International Communications in Heat and Mass Transfer 91 (2018) 1–10

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Assessment of vortex generator shapes and pin fin perforations for enhancing water-based heat sink performance

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ARTICLE INFO

Keywords:
Vortex generators
Micro-channel
Micro scale cooling system
Heat transfer enhancement
Water vs air efficiency

ABSTRACT

In this study, two models have been analysed numerically to examine the impact of the geometry and the working fluid under laminar flow on heat and flow characteristics. The first model is a perforated pinned heat sink (PPHS) and the second is a new design of a uniform micro-channel having different shapes of vortex generators (VGs) positioned at intervals along the base of the channel. The VG shapes are circular, triangular and rectangular, and are compared to each other based on constant volume. Models with Reynolds number in the range of 50 to 2300 are subjected to a uniform heat flux relevant to microelectronics air and water cooling. Validations against previous micro-channel studies were conducted using the COMSOL Multiphysics® software package and found to be in good agreement. The results show that there is no significant enhancement in heat transfer using water in PPFHS. However, the VGs described here are shown to offer significant potential in combatting the challenges of heat transfer in the technological drive toward lower weight/smaller volume electrical and electronic devices. It is also found that the circular VGs offer the best heat performance among the proposed shapes.

1. Introduction

Since 1931, researchers have explored ways of managing the heat flux generated from electrical devices and offering better heat transfer rates using different types of heat sink cooling systems. One of the most popular heat sinks used in air-cooled systems is a plate-fin heat sink (PFHS) because of its simplicity to manufacture. Many investigations of PFHSs have studied and optimized the fins' height, thickness and separation, yielding predictions of heat transfer and entropy [1–4]. Other designs such as pinned heat sinks (PHSs) have also been considered in both inline and staggered arrangements [5] to enhance the heat transfer rate. They can take several shapes such as rectangular, square, circular, elliptical, NACA and drop form [6–8].

Continuing developments in electronic and electrical devices, and the increased heat density associated with miniaturisation, mean that thermal management of high heat fluxes remains an active area of research [9]. One approach is to improve the thermo-physical properties of the coolants, for example by developing nanofluids [10,11]. Alternatively, the geometry of the heat sinks can be adapted to improve heat transfer, for example by modifying the pins in PHSs or the channels in PFHSs. One very successful approach is the use of micro-channels. Micro-channels first appeared in 1981 [12] and have been classified in terms of their hydraulic diameters, D_h, [13–15] and distinguished from conventional channels. Using micro-channels can enhance the thermal performance of cooling systems [16] while shrinking their size and weight [17].

Indeed, developments in manufacturing capabilities and processes have opened wide possibilities for modifying the heat sinks types to enhance the performance of cooling systems. Therefore, Al-Damook et al. [18] examined a modified perforated PHS numerically and experimentally with turbulent air as the working fluid. The results showed that the heat transfer rate enhanced and, at the same time, the pressure penalty and fan power decreased using perforated pin fins compared to solid pin fins.

Many experimental and numerical studies have investigated the heat transfer and fluid flow performance of various modified geometries such as micro-channels having grooves and ribs [19–22]. One of the effective modified micro-channel types is a uniform channel having vortex generators (VGs). The enhancement of heat transfer and fluid flow characteristics were investigated experimentally in 1969 [23]. VGs can take various forms such as protrusions, wings, inclined blocks, winglets, fins, and ribs [24,25], and have been used to enhance heat

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https://doi.org/10.1016/j.icheatmasstransfer.2017.11.002

Nomenclature

A_s	surface area of the whole heat sink (μm^2)
C_p	Specific heat, J/kg·K
D_h	Hydraulic diameter, μm
k	Thermal conductivity, W/m·K
L	Channel length, μm
p	Pressure, N/m^2
PFHS	Plate-fin heat sink
PHS	Pinned heat sink
q	Uniform heat flux, W/cm^2
Re	Reynolds number
T	Temperature, K
u,v,w	Velocity components
u_{in}	Inlet velocity
VG	Vortex generator
x	Axial distance, μm

Greek symbols

μ	Viscosity, kg/ms
θ	Thermal resistance, K/W
ρ	Density, kg/m^3

Subscripts

ave	average
In	inlet
L	liquid
Out	outlet
S	solid

transfer in different geometries such as circular and non-circular ducts under turbulent flow [26–29]. They have also been used in laminar flow [24,30–33] which is effective to enhance the heat transfer rate, with flat plate-fins in rectangular channels [34–36], tube heat exchangers [17,37], heat sinks [30,38] and rectangular narrow channels [32,39].

