DEPARTMENT OF MECHANICAL
ENGINEERING
INDIAN INSTITUTE OF INFORMATION
TECHNOLOGY, DESIGN AND
MANUFACTURING KANCHEEPURAM
CHENNAI - 600127

Synopsis Of

Design and Performance estimation of Modified Microchannel Heat Sink for Electronic Cooling

A Thesis

To be submitted by

RAJALINGAM A

For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

Electronic devices have become a very important aspect of our daily life. The performance improvement of these electronic devices leads to both a reduction in size and an increase in heat generation. Efficient heat dissipation is necessary to prevent device failures and maintain temperatures below critical limits for optimized performance. In recent times, air cooling has been nearly insufficient in terms of dissipating the required heat. Microchannel heat sinks (MCHS) using liquid as a working fluid offer an ideal solution due to their efficient heat transfer, compactness, and lower weight. Nonetheless, MCHS suffers from notable drawbacks like high-pressure drops and uneven heat dissipation along the channel. Thus, there is a need for technologies to address these limitations and meet future heat dissipation demands. Various mechanisms, including flow acceleration, boundary layer interruption, flow disturbance, and flow boiling, can enhance heat transfer performance. In this research, these mechanisms have been utilized to enhance the performance of MCHS. Incorporating microstructures inside the channel is a proven method for enhancing heat transfer by disrupting and accelerating the flow. This study explores the effect of different cross-sections and arrangements of blind holes and pillars. The trapped fluids within the blind holes reduce pressure drop, while flow disturbance enhances heat transfer. A novel arrangement where pillars are distributed throughout the channel with descending pillar density from upstream to downstream. The elliptical pillar shows the highest overall performance index among various pillar shapes. Next, it is observed that MCHS with micro-ribs at the bottom surface outperforms MCHS with pillars in terms of heat transfer and fluid flow characteristics. Aerofoil-shaped micro-ribs enhance heat transfer, while reversed aerofoil micro-ribs reduce pressure drop. Efforts have been made to investigate the effect of sudden and gradual variations of channel cross-sectional area. The convergence and divergence angles notably influence heat transfer and fluid flow characteristics in the converging-diverging channel. Sudden expansion gradually recovers pressure, while the sudden contraction increases the pressure drop. Introducing multiple sudden expansions and contractions in the channel cross-section in sequence, heat transfer performance was improved at the cost of higher pressure drop. The study of the placement of transverse channels was another focus. These channels, within microchannel heat sinks, improve heat dissipation performance without a change in pressure drop. The research also focuses on the effect of various arrangements and positions of pillars and blind holes under flow boiling conditions. From the study, it is observed that the pillar enhances heat transfer in single-phase flow and delays the phase change, while blind holes serve as nucleation sites. Optimal performance is achieved by positioning twelve pillars in the upstream half and twelve blind holes in the downstream half of the channel.

2 Objectives

The present research aims to enhance the heat transfer performance without sacrificing the pressure drop of the channel. Efforts have been made to improve the heat transfer performance of microchannel heat sink (MCHS) by the geometrical modifications and placing of microstructures inside the microchannel with both single-phase and two-phase flow conditions. The broad objectives of the thesis are listed as follows.

- To investigate the effect of various arrangements, positions, and cross-sections of pillars and blind holes on the performance of MCHS.

- To compare the performance of a microchannel with micro-pillars and ribs. Additionally, to study the effect of various cross-sections of micro-ribs and different arrangements of cross-sectional ribs on the thermohydraulic efficacy of heat sink.

- To optimize the location of throat position in converging-diverging microchannel and various arrangements of sudden expansion and contraction.

- To investigate the detailed effect of various configurations of transverse channels in the microchannel heat sink on the fluid flow and heat transfer characteristics.

- To analyze the effect of the arrangements of pillars and blind holes on the fluid flow characteristics and heat transfer performance of MCHS under flow boiling conditions with various inlet subcooling and put heat flux conditions.

