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Numerical study on the improvement of flow distribution uniformity among parallel mini-channels

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ABSTRACT

Parallel micro or mini-channels are widely used in various devices of process and energy engineering including micro-reactors, compact heat exchangers and fuel cells. Nevertheless, the flow maldistribution due to the improper design of distributor/collector is usually observed, leading to globally poor performances of these devices. The objective of this study is to optimize the shape of the distributor/collector pipes so as to achieve a uniform flow distribution among an array of parallel mini-channels. A Z-type ladder fluid network with 10 mini-channels in parallel having square section is introduced and investigated. Two methods are used to optimize the shape of distributor/collector pipes: an optimized discrete stairway shape and a continuous tapered shape with an inclined angle varying from 0° to 30°. 3D-CFD simulations are carried out using the ANSYS FLUENT code. Numerical results obtained show that a relatively uniform flow distribution may be reached by the discrete stairway shape or by the continuous tapered shape distributor/collector under very low flow-rate conditions. Larger inclined angle or fewer channels in parallel are favorable for more uniform flow distribution under higher flow-rate conditions. Nevertheless the distributor and the collector pipes occupy a large volume so that the entire device is less compact.

1. Introduction

Chemical industries and process engineering are undergoing rapid changes in the 21st century facing the challenges of climate change and energy shortage. Process intensification (PI) that leads to smaller, less costly, cleaner, safer, higher productivity and more energy efficient technologies is proposed as a new paradigm of process engineering [28]. Particularly, the innovative design of high yield processes or compact equipments has become one of the pressing industrial needs in recent years [5].

One of the routes to PI is the use of equipments with locally miniaturized structures, i.e., micro or mini-channels [4,17,5], because of their enhanced heat and mass transfer properties. Miniaturized process and energy equipments can either be heat exchangers (e.g., [8,9,15]), chemical mixers or reactors (e.g., [12,13,10]), fuel cells (e.g., [29,14])or integrated multifunctional systems (e.g., [2,11]). Nevertheless, to obtain a comparable productivity with that of conventional equipment, a number of micro/mini-channels should be installed in parallel. This so-called numbering-up process is the key issue for large-scale industrial applications of these miniaturized devices [1,17]. Therefore, the fluid distribution uniformity among the parallel channels may play an important role on the global performance improvement of multi-channel equipments.

This is particularly true when multi-scale ladder-type fluid networks (Fig. 1a) are involved [27,7]. In order to achieve uniform flow distribution among all parallel channels in the network, the first and essential step is the design of an optimized two-scale elementary Z-type ladder circuit, as shown in Fig. 1b. In this elementary fluidic circuit, the single inlet port and single outlet port are located on opposite sides of the bundle of parallel cross-channels, meaning that the flow direction is the same in the distributor and the collector pipes. All cross-channels are assumed to have the same geometrical characteristics so that the passage-to-passage maldistribution may be considered as negligible [25]. On the contrary, the improper design of fluid distributor/collector pipes is the main cause of flow maldistribution among the parallel cross-channels.

Many studies have then been focused on how to improve the flow distribution uniformity of the elemental Z-type ladder circuit. It is reported that a relatively uniform distribution may only be approached by making the hydraulic resistance of cross-channels

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Nomenclature

D_h Hydraulic diameter (m)
e Thickness of the fluidic network (m)
q Volume flow-rate ($m^3 s^{-1}$)
$\overline{q}$ Mean flow-rate among mini-channels ($m^3 s^{-1}$)
f Friction factor (–)
F Form factor (–)
$\vec{F}$ External body force ($kg\,m\,s^{-2}$)
g Gravitational acceleration ($m\,s^{-2}$)
I Unit tensor (–)
l_x Space between two mini-channels (m)
L Length (m)
MF Maldistribution factor (–)
N Number of parallel mini-channels (–)
p Static pressure (Pa)
R Hydraulic resistance ($Pa\,s\,m^{-3}$)
Re Reynolds number (–)
u Velocity ($m\,s^{-1}$)
U_{in} Velocity at the inlet of the network ($m\,s^{-1}$)
w Width (m)

Greek symbols
Δp Pressure loss (Pa)
θ Angle of distributor/collector pipes (°)
μ Viscosity ($kg\,m^{-1} s^{-1}$)
$\prod$ Stress tensor (–)
ρ Density of the fluid ($kg\,m^{-3}$)
σ Relative flow-rate deviation (–)

