International Journal of Heat and Mass Transfer 119 (2018) 152–162

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Flow and heat transfer characteristics and optimization study on the water-cooled microchannel heat sinks with dimple and pin-fin

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A R T I C L E I N F O

Article history:
Received 14 May 2017
Received in revised form 3 August 2017
Accepted 20 November 2017
Available online 25 November 2017

Keywords:
Heat transfer enhancement
Microchannel heat sink
Pin-fin
Dimple
Optimization

A B S T R A C T

In order to develop high-efficiency low-resistance heat exchangers, the heat transfer performance and further optimization of water-cooled microchannel heat sink with dimple and pin-fin were numerically studied in this work. Firstly, the combination effects of structure parameters (diameter of pin-fin D_1, depth of dimple δ and stream-wise spacing S) on flow structure and heat transfer were investigated in detail. The results show that the proposed designs exhibit heat transfer augmentation with energy-saving and low-resistance features. The increase of D_1 and decrease of S bring out the increase of Nu/Nu_0 under all Re studied. Flow structures induced by pin-fin make the development of separation flow in the dimple happened in advance. The increase of D_1 enlarges the scale and intensity of wake flow of pin-fin, resulting more violent actions of flow on heated walls, then, enhances the heat transfer augmentation. Also, relative small δ will be beneficial for heat transfer enhancement at lower Re conditions. Furthermore, the automatic calculation configuration optimization analysis by means of pattern search method was validated and conducted successfully to achieve better TP, and the maximum increasement of TP, 10.3%, is obtained at $Re = 200$ as a result. The area of high temperature regions, especially on the side walls, decreases, also, the temperature gradient decreases and the uniformity of heated walls is enhanced. The proposed method can be extended to optimize configuration of microchannel with flow control devices accurately with less time-consuming.

1. Introduction

In order to meet the increasing demand of heat removal, the high-efficiency low-resistance compact heat exchanger has gained more attractions in engineering applications. And, based on the investigations of flow and heat transfer mechanism in microchannels with multilayer [1,2], variable cross section shape [3,4], and different channel formation [5–7], microchannel heat sink has been verified as an effective cooling technology for high heat flux.

To increase heat transfer rate, comparison analysis of the microchannel with passive flow control techniques are conducted, including the structures of pin-fin [8], groove [9], cavity [10], tip clearance [11], rib [12], vortex generators [13], dimple/protrusion [14,15], and bifurcation [16]. Especially, microchannel modified by pin-fin and dimple interests more researchers. Kosar et al. [17] experimentally studied the forced water flow in microchannel with staggered and in-line circular/diamond pin-fins array, and found that at low Reynolds number, fin density and endwall effects influenced the flow resistance a lot, and then proposed a modified correlation to predict the pressure drop in microchannel. Later, they studied the Nusselt number, thermal resistance and friction factor of water flow in micro tank with staggered pin-fin in a large range of heat fluxes [18], and found the delay of flow separation due to compact fins at high Reynolds number depressed the endwall effects. Marques and Kelly [19] experimentally investigated the heat transfer and pressure penalty of a micro heat exchanger with pin-fin array, and the results indicated the heat transfer performance all exceeded the corresponding parallel plate heat exchanger, then a cooling effectiveness prediction model for micro pin-fin heat exchanger in gas turbine blade cooling application was further proposed. The pressure penalty analysis of microchannel with compact pin-fin array was conducted by Vanapalli et al. [20], and the results of different cross section shapes revealed that sine-shaped pin-fin showed best performance considering pressure penalty. Wang et al. [21] experimentally studied the heat transfer of microchannel with pin-fin in a large range of Reynolds number, and found its heat transfer coefficient was twice that of plate microchannel, moreover, the pin-fin with triangular cross

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.112
0017-9310/

Nomenclature

A	area of cross section of microchannel (m^2)
C	specific heat ($J\ kg^{-1}\ K^{-1}$)
D_1	diameter of pin-fin (μm)
D_2	diameter of dimple (μm)
D_h	characteristic length, hydraulic diameter (μm)
f	friction factor
H	microchannel height (μm)
h	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
Nu	Nusselt number
P	fluid pressure (Pa)
q''	heat flux ($W\ m^{-2}$)
Re	Reynolds number
S	stream-wise spacing between adjacent pin-fin and dimple (μm)
T	temperature (K)
TP	thermal performance
$U_{m,\ in}$	average velocity of inlet ($m\ s^{-1}$)
W	microchannel width (μm)
ΔP	pressure drop (Pa)
ΔT	mean temperature difference (K)
Greek symbols	
δ	relative depth of dimple (μm)
μ	fluid dynamic viscosity (Pa s)
λ	fluid thermal conductivity ($W\ m^{-1}\ K^{-1}$)
ρ	fluid density ($kg\ m^{-3}$)

