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Numerical study and performance analyses of the mini-channel with discrete double-inclined ribs

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ABSTRACT

A 3-D numerical study is carried out to investigate the laminar flow and heat transfer performance of the rectangular mini-channel where the discrete double-inclined ribs are worked as the longitudinal vortex generators. The effects of the Reynolds number, the height of the ribs and the number of double-inclined ribs along the mainstream on the heat transfer and flow performance of the mini-channel are examined and analyzed from the field synergy perspective and the entropy generation. The results show that the heat transfer performance is enhanced effectively by the double-inclined ribs which cause the generation of the longitudinal vortexes in the mini-channel. The heat transfer performance increase with the increasing height or number of the double-inclined ribs, but the flow resistance will increase at the same time. In order to obtain the best overall performance of the mini-channel, the height of the ribs should be reduced with the increase of the Reynolds, and the overall performance would be improved with the increase of the ribs number in the mini-channel. The heat transfer performance has a direct relation to the field synergy characteristic of the mini-channel. The entropy generation rate dues to heat transfer irreversibility and fluid frictional irreversibility can be used for the evaluation of the heat transfer and the flow performance of the mini-channel well respectively, while the total entropy generation rate cannot be used as a criterion for the overall performance.

1. Introduction

With the rapid development of microelectronics technology, the corresponding problem of heat dissipation with high heat-flux in a restricted space has become a focus of the heat transfer research nowadays. Since the concept of micro-channel cooling system was firstly proposed in 1980s [1], micro-channel heat sink shows great superiority in the cooling of the modern integrated electronic devices due to its high performance in heat transfer and the compact structure. Therefore, much attention has been attracted to the related study. In order to get higher performance, the structure of the macro-channel has been optimized by many researchers [2–4], and many new channel structures were proposed, such as the fractal tree-like structure [5], the diamond-shaped interrupted fins structure [6], the multilayer staggered honeycomb structure [7], etc.

The traditional heat transfer enhancement technologies, such as to increase the Reynolds number, to strengthen the flow disturbance, etc., were developed from experience rather than under the guidance of proper theories [8]. Generally, they always cause great increase in power consumption with the enhancement of the heat transfer. The longitudinal vortex heat transfer enhancement technology can improve the convection heat transfer performance effectively, and now is defined as the third generation heat transfer technology [8]. The typical longitudinal vortex generators are generally divided into four types, the delta wing, rectangular wing longitudinal vortex generator, the delta winglet and the rectangular winglet longitudinal generator. Researches show that performance of the delta winglet and the rectangular winglet longitudinal vortex generators is much better than the delta wing and the rectangular longitudinal vortex generators [9], and performance of the delta winglet longitudinal vortex generators is better than the rectangular winglet longitudinal vortex generator [10]. Research also shows that longitudinal vortexes can enhance the global heat transfer of channel, while transverse vortexes can only enhance the local heat transfer of channel [11]. However, look over the existing discussions on the longitudinal vortex generator, the wings or winglets are with a certain gap between the practical application since the thickness of the vortex generator are often

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neglected in most of the researches. And the number of the vortex generators in channels also seldom studied.

The field synergy theory which was proposed by Guo et al. [12] is committed to enhance convective heat transfer under constant power consumption, and is developed as a guidance theory for the convective heat transfer in recent years. In this theory, they proposed a concept that the physical nature of convective heat transfer is up to the synergetic relation between its velocity field and heat-flux field. Under the same boundary conditions of velocity and temperature, the better the synergy between velocity field and heat-flux field is, the higher the heat transfer intensity will be. Then based on the field synergy principle for heat transfer enhancement, the concept of physical quantity synergy in the laminar flow field was proposed by Liu [13]. The physical nature of enhancing heat transfer and reducing flow resistance, which is directly associated with synergy angles α, β, γ, ϕ and ψ, is also explained. It provides a basis to develop new heat transfer technologies or to evaluate the flow and heat transfer performance. The discrete double-inclined ribs tube [14] which was developed based on the convective heat transfer field synergy theory is a new technology for heat transfer enhancement, and its main advantage is that multi-longitudinal vortexes would generate spontaneously when fluid flow through the discrete double inclined ribs, so the discrete double-inclined tube can achieve heat transfer augmentation under the same power consumption and has a positive effect in energy-saving.

In addition, the minimum entropy generation principle has been widely adopted to evaluate the thermal systems for determining the optimal design recently [15,16], and the optimum system were designed and evaluated from the perspective of the second law of thermodynamics, which focus on the entropy generation due to the irreversible heat transfer and fluid flow. So in present study, the entropy generation is also considered to evaluate the performance of the mini-channel.

