JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Analysis of Fluid Flow and Heat Transfer in Microchannel Heat Sinks for Electronics Cooling Applications

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Abstract
Nowadays, microchannels have been widely utilized in various multidisciplinary fields, and as a consequence, some new and different requirements for microchannels in the process of practical application are required, such as structure, working fluid, and operating conditions, etc. This article reviews the current research achievement of microchannels, as well as the thermodynamic research on microchannels with different structures in the past five years, but mainly focuses on the numerical methods. The purpose of this review article aims to summarize a comprehensive overview of the latest developments of numerical methods in microchannel heat sinks, as well as to provide a useful benchmark for future research. Current work explored LP-MCHS has the lowest Nu/Nu_0 and lowest Pr/Pr_0. Three dimensional computational models based on finite volume approach were created incorporating the enhancement techniques and analysed numerically in ANSYS Workbench.

***IndexTerms* - CFD Analysis, Microchannel, Electronics Cooling, Improved MCHS**

I. INTRODUCTION

Many researchers have proposed various techniques to enhance the performance of microchannel heat sink. The enhancement methods can be broadly classified into active and passive methods. In the active methods, additional energy is needed for the enhancement. The active methods include application of vibration, flow pulsation and electrostatic fields, etc. Passive methods do not consume energy for the enhancement. They include flow disruptions, secondary flows, curved channels, out of plane mixing, re-entrant cavities, surface roughness, fluid additives, etc. Steinke and Kandlikar [2] stated that the heat removed by two-phase system is more than that of single phase system in macrochannels; however the system complexities, pumping requirements and pressure drop are more for two-phase flow systems in microchannel.

The basic idea of the present study is to explore novel designs of conventional MCHS which enhance its thermal capability. The conventional MCHS with modification in design for performance enhancement henceforth is termed as enhanced MCHS. The objective of present research is to explore passive enhancement methods such as secondary flows and flow disruption in enhanced MCHS and study the thermo- hydraulic performance of enhanced MCHS subjected to constant heat flux applied at base and cooled by de-ionized water (single phase cooling). Range of different parameters for the present research is as shown in table 1. The parameter range is decided after extensive study of research carried out in similar MCHS enhancement field. For ease of comparison, the conventional and enhanced MCHS have same channel dimensions and overall footprint. Thermo-hydraulic performance of three enhanced MCHS and conventional MCHS is studied numerically and compared to generate the conclusions.

Table 1 Parameters for current work

Parameters for the current study	**Parameters range**
Enhancement method	1. Secondary channel (Leaf venation pattern) 2. Flow disruption by using pin-fins 3. Combination of secondary channel and pin- fin
Microchannel material	Copper
Microchannel width	500 µm
Microchannel depth	900 to 1500 µm
Fluid	De-ionized water
Heat flux	65 to 200 W/cm^2
Flow rate	500 to 1000 ml/min

Lee et al. [3] carried out experimental investigations to explore the validity of conventional channel correlations in microchannel design. Ten parallel microchannels of aspect ratio of 5 and width ranging from 194 µm to 534 µm were fabricated on copper block. Deionized water was used as coolant having Reynolds number ranging from 300 to 3500. They reported that the numerical predictions obtained from classical continuum approach were found to be in good agreement with experimental data. They suggested that the conventional analysis approach can be employed in the microchannels provided sufficient care is taken in matching the entrance and boundary conditions of the experiments in the numerical analysis.

Steinke and Kandlikar [4] reviewed the enhancement techniques for single phase liquid cooled MCHS and claimed to match with the performance of two phase cooling system. The enhancement techniques can be broadly classified into active and passive types. Passive technique of enhancement of MCHS does not require external power or activation. Surface roughness, flow disruptions, channel curvature, secondary flows, out of plane mixing fluid additives are some of the passive techniques. Kandlikar et al. [5] reviewed the status of microchannel research and suggested the future research directions. For the single phase liquid flow in microchannel they suggested the flow mixing of different streams as a major form of enhancement technique. Surface roughness, secondary flow and flow disruptions were the other methods suggested. The next few sections look into the research work done in the area of passive enhancement.

