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Experimental analysis of fluid dynamics in microchannels featuring two-scale fin pin arrays

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Abstract. Optimizing the geometry of internal microchannel structures is critical to the design of efficient microfluidic devices. This study addresses the pressing issue of understanding how the distribution of circular cross-section pins within microchannels affects integral hydrodynamic performance. We employ a comprehensive experimental methodology combining high-speed imaging, optical microscopy, and microfluidic platform fabrication using polydimethylsiloxane based on the lab-on-a-chip technology. A series of experiments were conducted under varying pressure drops to assess the throughput of microchannel structures with different fin pin configurations. Results demonstrate a significant reduction in microchannel throughput upon the introduction of a secondary porosity scale.

1 Introduction

Understanding the fundamentals of microscale fluid flows and methods to control them is crucial in advancing various technologies, including microfluidic heat exchanger design, enhanced oil recovery, additive manufacturing, and composite material fabrication. In recent years, the electronics industry has made significant progress in developing three-dimensional chips, where multiple substrates with electronic components are arranged in parallel at distances of 50–100 μm. This three-dimensional structure complicates heat dissipation, driving increased interest in liquid-based microscale cooling systems. Integrating heat exchangers directly within chips enables microchannels to be positioned closer to highly heated regions, thereby enhancing cooling efficiency. Designing these systems requires an in-depth understanding of hydrodynamic behavior within microchannels.

Extensive research has been carried out to understand the fundamentals of the physics of fluid flow in microchannel heat transfer systems [1]. Intensification of heat transfer by changing the channel geometry is of active interest to the scientific community, both from the experimental point of view and from the theoretical one. To improve the efficiency of heat exchangers, microchannels with complex internal structure are actively used nowadays. For example, planar microchannels containing arrays of distributed columns of different shapes. The idea of this modification was proposed in the paper [2]. The main feature of the configuration is to increase the surface contact area with the coolant and realize better mixing in the flow. In addition, this design also helps to transform and reduce the thickness of the

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thermal boundary layer in the flow field, which helps to improve heat transfer. Developments in this field have several directions: variation of shape, height, packing density, and column distribution [3]. Varieties of studies have been conducted in the literature to investigate the influence of the shape of the posts on the heat transfer efficiency in microchannel systems. It is shown, that square and round cross-sectional pins are optimal [4].

The configuration of the microchannels is crucial, as it must provide both the maximum possible heat transfer surface and acceptable hydrodynamic losses. As the size of the heat sink elements is reduced, the surface area relative to the volume increases, thus promoting more efficient heat transfer. However, this can also increase fluid flow resistance and manufacturing complexity. Correct sizing, geometry, and distribution of elements within the microchannel are key to improving heat removal efficiency and optimizing the flow of coolant or other carrier fluids in the microchannel.

The study of flow regimes in microchannels of complex internal structure with the resulting hydraulic diameter less than 100 µm and integral characteristics of flow in such systems is an interesting task possessing essential novelty. The relevance of this study is due to the fact that when considering the fluid flow in complex domains at the microlevel, it is necessary to take into account their structural features, because they significantly affect the occurrence of stagnant zones and, as a consequence, change the carrying capacity of microstructures as a whole.

Most of the research focuses on models with homogeneous distribution of pins in the channel space. While models with multiple scales of pin distribution may be of interest for a number of applications. The dual porosity medium representation is also used in the study of reinforcing fiber impregnation processes in the composite materials industry [5]. In biomedical applications, dual porosity models are used to more correctly estimate the permeability of biological tissues [6]. Representation of pore space as micro-models with multiple porosity scales is also actively used in the oil and gas industry [7].

This work is devoted to the experimental study of the influence of the second scale of ordering of cylindrical pins on the hydrodynamic resistance of the microchannel section. The experimental approach used is based on modern methods using high-speed cameras, optical microscopy techniques, technology for the production of integrated microinstruments based on microfluidic devices created using lab-on-a-chip technology.

2 Materials and methods

In this work, to carry out the study of flows in microstructures of complex configuration the experimental setup was assembled on the basis of an Olympus IX-71 optical microscope (Fig. 1).