3 Existing Gaps Which Were Bridged

The existing studies have used various methods to enhance the heat transfer performance such as the placing of the pillar (Qidwai and Hasan (2019); Jia *et al.* (2018)), variation in the cross-sectional area of the channel along the flow direction, geometrical modifications, boiling phenomenon, etc. Nevertheless, few gaps have been identified and attempts have been taken to bridge those gaps as follows.

- There has been no in-depth analysis of the effect of blind holes placed at the bottom surface of the channel and their cross-sectional shapes on fluid flow and heat transfer characteristics. The current study addresses this gap.

- Some existing studies have studied the effect of the location of pillars (Jia *et al.* (2018); Yadav *et al.* (2016)). However, no existing literature studied the arrangement of pillars and blind holes. The present analysis bridges this gap and suggests a novel arrangement. The effect of various cross-sections of pillars with the novel arrangement also has been studied in detail.

- Though some existing studies investigated the performance of MCHS with pillars and micro-ribs (Chai *et al.* (2019); Li *et al.* (2016)), there is no detailed comparison of the performance enhancement between pillars and ribs on the various surfaces on the channel wall. There is also scope for a detailed investigation of the performance of MCHS with various cross-sections of an extended surface

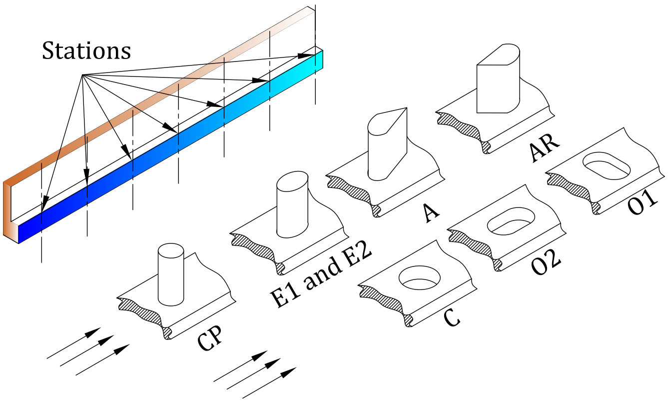

Figure 1: Considered shapes of microstructures

(especially, ribs on the bottom wall). The various arrangements of the different cross-sectional micro-ribs are also investigated and a novel arrangement with higher thermo-hydraulic performance is proposed.

- A few literatures have investigated the effect of converging and diverging of channel cross-section along the length (Ghaedamini *et al.* (2013); Ali *et al.* (2021)). However, no studies reported the effect of various locations of throat position of converging-diverging microchannel. Though few studies examined the effect of sudden expansion and contraction of the microchannel (Deng *et al.* (2019); Hajji *et al.* (2021)), no studies attempted to investigate the effect of various position of sudden expansion and contraction. The present study addresses these gaps.

- Some studies reported the effect of pillars and blind holes on the boiling phenomenon of MCHS (Jung *et al.* (2021); Li *et al.* (2020)). Nevertheless, there are no existing studies with detailed investigation of the influence of the positions and arrangements of the blind holes and pillars inside the microchannel heat sink (MCHS). The present study attempts to address this gap.

4 Most Important Contributions

The microchannel with a square cross-section (400 μm × 400 μm) and a length of 5 cm is located in a copper heat sink. In the heat sink, such microchannels are placed in parallel. Only a single channel has been considered for the present computational analysis (except for the analysis of the transverse channel where six parallel channels have been considered). ANSYS Fluent software package has been used to solve the governing equations. The Grid independence study has been performed to optimize the grid. The selected numerical schemes were validated by experimenting and also with the existing experimental and numerical data.

