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Numerical and statistical study of cylindrical heat sink performance with interrupted minichannels and twisted vortex generator

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Abstract

In the current study, fluid flow and heat transfer characteristics of water flow in a cylindrical heat sink with interrupted minichannels and twisted vortex generators are numerically evaluated. This study focuses on the determination of the influential design factors and their optimum levels. The design factors were selected at four levels comprising the angle of the vortex generators, twist angle of the vortex generators, the Reynolds number and the spacing of the vortex generators from the beginning of the interrupted section of minichannels. The output parameters in this study are included the Nusselt number, the Fanning friction factor and the total hydrothermal performance factor. To investigate the effect of design factors on output parameters, Taguchi statistical method with L16 orthogonal arrays and analysis of variance was carried out. The results demonstrated that the vortex generators, the Reynolds number and the spacing of the vortex generators play a vital role in JF with the contribution ratios of 61.59%, 11.89% and 19.22%, respectively. The twist angle of vortex generator has a small contribution to the output parameters. The optimized model is improved by 100%, 16.8% and 94% for Nu, f and JF, respectively, compared with the original model.

Keywords: Cylindrical heat sink, Interrupted minichannel, Twisted vortex generator, Taguchi method, Analysis of variance.

1. Introduction

Nowadays, the study of thermal and hydraulic characteristics of microchannel heat sinks has become attractive for many researchers. This is more vital to the use of micro/microchannel heat sinks in many high-power systems such as microelectronic device cooling, hybrid vehicle batteries management and micro-reactors cooling. [1-3]. Falahat et al. [4, 5] experimentally and numerically examined the thermal-hydraulic performance and entropy generation of water flow in a new cylindrical heat sink with helical minichannels. The authors reported that with increment the helix angle of the minichannels, the Nusselt number and friction factor decrease and the total entropy generation increases. Khalifa and Jafal [6] investigated the thermal and hydraulic efficiency of a cylindrical heat sink with three minichannels configuration (straight, wavy and helical), numerically and experimentally. They found that the best thermal-hydraulic performance was for the heat sink with helical minichannels. Data et al. [7] numerically studied the thermal-hydraulic characteristics in a microchannel heat sink with longitudinal vortex generators. They considered different combinations of two pairs of longitudinal vortex generators with various vortex generator angles and distances from the microchannel inlet. Their findings indicated that the optimal overall performance of heat sink occurred at a vortex generator angle of 30° and Reynolds numbers above 600.

The main aim of the present study is to numerically analyze the thermal-hydraulic characteristics of water fluid flow in a cylindrical heat sink with interrupted straight minichannels with a longitudinal twisted vortex generator. The influence of various design factors, such as the angle of the vortex generator, Reynolds number, twisted angle of the vortex generator, and the position of the vortex generator at the interrupted sections on the thermal-hydraulic characteristics of the cylindrical heat sink is studied. The Taguchi method [8, 9] and analysis of variance are employed to analyze the sensitivity of design factors and to determine the percentage contribution of each factor to the output parameters. Additionally, the best level of each factor for the output parameters is identified.

2. Numerical Simulation Method

A cylindrical heat sink with interrupted minichannels containing twisted vortex generators and the computational domain is shown in Figure 1. This heat sink consists of 36 interrupted minichannels, with twisted vortex generators located in the interrupted sections of the minichannels. Every minichannel consists of three interrupted sections, and each section containing a pair of twisted vortex generators. The cooling fluid is water and the heat sink material is copper. An interrupted straight minichannel with a periodic boundary condition is considered as the computational domain to minimize the grids numbers and computational time.

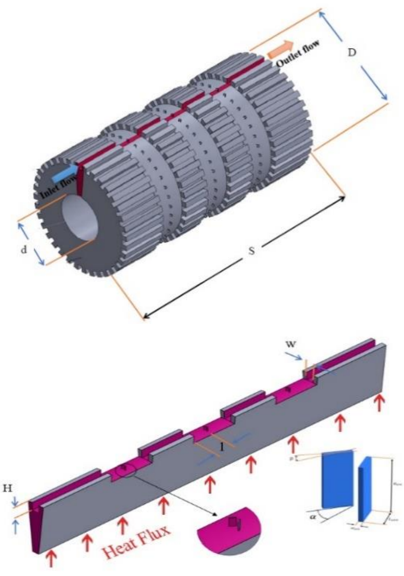

Figure 1. Cylindrical heat sink with interrupted minichannels including twisted vortex generator and computational domain.

To analyze the three-dimensional conjugate heat transfer in a cylindrical heat sink with interrupted minichannels and twisted vortex generators, it is assumed that the Newtonian fluid is incompressible, laminar, and stable, and natural convection, radiation, and viscous dissipation are neglected [6]. The thermo-physical properties of the fluid and solid are assumed to be temperature-dependent [10] and constant, respectively. Based on the above simplifying assumptions, the governing equations for the fluid and solid are as follows:

$$\nabla.\left(\vec{\mathrm{V}}\right) = 0 \tag{1}$$

$$\rho_f\left(\vec{\mathrm{V}}\,\nabla.\vec{\mathrm{V}}\right) = -\nabla \mathrm{P} + \mu_f \nabla^2\left(\vec{\mathrm{V}}\right) \tag{2}$$

