International Communications in Heat and Mass Transfer 76 (2016) 188–196

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Water cooled corrugated minichannel heat sink for electronic devices: Effect of corrugation shape☆

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ARTICLE INFO

Available online 25 May 2016

Keywords:
Corrugated minichannel
Different corrugation-shapes
Geometrical parameters
Experimental study

ABSTRACT

The main objective of the present study is to identify the potential of different geometries of the water cooled corrugated minichannel heat sink (CMCHS), i.e. triangular, trapezoidal, and sinusoidal, in comparison with the commercially available straight minichannel heat sink. The effects of the corrugation-length, corrugation-amplitude, and Reynolds number are investigated for each CMCHS. The results indicate that the trapezoidal CMCHS has the highest values of Nusselt number and pumping power, and the triangular and sinusoidal CMCHSs come in the second and third. It is also found that both the corrugation-length and the corrugation-amplitude have considerable effects on the thermal–hydraulic performances of the CMCHSs; Nusselt number and pumping power enhance, as the corrugation-length decreases and the corrugation-amplitude increases. Finally, the highest values of the heat transfer rate to the pumping power ratio are detected for the sinusoidal CMCHS.

1. Introduction

Due to rapid development in modern technologies like IT industry, current electronic systems generate a huge amount of heat, which deteriorates the performance of the devices and decreases their reliability [1]. The successful use of micro/mini-electronic mechanical systems in cooling applications made them the ultimate choice for thermal management control engineers [2]. One of the most feasible applications for micro/mini-electronic mechanical systems is the micro/mini-channel heat sink. In addition to microelectronics, the micro/mini-channel heat sinks have applications in other important and diverse fields including air conditioning, automotive, refrigeration, aerospace, bioengineering, cooling of gas turbine blades, power and process industries, infrared detectors and powerful laser mirrors and superconductors, and thermal control of film deposition. However, the application of microchannel heat sink is very hard because of very high pressure drop generated by the fluid flow through microchannels. On the other hand, the minichannel heat sink (MCHS) with hydraulic diameter between 0.2 and 3 mm can be used with a quite high heat flux and a mild pressure drop [3].

The nanofluid flow with different volume fractions of nanoparticle as a coolant in the straight MCHS was studied numerically by Ijam et al. [4]. It was found that using nanofluid such as Al_2O_3–water instead of water, improved the cooling by 2.95% to 17.32% and by using TiO_2–water, 1.88% to 16.53% was achieved. Keshavarz Moraveji et al. [5,6] conducted CFD simulations on the nanofluid flow through the straight MCHS. Individual models (single phase, VOF, mixture, Eulerian) were applied. It was shown that the difference between the two-phase models results was marginal, and they were more precise by comparison with experimental reference data than the single phase model. Ho et al. [7] performed an experimental study to investigate the cooling performance of a MCHS with microencapsulated phase change material particles/water as the coolant. The measured results reveal that the thermal performance can be enhanced by addition of the particles in water with low values of latent-sensible heat ratio and using a low flow rate of coolant as compared to those of the pure water. In the other experimental study, Sohel et al. [8] displayed a higher improvement of the thermal performances using nanofluid instead of pure distilled water in the straight MCHS. The heat transfer coefficient was found to be enhanced up to 18% successfully. For effective thermal management of high heat generating microprocessors, five MCHSs with different fin pitches were investigated experimentally by Jajja et al. [9]. The base temperature and thermal resistance of the heat sinks were found to drop by decreasing the fin pitch and by increasing volumetric flow rate of working fluid circulating through the MCHS. A numerical simulation a long with an experimental study were performed on the turbulent heat transfer and flow characteristics of nanofluids in the MCHS by Naphon and Nakharintr [10]. It was detected that similar to Keshavarz Moraveji et al. [5] for the nanofluids flow, the two phase models (mixture two phase and VOF) were more appropriate the homogeneous model (single phase). The performance of the MCHS can be affected greatly by working fluid flow distribution. In order to improve the flow distribution and heat transfer performances in the MCHSs, the use of non-uniform mini baffles was proposed by Liu and

☆ Communicated by W.J. Minkowycz.

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.05.021
0735-1933/

Nomenclature

A	surface area, m^2
a	corrugation-amplitude, m
C_p	specific heat capacity, J kg^{-1} °C^{-1}
D_h	hydraulic diameter, m
G	mass velocity, kg m^{-2} s^{-1}
H	minichannel height, m
h	heat transfer coefficient W m^{-2} °C^{-1}
L	minichannel length, m
l	corrugation-length, m
m	mass flow rate, kg s^{-1}
Q	convective heat transfer rate, W
P_P	pumping power, W
Δp	pressure drop, Pa
s	distance between thermocouples location and MCHS
T	temperature, °C
W	minichannel width, m

Greek symbols

ρ	density, kg m^{-3}
μ	dynamic viscosity, Pa s
κ	thermal conductivity, W m^{-1} °C^{-1}

Subscripts

cond	conduction
conv	convection
f	fluid
in	inlet
m	mean
out	outlet
s	solid
w	wall

Acronyms

CFD	computational fluid dynamics
CMCHS	corrugated minichannel heat sink
MCHS	minichannel heat sink

Yu [11]. The simulation comparisons shown that the improvements in the flow maldistribution of the MCHS can be achieved through the non-uniform baffles, resulting in better uniformity of the temperature distribution.

