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Numerical study of fluid flow and heat transfer phenomenon within microchannels comprising different superhydrophobic structures

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ABSTRACT

This research aims at numerical study of fluid flow and heat transfer through microchannels having superhydrophobic surfaces consisting of aligned and staggered micropost patterns in the fully developed laminar flow regime. In this work, at the condition of constant surface heat flux, Poiseuille number, Nusselt number and also overall microchannel performance are examined at relative module width of W_m = 0.01, 0.1 and 1, cavity fraction range of F_c = 0.1 to 0.9 and Reynolds numbers of R_e=10 and 100. In order to validate the current results, comparisons are made with theoretical and experimental approach and good agreements are observed. Numerical findings show that the staggered pattern is capable of producing higher frictional resistance and better thermal transport than the aligned structure. It is shown that an increase in the cavity fraction leads to a decrease in the Poiseuille and Nusselt numbers for the two micropost structures and this decrease becomes pronounced with increasing the relative module width. Results indicate that for the two micropost patterns, the role of increase in the relative module width is to decrease the Poiseuille and Nusselt numbers. It is found that the staggered arrangement could lead to higher overall performance than the corresponding aligned structure and enhancement in the performance becomes remarkable at high values of relative module width. Numerical findings indicate that for each micropost structure, an increase in the Reynolds number causes the microchannel overall performance to increase and the highest overall performance is attained at high relative module width and cavity fraction values.

1. Introduction

Nowadays, the subject of heat removal from the electronic devices in the micro-scale is an important issue in the design process of such devices. In this context, employment of a microchannel which meets the desired conditions in terms of heat removal capacity and also frictional resistance has always been a challenging problem. Although some efforts are made to fulfill the desired heat removal ability of the microchannles such as employing of tree-shape [1], zigzag [2] or wavy [3,4] microchannels, however, the subject of pressure gradient associated to these microchannels has always been an open problem.

Reviewing literature indicates that many researches are devoted for evaluation of microchannels performance in hydrodynamic point of view [5–8]. In the field of micro-scale devices, some researchers analyzed the flow through the microchannles which were used as the heat sink. Hung et al. [9] performed an optimization procedure to find the optimum microchannel heat sink among different geometric structures such as the single layered, double-layered or tapered microchannels. In their research, they concluded that the tapered microchannel had the best performance among the considered geometries. Wei et al. [10] assessed the pressure drop as well as heat transfer characteristic of the transversal elliptical microchannels. They found that the periodic transversal elliptical microchannel could be viewed as an alternative to the conventional microchannels since they had a potential to reduce pressure drop and also enhance the heat transfer rate. Xie et al. [11] conducted a research to examine the thermal performance of a transversal wavy microchannel. In their study, they found that for a same Reynolds number, this type of microchannel could have a higher thermal performance compared to the traditional straight rectangular microchannel especially at high wave amplitude. Chai et al. [12] studied the effect of dimensions and positions of rectangular ribs on the fluid flow and rate of heat transfer for the transverse microchambers. In this research, they indicated the optimum dimensions and position parameters of the ribs. Xie et al. [13] investigated the role of bifurcation on the thermal performance of the heat sink microchannels. Their results showed that the thermal performance of the microchannel with multistage bifurcation flow was better in comparison with straight microchannels. They also expressed that the utilization of multistage

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bifurcated plates could reduce the overall thermal resistance and the best number of stages of bifurcations was two. Chai et al. [14–16] carried out a parametric study to evaluate the heat transfer rate, pressure drop and overall performance of fluid flow through microchannels. They focused on the aligned and offset fan-shaped ribs mounting on the microchannel walls. Xie et al. [17] examined the thermal performance of the longitudinal and transversal wavy microchannels. Their numerical findings revealed that the longitudinal wavy microchannels were inferior while the transversal wavy microchannels were superior to the conventional rectangular microchannels in terms of overall thermal performance.

In the context of fluid flow through the heat sink microchannels, the channels employing superhydrophobic surfaces (SHSs) as the channel walls could be viewed as a good alternative to overcome the high pressure loss associated with them. The SHSs are combination of hydrophobicity utilizing a thin hydrophobic layer as well as micro-sized protrusions emerging from the surface; or in the other form, microholes carved in the surface. One of the features associated to these surfaces is that they could lead to a contact angle of more than 150° for a water droplet resting on them [18]. Since the protrusions or holes are made in a low size, the penetrating of fluid in between the protrusions or holes is not possible due to surface tension effect and so, the air traps in the cavities. Accordingly, the wetted contact area between the fluid and solid surface decreases, resulting in the mitigation of frictional resistance for the fluid flowing through the channel [19].