II. NUMERICAL ANALYSIS OF MICROCHANNEL

Use of pins to divert the flow into secondary channels is explored in this design. Secondary channel and flow disrupting pins are combined to form the new design (figure 1). The design connects three parallel channels with secondary channels forming a leaf venation type pattern. The secondary channels are different from those in LV-MCHS. The secondary channels are branched at four locations. The branching is symmetric instead of asymmetric in LV-MCHS and the width of secondary channels is 500 µm. Square pins are introduced into the central channel from top acrylic cover of MCHS. The pins have height equal to height of channel and act very much similar to conventional pin-fins emerging from the base of channel. The introduction of pins from top reduces the manufacturing cost considerably. The dimensions of the conventional and enhanced LP-MCHS are given in table 1.

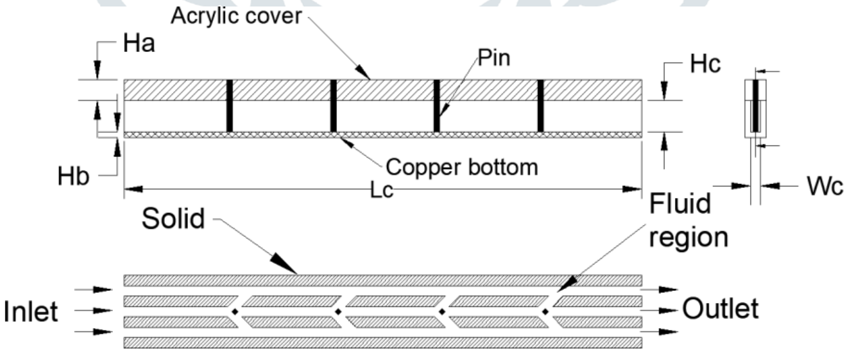


Figure 1 Square pins inserted from top acrylic cover and leaf venation channel network in sectional front view and top view of single set of enhanced LP-MCHS

Table 1 Dimensions of LP-MCHS

Characteristics	**Conventional MCHS**	**Enhanced LP-MCHS**
Material	Copper	Copper
Footprint L x W (mm)	25 x 25	25 x 25
Channel width Wc (µm)	500	500
Wall width Ww (µm)	500	500
Channel height Hc (µm)	1500	1500
Aspect ratio (Hc/ Wc)	3	3
Height of acrylic cover Ha (µm)	1000	1000
Height of copper bottom Hb (µm)	300	300
Number of pins in a single channel	--	4
Square pin size (µm)	--	250
Secondary channel width Ws (µm)	--	500
Secondary channel angle (deg)	--	27

2.1 Numerical analysis of enhanced MCHS

Any engineering problem can be solved using analytical method, experimental method or numerical method. Analytical methods for heat transfer and fluid flow problems are difficult to achieve due to a) the three dimensional equations b) the equations are strongly coupled and non-linear and c) the solution domains are mostly complex. Numerical method holds certain advantages over other methods due to the developments in the computing capabilities and computer codes for complex domains and boundary conditions. In many research areas numerical analysis is done before conducting experimentation. Numerical analysis can save a lot of trials in experimentation so the researchers can eliminate the unwanted designs and concentrate on the designs proven by numerical analysis. Computational fluid dynamics is the computer based simulation technique used to analyse systems which involve fluid flow and heat transfer phenomenon. Three dimensional computational models based on finite volume approach were created incorporating the enhancement techniques and analysed numerically in ANSYS WORKBENCH. Heat transfer and fluid flow characteristics of enhanced MCHS designs are studied in this chapter using computational fluid dynamics.