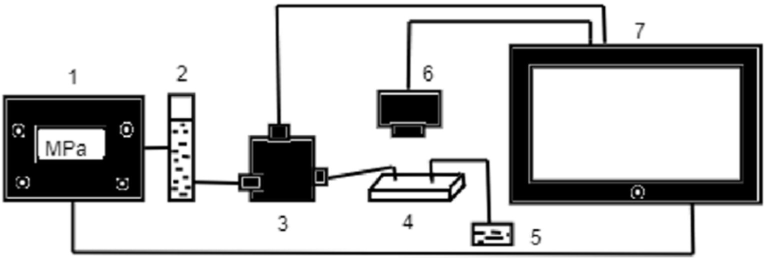

Fig. 1. Scheme of the experimental setup: 1 – Pressure controller (Parker Hannifin); 2 – Fluid tank; 3 – Flow sensor (Sensirion); 4 - Microfluidic chip; 5 – Drain; 6 – Optical microscope with video camera (Olympus IX-71, Lumenera Infinity 2); 7 – PC.

Fluid flows in the chip were created using a syringe pump and VSO-BT pressure controller (Parker Hannifin). Hydraulic losses during fluid flow through the microfluidic chip were determined using differential pressure sensors. Using soft lithography methods [8], three microfluidic chips from a two-component cross-linked polymer - polydimethylsiloxane (PDMS), with different porous structures formed by a system of cylindrical pins of the same diameter $d = 120\ \mu m$, the height of the pins was equal to the channel height $h = 23\ \mu m$, were fabricated.

This work investigated the effect of spatial redistribution of pins within the channel, so three chip configurations were developed. In order to form the second scale of porosity at constant number of pins, their spatial distribution was changed - groups of 9 columns located at a certain angle to the flow direction were formed. Thus, the void fraction of all variants remained constant and was equal to $\varphi = 0.8$. The total void fraction φ of the microchannel cross-section in the *xOy* plane was calculated as the ratio of the sum of the cross-sectional areas of the pins to the cross-sectional area of the whole channel section.

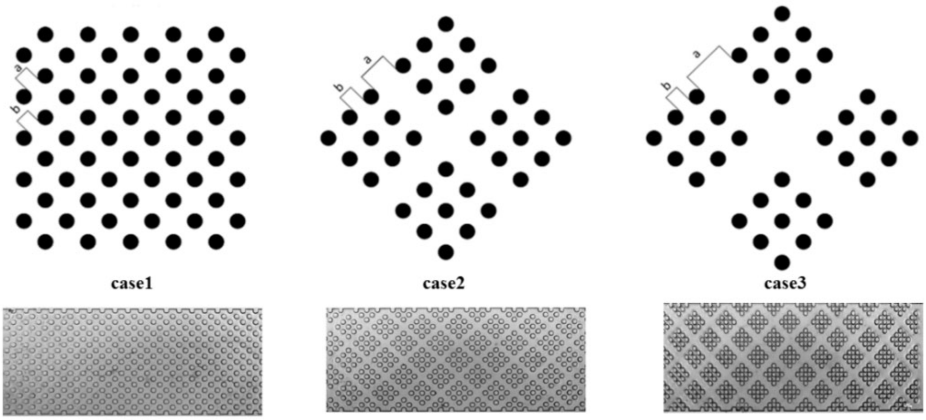

Fig. 2. Schematic representation of pin array configurations in a microchannel.

A schematic representation of the three configurations is shown in Fig. 2., where a and b are the channel widths between pin blocks and between pins within grouping blocks, respectively. For all cases, the distance $a + 2b = 270\ \mu m$ remains constant, while for the case1 $a = b = 90\ \mu m$, for the case2 - $a = 150 \mu m,\ b = 60\ \mu m$, for the case3 - $a = 190 \mu m$, $b = 40\ \mu m$. The geometry of the computational domain includes two levels of voids: wide channels between blocks and narrow channels between the elements. To estimate the hydraulic radius of the wide and narrow channels, a geometric coefficient is introduced. The change in this coefficient affects the overall flow pattern in the channel. The coefficient is defined as the ratio of the hydraulic diameters: $k_r = r_a/r_b$, where $r_b = hb/2(h + b)$, $r_a = ha/2(h + a)$. In this work we considered $k_r = 1$, $k_r = 1.2$, $k_r = 1.4$.