section showed best heat transfer performance. Isaev et al. [22] numerically studied the heat transfer enhancement in microchannel with oval dimple, and 10% increase in heat transfer rate and 13% increase in thermal efficiency were achieved. Lan et al. [23] numerically investigated the flow and heat transfer in water-cooled microchannel with dimple, and the results showed that dimple improved heat transfer rate with low pressure penalty. Gong et al. [24,25] studied the heat transfer and flow resistance of microchannel with dimple used for microchips cooling, and the results revealed that dimple disturbed the development of boundary layer and enhance convective heat transfer, and 15% increase in Nusselt number was obtained comparing with smooth channel. The authors comparatively studied the flow structures and heat transfer mechanism of mirochannel modified by dimple and other flow control devices with nanofluids [26,27] and non-Newtonian fluids [28] as coolants, and found that dimple can produce considerable heat transfer augmentation with favorable energy-saving performance in liquid-cooled microchannels, and then proposed novel correlations to predict the Nusselt number and Fanning friction factor in this applications. Viewing from the above-mentioned literatures, pin-fin can produce considerable heat transfer augmentation in microchannel, and dimple can decrease pressure drop penalty during increasing heat transfer, therefore, the detailed investigation of the combination effects of pin-fin and dimple on the development of high-efficiency low-resistance microchannel heat sink for high heat flux applications should be endeavored to conduct next.

Furthermore, recently, optimization methods have been used widely in the performance improvement of liquid-cooled microchannel heat sink. Ryu et al. [29] conducted three dimensional configuration optimization of microchannel heat sink by means of steepest descent technique, and the thermal resistance was more than 50% reduced at the optimization results, also, they obtained the key affecting parameters for the heat transfer improvement. Wei and Joshi [30] employed genetic algorithms to optimize the thermal resistance in stacked microchannel heat sink, and the results showed that the channel length and configuration highly influenced the overall thermal resistance. The geometrical parameters optimization of microchannel heat sink conducted by Li and Peterson [31] reflected that 20% increase in cooling performance could be obtained under a fixed pumping poser. Husain and Kim [32] employed surrogate analysis and evolutionary algorithm to optimize the depth, width and fin width of a water-cooled microchannel heat sink successfully. Wang et al. [33] optimized the configuration and geometrical parameters of water-cooled microchannel heat sink by means of inverse problem method, and obtained its optimal thermal resistance. Lee et al. [34] conducted multi-objective optimization of microchannel with dimple and protrusion, and 28% increase in heat transfer performance was obtained comparing with the corresponding case. Lin et al. [35] optimized geometry and coolant velocity of water-cooled microchannel heat sink to promote flow and heat transfer performances and reach minimum thermal resistance. Based on the previous literatures, the geometrical structures have great effects on the flow resistance and heat transfer performance of microchannel heat sink, and main optimization should be focused on the geometrical parameters, to achieve best performance for the proposed model.

As stated in the literature review, in order to develop the high-efficiency low-resistance heat exchanger, the combination effects and mechanism of pin-fin and dimple on the performance of microchannel heat sink should be carefully studied, and, the geometrical optimization should be also conducted to obtain the favorable configuration for heat transfer enhancement.

Therefore, in this work, the flow structure, heat transfer characteristics, and the performance analysis of the water-cooled microchannel with pin-fin and dimple are investigated in detail, further, optimization of geometrical parameters is conducted by means of pattern search algorithm, to achieve optimal configuration for maximum thermal performance.

2. Solution methods

2.1. Physical model and boundary conditions

Fully developed periodic velocity and temperature can be obtained after some typical stream-wise sections with pin-fin and dimple in the microchannel, and the typical flow domain is the smallest periodical unit, so the periodical domain is selected to reflect the flow and heat transfer characteristics, similar with our previous researches [15,26–28]. Three-dimensional models of microchannel with pin-fin and dimple and its periodical flow domain are shown in Fig. 1. The microchannel is 50 m (W) × 200 m (H) in cross-section, and pin-fin and dimple are arranged on the wall with a width of 200 m. Fig. 1(b) shows the side view of the periodical flow domain, where S is the stream-wise spacing between adjacent pin-fin and dimple, and D_1 and D_2 are the diameters of pin-fin and dimple, and δ is the relative depth of dimple. And then, the length of microchannel is 2S.

A uniform constant heat flux of $q'' = 5 \times 10^5\ W\ m^{-2}$ and no-slip boundary condition are specified at the solid surfaces of the microchannel, including the pin-fin and dimple surface. Transitional periodic boundary condition is applied at the inlet