2.2 Enhanced LP-MCHS

The computational model for conventional MCHS required for numerical analysis has three parallel channels forming a set as shown in figure 2. The enhanced LP-MCHS computational model is as shown in figure 3. The three parallel channels are connected by secondary channels branching symmetrically at four different locations. Square shaped pins are inserted with the help of top acrylic cover at strategic locations forflow disruption and directing the flow into the secondary channels. The top acrylic cover is removed in the figure for visualization of pins and secondary channels.

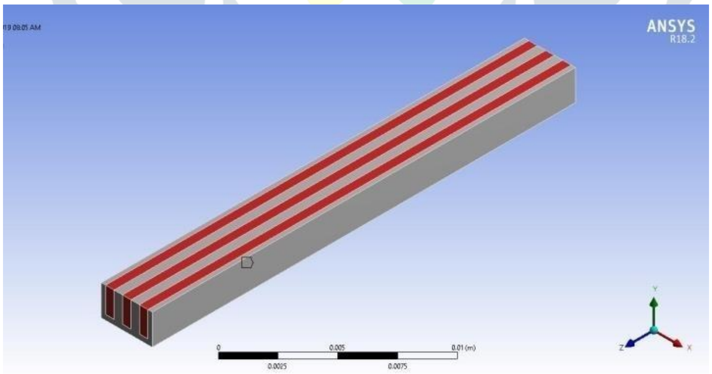
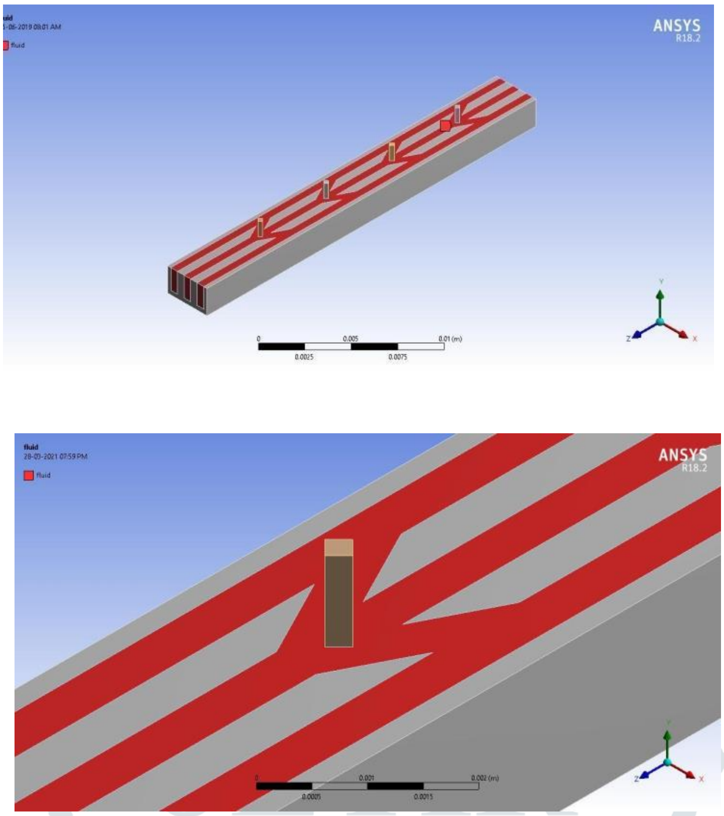


Figure 2 Conventional MCHS computational model having three parallel channels



a)

b)

Figure 3 Enhanced LP-MCHS computational model showing a) three parallel channelsconnected by secondary channels and square pin placed at appropriate location b) zoomed view showing the square pin location

To make sure the results are free of grid size, the maximum face size of the elements in conventional MCHS is varied from 1x10^{-4} m to 5x10^{-5} m and to 4x10^{-5} m and the relative error of fluid outlet temperature is calculated. The relative error of fluid outlet temperature from first maximum face size to second size is 1.11 percent and the same for second to third face size is 0.69 percent. Hence the grid with maximum face size of 5x10^{-5} m is selected for further simulations.