$$\vec{\mathrm{V}}\,\nabla.\mathrm{T} = \frac{k_f}{\rho_f\, C_{Pf}}\nabla^2 T \tag{3}$$

$$\nabla^2 \mathrm{T_s} = 0 \tag{4}$$

The convection heat transfer coefficient and the average Nusselt number are calculated according to the following equations [9]:

$$\mathrm{h} = \frac{\mathrm{q}}{\mathrm{A_c}\left[\mathrm{T_w} - \left(\frac{\mathrm{T_{in}} + \mathrm{T_{out}}}{2}\right)\right]} \tag{5}$$

$$\mathrm{Nu} = \frac{\mathrm{h}\,\mathrm{D_h}}{\mathrm{k_f}} \tag{6}$$

In the above equations, q, $\mathrm{T_w}$, and A_c are, the heat absorbed by the fluid, the temperature of the heat transfer surface of the minichannel, and the heat transfer surface, respectively. The Fanning friction factor is calculated according to the following equation:

$$\mathrm{f} = \frac{\Delta \mathrm{P D_h}}{2\mathrm{S}\rho_\mathrm{f} \mathrm{u_{in}^2}} \tag{7}$$

The total thermal efficiency coefficient is calculated using the following equation [5]:

$$\mathrm{JF} = (\mathrm{Nu}/\mathrm{Nu_0})(\mathrm{f}/\mathrm{f_0})^{-1/3} \tag{8}$$

In this equation, the index 0 refers to the condition where the minichannel is straight without interruption and a twisted vortex generator.

In the current study, the governing equations were solved using the finite volume method by Fluent software with a double-precision pressure-based discrete solver. The SIMPLE algorithm was used to couple velocity and pressure. The momentum and energy equations were discretized using the second-order upstream method. The convergence criterion for the continuity and momentum equations was less than 10^{-6} and for the energy equation was less than 10^{-9}. In order to obtain results with higher accuracy, grid independence was performed for all models.

3. Results and discussion

To validate the numerical simulation results of this study, the numerical results were compared with the experimental results of Falahat et al. [5] and Azizi et al. [11]. The maximum relative errors compared to the experimental results of Falahat et al. [5] and Azizi et al. [11] are about 2.38% and 9.57%, respectively (See Figure 2).

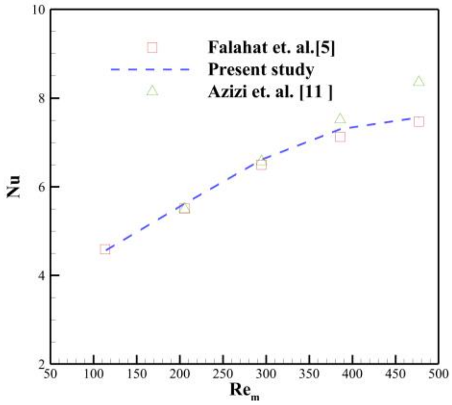

Figure 2. Comparison between numerical results with Falahat et al. [5] and Azizi et al. [11].

The signal-to-noise ratio of the four design factors at various levels for the JF is shown in Table 1. The JF value being greater than unity indicates that the improvement in heat transfer has overcome the increase in pressure drop. According to Table 1, the most effective factors on the JF are the Reynolds number, the distance of the vortex generator from the beginning of the interrupted sections, and the angle of the vortex generator, respectively. It should be noted that the twist angle of the vortex generator has minimal effect on JF. It is concluded that using a vortex generator in cylindrical heat sinks with interrupted minichannels increases the JF. According to Table 1, the optimal model for the total thermal efficiency coefficient is A3B4C2D1.

Table 1. Average signal-to-noise ratio for JF

Level	A	B	C	D
1	2.27	3.22	3.54	4.11
2	3.60	3.41	3.70	3.76
3	4.22	3.56	3.51	3.24
4	4.15	4.04	3.48	3.12
Delta	1.95	0.83	0.21	0.99
Rank	1	3	4	2

The results of the analysis of variance for the output parameters of this study are shown in Figure 3.

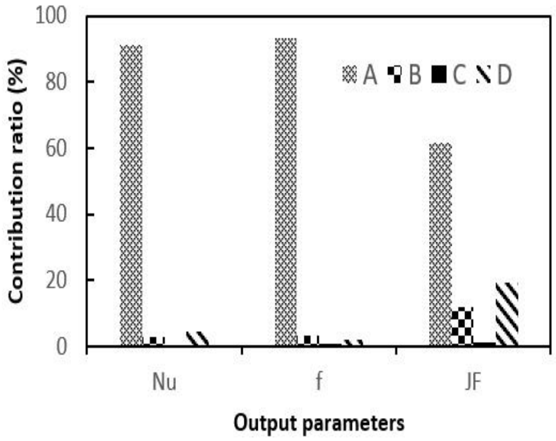

Figure 3. The contribution of design factors on research output parameters.

4.Conclusions

The key findings from this study are as follows:

1- The Reynolds number, the distance of the vortex generator from the beginning of the interrupted section, and the angle of the vortex generator play a significant role in the JF.

2- The highest contribution ratio of the distance of the vertex generator from the beginning of the interrupted section and the angle of the vortex generator to the output parameters is 19.22% and 11.89%, respectively.

3- Considering the average signal-to-noise ratios, the optimal conditions for the JF are A3B4C2D1.

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