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Numerical analysis on the effect of bifurcation angle and inlet velocity on the distribution uniformity performance of consecutive bifurcating fluid flow distributors

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ABSTRACT

2-D numerical models have been used to analyze flow distribution performance in consecutive bifurcating fluid flow distributors according to constructal theory. The quantitative analysis of flow distribution uniformity performance for Y shape distributors with different bifurcation angles as well as inlet velocities are evaluated with water as working fluid, a hypothesis on the mechanism for the maldistribution is also presented. It is found that the flow distribution uniformity deteriorates with the increase of bifurcation angles from 15° to 90°, and the worst performance occurs when bifurcation angle is 90°, where the largest pressure drop also appears. Furthermore, the flow distribution performance also decreases with increasing inlet velocity for the same distributor. Finally, an improvement to obtain more uniform flow uniformity for the T shape distributor is proposed by 'shrinking' the vertical channel width of each bifurcation. The conclusions obtained in this paper are potentially helpful for the design of fluid distributors for multi channel devices.

1. Introduction

Flow distribution has significant influences on the performance of fluidic devices in many industrial applications. Such as micro-channel reactors [1–2], plate-type heat exchangers [3–5], as well as in various types of fuel cells [6–9]. Better heat transfer and temperature control, low pressure losses (which means less pumping power), and a minimization of energy dissipation can always be provided through uniform flow distribution, especially for the numbering up of devices for industrial-scale applications with thousands of parallel channels.

A lot of investigations have been made in recent years to get better flow uniformity. Setting punched baffle in the inlet header is proved in experiment by Lalot et al. [10], they found that the maximal velocity ratio decreases between different channels when the punched baffle is used, which leads to an increase of efficiency up to 25% for a cross-flow heat exchanger. Besides setting baffle, U-shape, *Z*-shape, and slanted Z-shape [11–12] configurations are very typical 2D flow distribution designs. In general, many of these similar types of distribution manifold configurations do not exhibit high uniformity of flow distribution to parallel channels.

In order to solve the maldistribution problem, Bejan et al. [13] proposed a new constructal theory, and pointed out that each constructal distributor has a specific topologically structure which connects one point to a finite area by branched channels, the energy dissipation and residence time could be decreased and the back flow that usually occurs in traditional flow distributors can also be suppressed by the constructal structure.

Based on the constructal theory, the so called 2D flow distributor has been paid a lot of attention as a uniform flow distribution could be obtained for multiple parallel flow channels on a flat plate, as well as its small volume and easy fabrication [14–16]. 2D distributor is always geometrically symmetrical because all the outlets come from one inlet by a few stages of symmetrical bifurcation. Luo et al. [17] investigated the thermal performance and pressure drop in mini crossflow heat exchanger with constructal distributors and conventional pyramid distributors, experimental results show that the integration of constructal distributor could homogenize the fluid flow distribution and consequently lead to a better thermal performance of the mini crossflow heat exchanger. Fan et al. [18] experimentally studied the flow distribution behavior of a plate-type flow distributor with one inlet and 16 outlets, good flow distribution is achieved by the constructal distributor with standard deviation of the flow rates from 0.050 to 0.069, and the ratio of the highest flow rate to the lowest among all the 16 outlets are from 1.170 to 1.252 when the averaged Re increases from 1020 to 2247. A

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Nomenclature

c_i	Width of channels(m)
c_r	Ratio of width of channels of one stage against that of the previous stage
f_i	length of vertical part of bifurcation channels(m)
f_r	the ratio of c against f
p	Pressure (Pa)
U_i	average velocity at the outlet of channel i (m/s)
U_{in}	Inlet velocity(m/s)
U_{mean}	average value of all the velocities Ui of a flow distributor (m/s)
U_{max}	Maximal average velocity among the 16 outlets(m/s)
U_{min}	Minimal average velocity among the 16 outlets(m/s)
w_i	Channel gap width of outlet channels(m)

Greek symbols

α	The angle of channel bifurcation
β	Non-dimensional parameter indicating overall flow distribution uniformity
ξ	Non-dimensional parameter indicating the worst case of flow distribution uniformity
ρ_{mix}	Density working fluid (kg m^{-3})
μ	Viscosity of working fluid(Pa s)

multichannel heat exchanger-reactor with arborescent structure was designed, fabricated and tested by Guo et al. [19], it was found that the proposed arborescent structure provides almost uniform distributing feature among channels, and maximum deviation of flowrate with respect to the mean value is < 10% for the 16 channels. Ramos-Alvarado et al. [20] implemented a plate-type constructal flow distributor as a gas distributor for a proton exchange membrane fuel cell, a 3D model was developed to simulate the constructal flow configuration, and they found that the number of branches is the key parameter in the performance of a fuel cell when using the constructal distributors as flow channels.