III. RESULTS AND DISCUSSIONS

Thermo-hydraulic performance for all MCHS subjected to heat flux of 100W/cm^2 and Reynolds number ranging from 650 to 1310 is discussed here (figure 4 - 7).Thermal performance is assessed by estimating the Nusselt number for all cases. Figure 5 shows that the Nusselt number increases linearly with increasing Reynolds number for all cases. Maximum rise in Nusselt number of enhanced LP-MCHS is by 29% compared to the conventional MCHS. Pressure drop across channel increases linearly with increase in Reynolds number for all cases. Pressure drop increases rapidly for enhanced LP-MCHS with rise in Reynolds number (figure 5). Maximum rise in pressure drop of enhanced LP-MCHS is by 44% more than conventional MCHS. Effect of Reynolds number on maximum bottom surface temperature is shown in figure 6. Conventional MCHS shows higher temperature than enhanced LP-MCHS indicating lower thermal performance. Comparison of various parameters of enhanced LP-MCHS at heat flux of 100 W/cm^2 with conventional MCHS is shown in figure 4.45 with the subscript 0 indicating the values of conventional MCHS. The average value of Nusselt number ratio is 1.23 over the entire Reynolds number. The P/P_0 ratio is the pressure drop factor which increases with higher Reynolds number. The average value of pressure drop ratio is 1.43 over the entire Reynolds number.

The enhancement factor decreases with increase in Reynolds number which can be attributed to the high pressure drop at higher flow rates whereas the Nusselt number ratio decreases for higher flow rates. Maximum value of enhancement factor for enhanced LP- MCHS is 1.20. Comparison of all the parameters indicates that the thermal performance of enhanced LP-MCHS is better than conventional MCHS. Compared to earlier work of Ghani et al. which placed rectangular plate fin for flow diversion into secondary channel, the pressure drop in LP-MCHS is considerably lower. The maximum pressure drop in Ghani et al. is 45000 Pascal while the maximum pressure drop in LP-MCHS is 4000 Pascal. This is due to gradual diversion of fluid due to square pins instead of sudden blocking of path done in Ghani et al. The cost of inserting square pins is very small compared to fabricating pin-fins from the base of microchannel. The improvement in thermal performance is significant considering the additional cost incurred.

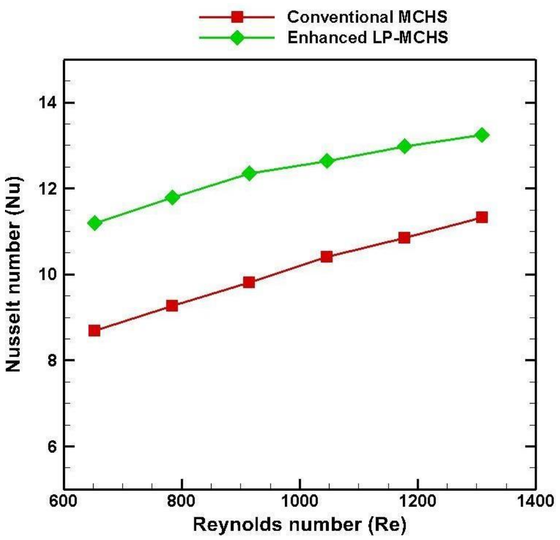


Figure 4 Variation of Nusselt number at various Reynolds number for conventionaland LP-MCHS for heat flux of 100 W/cm^2