Mini-channel can be applied in various kinds of applications, such as applied in the mini-channel heat sink for the cooling of the electronic devices with high heat flux [17,18], applied in the proton exchange membrane fuel cell to enhance the heat and mass transfer in the gas channel or to enhance the heat transfer in the coolant channel [19,4], etc. In the present paper, the discrete double-inclined ribs are applied to mini-channel to give a new kind of mini-channel for the applications above. According to a typical mini-channel structure used in the mini-channel heat sink, the size of the new type mini-channel is determined, and the discrete double-inclined ribs with a certain thickness are arranged in the rectangular channel on the wall which is corresponding to the heated wall. Three dimensional models are established to investigate the performance of the mini-channel with the discrete double-inclined ribs.

2. Physical model and mathematical description

Fig. 1 shows the physical model of the mini-channel analyzed in the present work, where some pairs of the discrete double-inclined ribs with a certain thickness are arranged in the rectangular mini-channel. As shown in the figure, the ribs pairs are numbered from 1 to 10 in sequence along the flow direction. The effects of the ribs height and the ribs number on the performance are the main objects to investigate. In the present work, heights of ribs are taken as $H = 0.25, 0.50, 0.75, 1.00, 1.25$ mm, and compared with the plain channel ($H = 0$); the numbers of the ribs pairs have three cases: (1) as shown in Fig. 1, 10 pairs of ribs in the mini-channel ($N = 10$), (2) removing the even-numbered ribs pair, 5 pair of ribs remained in the mini-channel ($N = 5$), (3) only remain the ribs pair numbered 1 in the mini-channel ($N = 1$). The other main geometry parameters are shown in Table 1.

According the model, the average Nusselt number (Nu) and the average flow resistance coefficient (f) for the current problem are defined as

$$h = \frac{Q}{A_\mathrm{w}\Delta T_\mathrm{m}} \tag{1}$$

$$Nu = \frac{hD_\mathrm{h}}{k} \tag{2}$$

$$f = \frac{\Delta P}{\rho u_\mathrm{a}^2/2}\frac{D_\mathrm{h}}{L} \tag{3}$$

where Q is the total heat flux of the heated wall, $A_\mathrm{w} = W \times L$ is the nominal heat transfer area, ΔT_m is the average temperature difference of the heated wall and the fluid field, h is the heat transfer coefficient, k is the thermal conductivity of the fluid medium, ΔP is the pressure drop of the fluid medium from the inlet to the outlet, ρ is the density of the fluid medium, u_a is the average flow velocity of the fluid medium in the mini-channel, D_h is the hydraulic diameter of the mini-channel, which is defined as $D_\mathrm{h} = 2w \times h/(w+h)$.

The present problem is about the three-dimensional flow and heat transfer processes with laminar and steady condition. The relevant control equations are continuity equation, momentum equation and energy equation. The general form of these equations is as follow

$$\frac{\partial(\rho u\varphi)}{\partial x} + \frac{\partial(\rho v\varphi)}{\partial y} + \frac{\partial(\rho w\varphi)}{\partial z} = \frac{\partial}{\partial x}\left(\Gamma_\varphi \frac{\partial\varphi}{\partial x}\right) + \frac{\partial}{\partial y}\left(\Gamma_\varphi \frac{\partial\varphi}{\partial y}\right) + \frac{\partial}{\partial z}\left(\Gamma_\varphi \frac{\partial\varphi}{\partial z}\right) + S_\varphi \tag{4}$$

where u, v and w refer to the fluid velocity components in x, y and z directions, respectively; φ refers to the generalized variable to be displaced by $\varphi = 1$ for continuity equation, $\varphi = u$, v and w for momentum equation, and $\varphi = T$ for energy equation; Γ_φ refers to generalized diffusion coefficient defined in Ref. [20], S_φ refers to source term with different meanings in different equations.

According to the velocity and temperature fields solved by using the above equations and the given boundary conditions, the synergy angle β' between velocity $\boldsymbol{U}$ and temperature gradient ∇T for any element in the fluid field can be calculated as [13]

$$\beta' = \arccos\frac{\boldsymbol{U}\cdot\nabla T}{|\boldsymbol{U}||\nabla T|} \tag{5}$$

The average synergy angle of the whole fluid field β can be calculated by the volume weighted average method through the synergy angle of all the elements.

The local volumetric entropy generation due to the heat transfer irreversibility (S_T) and the fluid frictional irreversibility (S_P) can be calculated by the following equations [16]

$$S_\mathrm{T} = \frac{k}{T^2}(|\nabla T|)^2 \tag{6}$$

$$S_\mathrm{P} = \frac{\mu}{T}\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} \tag{7}$$

where μ is the kinetic viscosity of the fluid medium. Entropy generation due to heat transfer irreversibility and fluid frictional irreversibility are the measures of the irreversibility of the practical heat transfer process and fluid flow process respectively, and it will be used for the evaluation of the heat transfer and fluid flow performance.

Then the local volumetric entropy generation (S_g) can be obtained by

$$S_\mathrm{g} = S_\mathrm{T} + S_\mathrm{P} \tag{8}$$