Among different types of micro channel shapes, the rectangular micro-channel was the best geometry based on the numerical investigation of Xia et al. [40], who considered various microchannel shapes. They also investigated the distribution of flow through a collection of 30 micro-channels forming a heat sink, considering different header chamber shapes and inlet/outlet positions.

Recently, research has focused on VGs located on the channel sidewalls of the geometry. For example, Chia et al. [41] studied numerically the influence of fan-shaped ribs on the sidewalls of a silicon micro-channel with water in laminar flow. The results indicate that using fan-shaped ribs in the micro-channel can decrease the thermal resistance by up to 40% compared to a smooth channel. Furthermore, another study by Chia et al. [42] investigated the effect of five shapes of sidewall ribs in comparison to the performance of a smooth micro-channel using water in laminar flow. The rib cross-sections were rectangular, forward triangular, backward triangular, equal side triangular and semi-circular, and the results showed that the heat transfer rate was enhanced while the pressure penalty increased compare to the smooth channel. Also, it was found that the circular ribs offered the best thermal performance among VG models.

A 2D numerical study by Cheraghi et al. [16] considered a smooth channel, with fixed heat flux applied to the wall sides, having an adiabatic cylinder inside which was perpendicular to the laminar flow direction with a Reynolds number of 100 and Prandtl number ranging from 0.1 to 1. They investigated the influence of the position of the cylinder and found that the maximum enhancement occurred when the cylinder was fixed halfway from the base to the top of the channel. Also, the results showed that the low Prandtl number had a positive effect on heat transfer enhancement.

Furthermore, a modified channel having cylindrical vortex generators inside a uniform channel using turbulent flow with a Reynolds number of 3745 has been investigated numerically [43]. It was found that using a cylindrical vortex generator enhanced the heat transfer by 1.18 times compared to the uniform channel.

In addition, a recent investigation by Al-asadi et al. [44] studied the influence of cylindrical VGs with radii up to 400 μm on heat transfer and pressure drop characteristics under laminar flow conditions. Quarter- and half-circular VGs on the base of the micro-channel were considered with a constant heat flux ranging from 100 to 300 W/cm^2 and Reynolds number up to 2300. The results showed that heat transfer was enhanced using half-circular VGs, whereas the quarter-circle VGs offered no improvement. The results also indicated that the heat

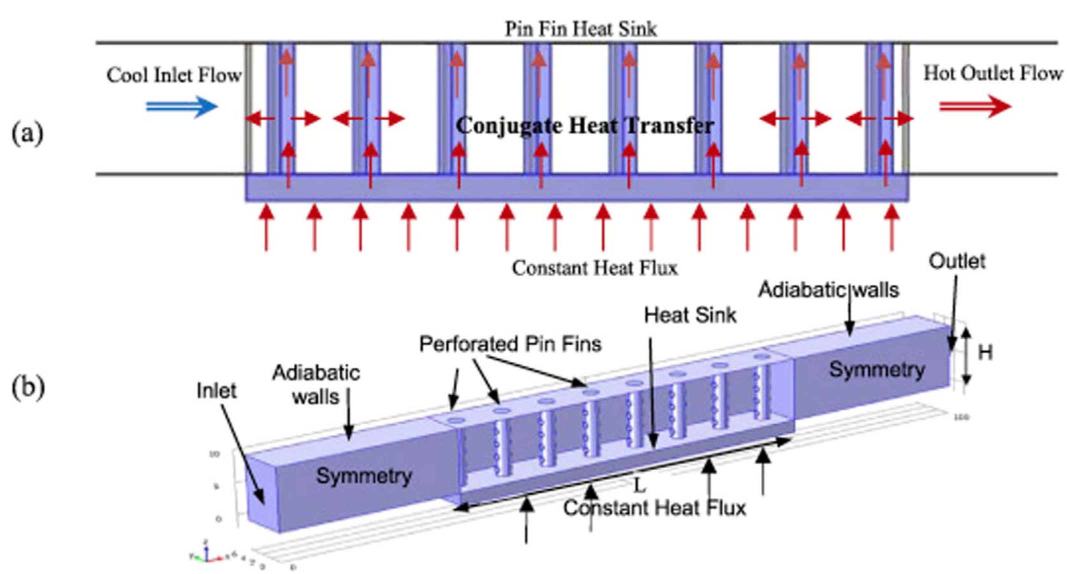

Fig. 1. PPHS model description, (a) pinned heat sink; (b) boundary condition of perforated pinned heat sink [17].