	-	413.2	-

6 4.4 Discussions

7 A close investigation on the flow streamlines in the distributing manifold indicates that
8 the locations and sizes of vortices are influenced significantly by the total inlet flow-rate. The
9 discrepancies between CFD and PIV results under high flow-rate condition can be observed
10 due to the well-known difficulty of correctly modelling turbulent flow. Consequently, the
11 flow distribution optimization under high flow-rate conditions is relatively more difficult
12 because the evolutionary algorithm used to optimize the perforated baffles relies on CFD
13 simulation results. Therefore, high performance computational facilities are generally
14 required for more accurate simulation of fluid flow. Meanwhile, CFD results must be
15 validated by experimental measurements, especially under turbulent flow condition.

16 In our evolutionary algorithm, it is basically recommended that each optimized perforated
17 baffle works under its design flow-rate to reach the best performance on flow distribution.
18 However, a deviation of flow-rate with a factor of 0.1-2.0 from the design value will not

1 significantly influence the flow distribution uniformity under our tested conditions. Therefore,
2 the replacement of the perforated baffle can be performed according to the tolerance on flow
3 distribution quality and the costs. If the larger deviation from the target curve cannot be
4 accepted, a new perforated baffle has to be optimized and reinstalled. The proper design of
5 new perforated baffle calls for the running of whole optimization process which might be
6 time-consuming. Alternatively, some rapid designs may also be proposed following the
7 similar pattern or tendency of baffle configurations already obtained.

8 In actual applications, some practical issues must be carefully considered, such as the
9 orifice blocking or abrasion which may potentially modify the effective sizes of orifices on
10 the perforated baffles. These problems can be solved by adding a filter on the inlet tube or
11 using wear resistant materials for the fabrication of baffles. The flow distribution
12 optimization is a systematic task, not simply depends on local design or structural
13 optimization of the distributor.

14 **5 Conclusion**

15 In this paper, CFD simulations and experimental (PIV) measurements have been
16 performed in a 15-channel fluidic network to validate the realization of target flow
17 distribution by the method of geometrically optimized baffle insertion. CFD and PIV results
18 obtained indicate that various target flow distributions (uniform, ascending and descending
19 curves) can be approached under different inlet mass flow-rate conditions. Main conclusions
20 are summarized as follows:

- 21 • Different CFD models used for simulations are validated by the PIV results. For
22 laminar flow, CFD simulation results (both flow distribution and streamlines) are in
23 excellent agreement with PIV measurements. For turbulent flow, CFD and PIV results
24 are also in good agreement with each other, but with a small deviation.
- 25 • The realization of different target fluid flow distributions (uniform, ascending and
26 descending curves) by the insertion of geometrically optimized baffles is validated by
27 PIV measurement. The MF values can be reduced from more than 0.5 to less than
28 0.05 for all cases by using the optimized baffles. Likewise, the values of θ_{\max} are
29 reduced from more than 100% to less than 10%.
- 30 • The robustness study implies that for uniform fluid flow distribution, the optimal
31 baffle can be used within a relative wide range of inlet flow-rate condition (by a factor
32 of 0.1 to 2.0 with respect to the design value), without affecting much the flow
33 distribution uniformity ($MF < 0.1$). For non-uniform target distribution, the robustness
34 depends clearly on the shape of target curve so that the influences will be more
35 complex and should be tested case by case.

36 Note that the fluidic network used in this paper is just a model example without any
37 practical application background. The method of realizing target flow distribution by the
38 insertion of a geometrically optimized baffle, which has been proposed and developed in Wei

1 et al. (2015b) and validated experimentally in this study, can be applied in various
2 engineering fields dealing with fluid distribution problem. This will be the main direction of
3 our future work.

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10 experimental set-up.

11 **Notations**

e	depth of fluidic network	m
m	fluid mass flow-rate	$\text{kg}\cdot\text{s}^{-1}$
m'	target fluid mass flow-rate	$\text{kg}\cdot\text{s}^{-1}$
\bar{m}	average fluid mass flow-rate	$\text{kg}\cdot\text{s}^{-1}$
M	total amount of parallel channels	-
MF	maldistribution factor	-
Δp	pressure drop	Pa
Q	volume flow-rate	$\text{L}\cdot\text{min}^{-1}$
Re	Reynolds number	-

12

13 *Greek symbols*

θ_{\max}	maximum deviation	-
σ	flow-rate ratio	-

Subscripts

ch	channels
in	inlet
k	channel index

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5 Figure 10: Pressure distributions in the distributing manifold.

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