Although some researches are performed to assess the effects of different parameters on the fluid flow and heat transfer phenomenon within the microchannels employing SHSs, however, they were rare and were also limited to few cases. In this field, Maynes et al. [20] carried out an analytical approach to analyze the thermal transport in microchannels with transverse rib and cavity structured superhydrophobic walls. In their work, it is shown that an increase in the cavity fraction causes the average Nusselt number to decrease and an increase in the relative rib-cavity module length led to a decrease in the Nusselt number. Maynes and Crockett [21] studied the apparent temperature jump and also thermal transport in microchannels consisting of rib and cavity aligned in the streamwise direction. Their results revealed that the relative size of cavity in comparison with the cavity fraction affected the overall thermal behavior. It was also shown that the relative size of the rib and cavity module width compared to the relative module width influenced the thermal behavior. Enright et al. [22] presented some expressions for the thermal and hydrodynamic slip lengths for the pillar and also ridge structures. In their research, they also described the conditions under which the heat transfer rate might be enhanced. Ng and Wang [23] performed numerical approach for determining of temperature jump coefficient for different SHSs. The SHSs they focused on were parallel grooves, circular and square posts and holes. Enright and Hodes [24] examined the thermal transport behavior of a specific microchannel consisting of pillar-structured superhydrophobic surface and demonstrated that the apparent slip length could increase against the adverse microchannel temperature gradient. Cowley et al. [25] investigated the heat transfer rate in a microchannel having micro-ribs and cavities which were aligned and perpendicular to the flow direction and ware also made of a highly conductive material. In this work, they declared the significance of axial heat conduction. Cowley et al. [26] conducted a numerical approach to investigate the effects of inertia on the flow through microchannels comprised of square array of square pillars which were aligned with the flow direction. They explored the effect of Peclet number, solid fractions and relative channel spacing size on the Nusselt number, friction factor-Reynolds number product and temperature jump length and hydrodynamic slip length. Cheng et al. [27] assessed frictional resistance and thermal performance of flow though microchannels employing square holes, posts and transverse and longitudinal grooves. They also evaluated the combined frictional and thermal performance of microchannels by calculation of goodness factors of the considered microchannels.

As shown by Cheng et al. [27], in the laminar flow regime, the microchannels employing micropost-structured SHS in aligned form are a good alternative to the traditional microchannels for heat removal purposes in the mico-scale devices since they lead to a rather low frictional resistance and high heat transfer rate. In the research conducted by Cheng et al. [27], it was also shown that for the flow through microchannels, the capability of the channel in increasing the Nusselt number increased when the flow experienced flow acceleration and deceleration at each microchannel spanwise direction. So, one could infer that microchannels having the micropost-structured SHS in the staggered form (which, contrary to the aligned structure, causes the flow to experience flow acceleration and deceleration at each spanwise location) could be viewed as a promising alternative in order to have high Nusselt number with a rather low frictional resistance. In this context, the question may arise about the extent to which a microchannel which uses the micropost-structured SHS in the staggered could enhance the microchannel performance, which is the motivation for the present study. In this study, the frictional resistance, heat transfer phenomenon and also overall performance of different microchannels employing SHS in the form of aligned and staggered micropost are evaluated and compared in the laminar flow regime. In this research, for better understanding of role of each micropost pattern on the microchannel performance, results are obtained at different relative module widths, cavity fractions and Reynolds numbers.

1.1. Problem description

In this work, the microposts shape is assumed to be square and flow through an infinite width rectangular microchannel is concerned. Fig. 1 depicts the aligned and staggered micropost configurations. In this figure, H denoted the microchannel height. In order to perform numerical calculation, owing to symmetry, only half of microchannel height is considered. Shown in Fig. 2, are the top and right side views for half of the channel height for the aligned and staggered micropost structures. In Fig. 2, dark regions represent the considered computational domain and W_C and W represent the cavity width and combined post and cavity width, respectively.

The microchannel hydraulic diameter is defined as $D_h = 4A/P_w$ where A and P_w represent flow area and total liquid perimeter, respectively. Flow area and total liquid perimeter are $A = Hb$ and $P_w = 2(H + b)$ where b stands for the microchannel width. Assuming infinite width microchannel (i.e. $b \to \infty$), the microchannel hydraulic diameter would be $D_h = 2H$. In this work, relative module width and cavity fraction are defined as $W_m = W/D_h$ and $F_c = A_f/A_t$, respectively, where A_f is the cavity area and A_t denotes the total area of the microchannel wall. Reynolds number is also defined as $\mathrm{R_e} = \bar{u}_m D_h/\nu$ where $\bar{u}_m$ and ν are mean flow velocity through the channel and kinematic viscosity, respectively. To study the heat transfer phenomenon within the microchannel, the solid portion of the solid-cavity composite surface is assumed to be subjected to a uniform heat flux.

In order to assess the effect of different micropost patterns on the frictional resistance and heat transfer phenomenon of flow through the

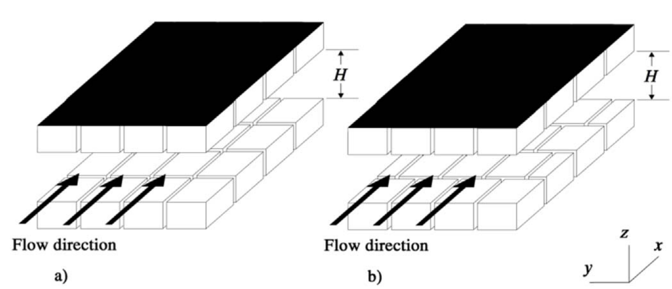

Fig. 1. Different microchannel arrangements, a) aligned and b) staggered arrangement.