One of the geometry parameters of the model that determines the heat transfer efficiency is also the aspect ratio A_r defined as $A_r = \frac{h}{r_b}$, where r_b is the hydraulic diameter of the channels between the pins. In our study we consider two scale of pins distribution inside the cannel, therefore we will introduce two coefficients for wide channels $A_{ra} = \frac{h}{r_a}$ and narrow channels $A_{rb} = \frac{h}{r_b}$. The values of the coefficients vary depending on the variation of k_r.While k_r is changing from 1 to 1.4 the aspect ratio varies from 2.24 to 3.15.

3 Experimental results

Previously, in similar structures, the authors of the paper considered the features of fluid flow patterns [9] and air bubble entrapment when the microstructure is filled with liquid. The variations in the longitudinal and transverse velocity components within small and large pore channels are analyzed as functions of their geometric characteristics and volumetric flow rate [9]. But the influence of the introduction of the second scale of porosity on the integral flow characteristics was not evaluated.

A series of experiments were carried out for all three structures at a constant pressure drop set in the range from 10 to 70 kPa with a step of 5 kPa. Using a fluid flow sensor, the volume flow rate of fluid, which was used as vaseline oil, was measured. The measurements were performed after the model was completely saturated with fluid after pumping several pore volumes through the microfluidic system. For each pressure drop, the value of the volume flow rate was obtained after the steady-state value was established.

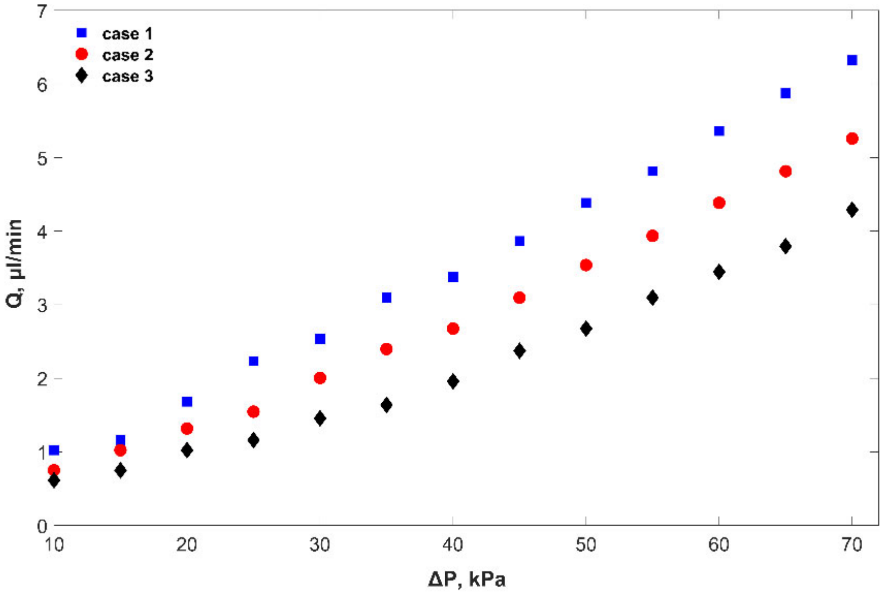

Fig. 3. Dependence of the flow rate on the pressure drop.

Figure 3 shows a joint graph of the dependence of the fluid volume flow rate on a given constant pressure drop for all considered microchannel configurations. It is shown, that for all cases the flow rate increases with increasing value of the fluid pressure drop, at the same time the angle of slope of the curves differs. It is also revealed, that the throughput of the microfluidic channel element decreases when a second scale of porosity is introduced. When the flow rate increases, the difference between the volume flow rate values become more significant up to 18%. Which may be due to more complex redistribution of flow when the second scale of porosity is introduced.

4 Conclusion

This study focuses on fluid dynamics within flat microchannels containing fin pin arrays. The influence of fin pin array distribution on the throughput capacity of microchannel sections was investigated experimentally. Utilizing lab-on-a-chip devices, our experimental approach offers valuable insights for advancing the design and optimization of microfluidic heat exchangers, underscoring the versatility and wide applicability of the presented methodologies. We demonstrate the significant impact of introducing a secondary distribution scale of pins in the microchannel region while maintaining a constant liquid contact area. Achieving an optimal balance between channel capacity and contact area is critical to maximizing heat dissipation with minimal energy cost. This study provides a hydrodynamic framework for selecting optimal microchannel geometries. Future work will involve evaluating heat transfer characteristics to fully optimize microfluidic cooling system designs, a promising area with significant scientific and practical potential.

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