Among the bifurcation structure distributors, the tree-shape distributor is easy to design and manufacture, moreover, as its end part fit the parallel microchannel structure very well, thus has particularly great potential to be used in microchannel heat exchangers and microreactors. Liu et al. [21] experimentally studied two typical designs, T-shape and circular-shape flow bifurcations, and found that the circular shape bifurcation structure to deliver more uniform distributions that than the T-shaped one. However, the tree-shape bifurcation distributor and its angle effect on the flow uniformity have not been investigated.

The specific geometrical structure of the tree-shape bifurcation distributor affects the flow uniformity significantly. In this work, the velocity distribution in tree-shape flow distributors with different bifurcation angles are investigated numerically, the flow distribution performance of the designed distributors are analyzed quantitatively using non-dimensional parameters. The improvement of T shaped flow distributors will also be carried out, which are expected to be of interest in industrial applications.

2. Mathematical model

A schematic diagram of the tree shape bifurcation distributor is shown in Fig. 1. The following parameters are used to identify the geometry of the flow distributor: α is the half value of bifurcation angle, w_i denotes the fin width between outlet channels, c_i and f_i denote the channel width and the length from the end of one bifurcation to the beginning of the next bifurcation of i stage, the ratio $c_r = c_{i+1}/c_i$ and $f_r = f_i/c_i$ are both defined for the geometry description. A value of $c_r = 0.5$ is used in this work to avoid acceleration between the total inlet and outlet channels. f_r can affect the uniformity of the flow, here $f_r = 2$ is used for all the stages.

In order to get a clear distribution performance comparison of different distributors, the channel length f_4, width c_4 as well as channel fin width w_4 of the last stage bifurcation, which is stage 4 in this study, are fixed and set as the same for all the models in this study.

The continuum equation and laminar flow Navier-Stokes equations are used as the governing equations to calculate the velocity field distribution in distributors:

$$\nabla\cdot\vec{u} = 0 \quad (1)$$

$$\rho\vec{u}\cdot\nabla\vec{u} = -\nabla p + \mu\nabla^2\vec{u} \quad (2)$$

The parameters used in the calculation are listed in Table 1. Based on the parameters, the software COMSOL Multiphysics was used for all calculations. Simulations have been conducted under stationary conditions, and all the results are mesh-independent.

3. Results and discussion

3.1. The effect of bifurcation angle on flow distribution uniformity

The non-dimensional average velocities at each of the 16 outlet channels of distributors with different bifurcation angles using an inlet velocity of $U_{in} = 0.1$ m/s are shown in Fig. 2. It can be seen that the velocity at 16 outlets show a small deviation from uniformity when the bifurcation angle varies from 15° to 45°, the maximal average outlet velocity U_{max} is within 5% of U_{mean}. Thus the effect of bifurcation angle on the velocity uniformity performance is not significant at this range of angles. However, the velocity difference among the 16 outlet channels gets larger when α increases. It can be noted from Fig. 2 that the deviation between U_{max} and U_{mean} increases to 16% when α = 90°.

In order to quantify the flow uniformity of each flow distributor, two non-dimensional parameters are adopted from [21]. The first

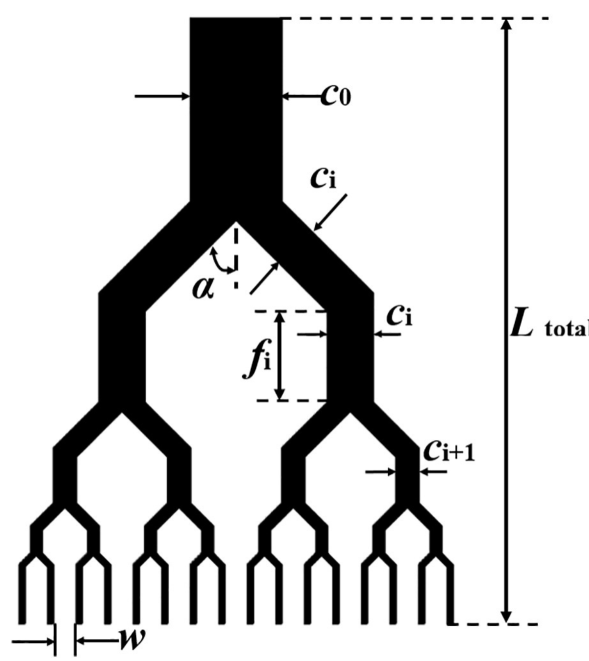

Fig. 1. Schematic of bifurcation structures analyzed in the simulation.