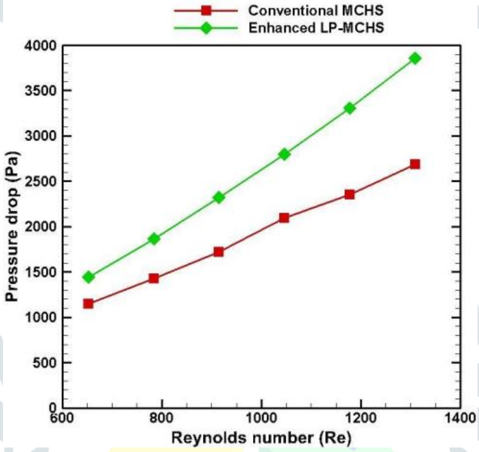


Figure 5 Variation of pressure drop at various Reynolds number for conventional and LP-MCHS for heat flux of 100 W/cm^2

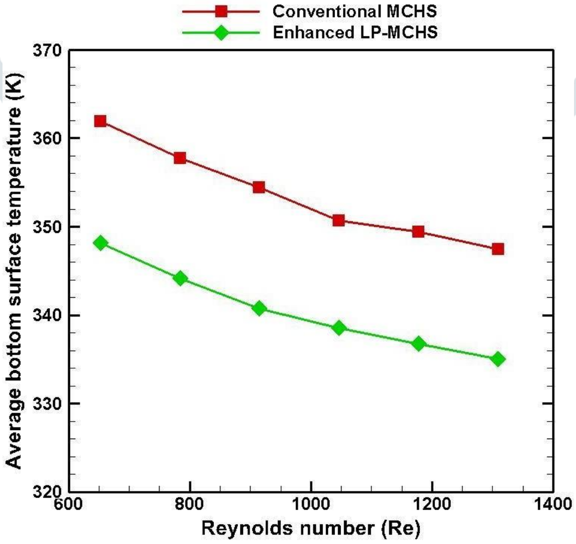


Figure 6 Variation of bottom surface temperature at various Reynolds number forconventional and LP-MCHS for heat flux of 100 W/cm^2

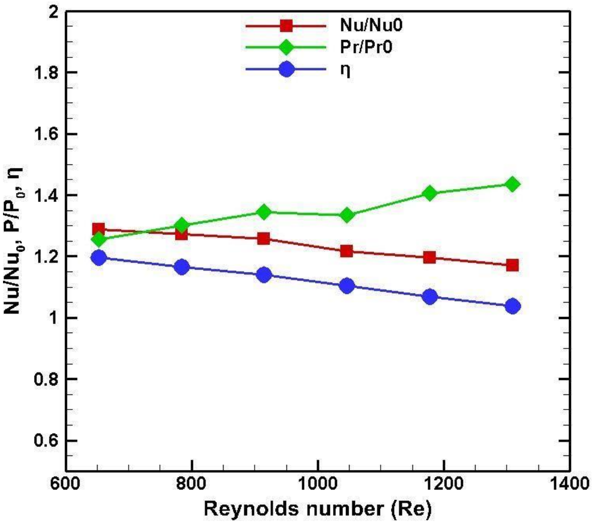


Figure 7 Nusselt number ratio, Pressure drop ratio and enhancement factor at variousReynolds number for enhanced LP-MCHS for heat flux of 100 W/cm^2

IV. CONCLUSIONS

Thermo-hydraulic performance of pins of various shapes was compared and square shaped pins were selected for further study. The square pins inserted from top cover serve dual purpose of flow disruption and rerouting the flow into secondary channels. Velocity streamlines give insight into the fluid movement into secondary channel due to the presence of square pins. Using numerical analysis, for same boundary conditions, the location of pin and size of pin were varied and optimum values determined. Thermal performance of the enhanced LP-MCHS is better than conventional MCHS. The Nusselt number of enhanced LP-MCHS is more by 23 percent than conventional MCHS for all heat flux. The pressure drop in LP-MCHS is more by 35 percent than conventional MCHS for all heat flux. Maximum surface temperature is below 358 K (85 °C) for heat flux of 65 and 100 W/cm^2 for all flow rates. Maximum value of enhancement factor over conventional MCHS for enhanced LP-MCHS (η) is 1.20.

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