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

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ABSTRACT

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

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

1. Introduction

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

In the majority of the existing literature, flow maldistribution is synonymous with "non-uniform flow distribution", implying that uniform shape is assumed, or considered to be the optimal distribution among parallel channels. Various methods have been proposed to improve the fluid flow uniformity, as summarized in Rebrov et al. (2011) and Luo et al. (2015). Through continuous efforts of academic or industrial researches, uniform fluid flow distribution has become a more or less realistic goal. However, recent studies (e.g., Milman

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Nomenclature

e	depth of fluidic network (m)
m	fluid mass flow-rate(kg s^{-1})
m'	target fluid mass flow-rate (kg s^{-1})
$\bar{m}$	average fluid mass flow-rate (kg s^{-1})
M	total amount of parallel channels
MF	maldistribution factor
Δp	pressure drop (Pa)
Q	volume flow-rate (L min^{-1})
Re	Reynolds number
Greek symbols	
$\theta_{\max}$	maximum deviation
σ	flow-rate ratio
Subscripts	
ch	channels
in	inlet
k	channel index

et al., 2012; Boerema et al., 2013; Wei et al., 2015a) clearly show that the optimal flow distribution may not necessarily be uniform, but usually non-uniform corresponding to a defined objective function and constraints for optimization. The extension of the term “flow maldistribution” from “non-uniform distribution” to “non-optimal distribution” (Wei et al., 2015b) raises higher requirements for the design and optimization of flow distribution devices which are beyond the capabilities of conventional empirical propositions or trial-and-error attempts.

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

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

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

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

2. Fluidic network device and optimized baffles

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

2.1. 15-channel device

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

There are fifteen parallel straight channels having identical width of 2 mm, length of 60 mm and depth of 2 mm. They are evenly spaced at 4 mm between the axis of one channel and