Subscripts
c Collector pipe
ch Mini-channel
d Distributor pipe
in Inlet
k Channel index
out Outlet

much larger than that of the distributor and collector pipes if the latter have a uniform profile (e.g., [26,30]). This usually implies that the distributor and collector pipes are large and encumbering, which is clearly unfavorable for miniaturized devices. Instead of the uniform profile (rectangular or cylinder shape) of the distributor and collector, alternative shapes were proposed, such as triangular or trapezoidal-type (e.g., [16,6,23]) or curvatured shape (e.g., [22,3,14]). In particular, Tondeur et al. [31] proposed to taper the profile of distributor and collector pipes in a discrete stairway so that the flow resistances vary linearly with position, which may offer a uniform flow distribution among the parallel cross-channels. Analytical scaling relations were established based on the assumptions of Poiseuille flow and negligible singular losses (pressure losses due to divergent/convergent branching). However, no numerical or experimental work has been performed to evaluate the validity and the effective range of this analytical model. The sensitivity of the flow distribution characteristics subjected to different working conditions (e.g., different flow-rate) has not yet been reported.

In the present work, the flow distribution properties on a typical Z-type elemental ladder circuit are systematically investigated. We will first describe the design of a mini-channel array with integrated discrete stairway shape distributor and collector pipes based on the scaling relations proposed by Tondeur et al. [31]. In addition, a continuous model with progressive dimension reduction (or increase) for the distributor pipe (or the collector pipe) is also introduced for comparison. Then, computational fluid dynamics (CFD) simulation results for both models will be reported, under a variety of flow-rate conditions. After that influences of some design parameters including the inclined angle and the number of parallel channels will also be discussed. Finally, main conclusions and perspectives will be summarized.

2. Geometry and numerical parameters

In this section, the design of parallel mini-channel array with integrated distributor/collector pipes based on two models, i.e., the discrete stairway model and the continuous tapered model will be briefly described. The CFD simulation tool and the controlling parameters will be introduced as well.

2.1. Geometry of the tested mini-channel array

Fig. 2 shows a representative schematic view of Z-type elemental ladder fluid circuit. The 3D fluid domain consists of 3 sections: inlet distributor pipe, parallel mini-channel array, and outlet collector pipe. This Z-type elemental ladder network is widely used in different applications such as catalytic reactors, solar receivers, heat exchanger plates, elements of fuel cells, electrochemical microreactors, cooling network of heat sinks, or other process components. For the convenience of potential fabrication, the entire fluidic circuit has the identical channel depth (e = 1 mm). There are 10 parallel straight channels (N = 10) of identical length (L_{ch} = 20 mm), width (w_{ch} = 1 mm) and depth (e = 1 mm). They are evenly spaced (l_x = 2 mm) between the axis of one channel and another. Square cross-section is used for the channels because it is adapted for future experimental visualization of the internal flow using digital camera and optical tracers. Here we introduced a millimetric design (hydraulic diameter of

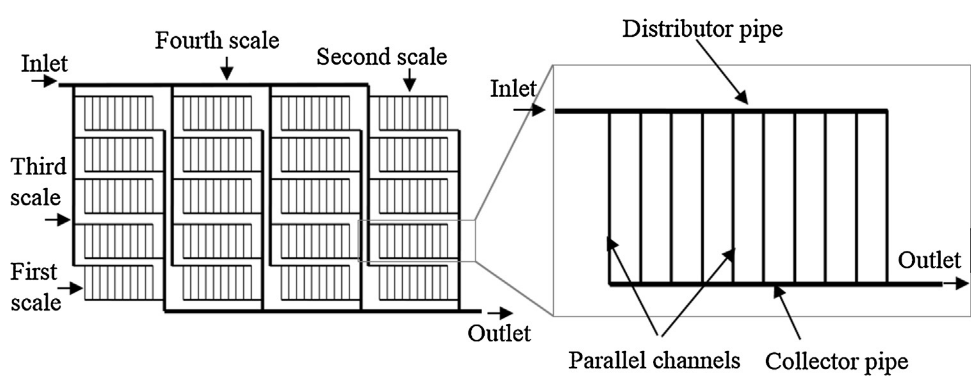

Fig. 1. Multi-scale fluidic network (a) and elementary Z-type ladder circuit (b).