Based on the mentioned literature, generally two types of passive heat transfer enhancement technique can be employed in order to improve the performance of the MCHSs. The first type is to modify the geometry of flow pass and the second one is to modify the thermophysical properties of working fluid. Comparative studies show that using an enhanced surface like complicated minichannels in the MCHSs is more effective than using an enhanced coolant like nanofluids [12]. Moreover, the use of nanofluids is still ambiguous due to many problems associated with them, i.e. more maintenance required, higher cost, aggregation and deposition of nanoparticles [13]. On the other hand, although many analytical and numerical studies have been done on the MCHSs in the open literature, the number of experimental studies conducted is very limited. Also to the best of the author's knowledge, no attempt has been made to investigate the effects of corrugation shape on fluid flow and heat transfer characteristics of the corrugated minichannel heat sink (CMCHS). In fact, this motivates the present study. In this work, the cooling performance of the CMCHS with different corrugation-shapes, i.e. triangular, trapezoidal, and sinusoidal, are investigated experimentally with pure water as coolant. Also, systematic effects of corrugated minichannels geometry (corrugation-length and corrugation-amplitude) are investigated. All the CMCHSs fabricated from aluminum consist of 8 rectangular minichannels with a width and a depth of 1 mm and a length of 100 mm.

2. Research apparatus and methods

2.1. Test setup

Fig. 1(a) is the simple schematic of the experimental setup which is built in Advanced Laboratory of Chemical Engineering Department of IAU, Shahrood Branch. The major components of this close loop are transmission fluid state, measuring equipment, test module, power supply, cooling unit, and monitoring system.

Water as the coolant enters the loop from a reservoir through a filter and is continuously circulated by a centrifugal pump. The pump creates enough pressure to force the coolant to pass through the test module. The flow rate of coolant is controlled using a by-pass loop comprising a ball valve and a needle value. Mass flow rate inside the loop is measured by a flow rate measurement system. It consists of a digital timer, electrical valves, and a digital balance. To simulate the processor of electronic devices cooling, a test model is designed and assembled. The test module comprising a heating block and minichannels, two bulk thermocouples, two pressure transmitters, nine surface thermocouples, and eight cartridge heaters is shown in Fig. 1(b). Inlet/outlet deep and shallow pendulums are fabricated at the upstream and downstream parts to provide a relative uniform flow distribution, where taps of bulk thermocouples and pressure transmitter are positioned. Nine small holes are drilled along the centerline of the MCHS base, where surface thermocouples are installed to evaluate the base temperature. These holes which are located at a distance of 5 mm beneath the base surfaces of minichannels have the same longitudinal distance. The test module components are placed and fitted in a container made of Plexiglass insulator. The supplied voltage and current to the heaters are justified by a variac variable transformer and measured by a digital multifunction instrument. The cooling unit is used to cool down the heated coolant before entering the storage tank for recirculation. It consists of a plate heat exchanger and a fabricated water bath system to supply the cooling fluid through the plate heat exchanger. Finally, all the measured quantities are logged by the monitoring system. The details of experimental setup are available in the related work [12].

2.2. Corrugated minichannel configurations

To determine the suitable corrugation shape for the corrugated minichannels, three typical configurations, namely triangular, trapezoidal, and sinusoidal, are examined. Each corrugated minichannel has a width and a deep of 1 mm which are kept constant for all models. The corrugated minichannels are fabricated from aluminum plates by a precision sawing technique. In order to have a detailed result, the effects of two specific geometrical parameters of the corrugated minichannels, i.e. corrugation-length and corrugation-amplitude, are also investigated for each configuration of CMCHS. Considered values in the present study are 10, 20, and 30 mm for the corrugation-length and 0.5, 1.0, and 1.5 for the corrugation-amplitude. The geometric structure of corrugated minichannels is depicted schematically in Fig. 2 and the detailed dimensions are summarized in Table 1. A photograph of the fabricated and tested CMCHSs is also shown in Fig. 3.

2.3. Data calculation

During passing through the corrugated minichannels the coolant absorbs heat produced by the electrical heaters. This is expressed by the conservation of energy principle, Eq. (1),

$$Q_{conv} = mC_p(T_{out} - T_{in}). \tag{1}$$