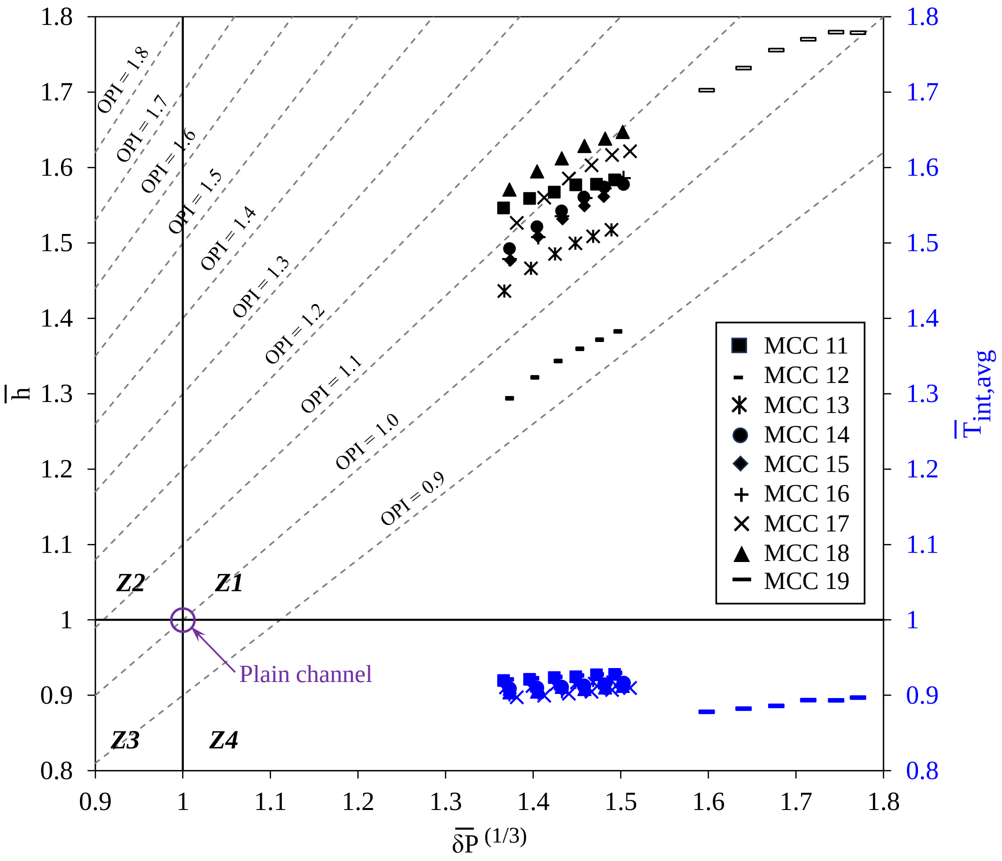

Figure 2: Considered shapes of microstructures

4.1 Effect of pillars and blind holes

The effect of arrangement and the shape of micro-structure (pillars and blind holes) on the thermohydraulic performance of MCHS is analyzed. This has been achieved through four different steps. The considered shapes of microstructures are shown in Fig. 1. In the first step, the effect of cross sections of blind holes has been investigated and the circular blind hole has been identified as the optimized one. The arrangement of the circular pillar and blind hole is optimized in the next step (performances are shown in Fig. 2 where, $\overline{h}$, $\overline{\delta P}$, $\overline{T_{int}}$ and OPI (OPI = $\frac{\overline{h}}{\overline{\delta P}^{(1/3)}}$) are normalized (by the plain channel) heat transfer, pressure drop, average interface temperature and overall performance index respectively) by selecting the hole shape as circular where it is observed that the pillars should be distributed throughout the channel length and more pillars should be located at the channel upstream region for the maximum overall performance index (MCC 18). This phenomenon is detailly investigated in the third analysis. Better overall performance is attained by placing six pillars at upstream stations and distributing the remaining pillars at the downstream among the blind holes. In the final step, the effect of various cross-sections is optimized for selecting the best arrangement from the second step. Though the higher heat transfer coefficient is observed for the circular pillar, the high pumping power makes its hydraulic performance poorer than some other MCCs. The minimum pumping pressure as well as lower heat transfer coefficient is observed for MCHS with an aerofoil pillar (the tail end of the pillar faces the flow). Therefore, it can be concluded that the performance of the MCHS significantly depends on the cross-section of pillars and blind holes. The overall performance index of MCHS with elliptical pillars is found to be the best and it successfully maintained the lower average interface temperature.

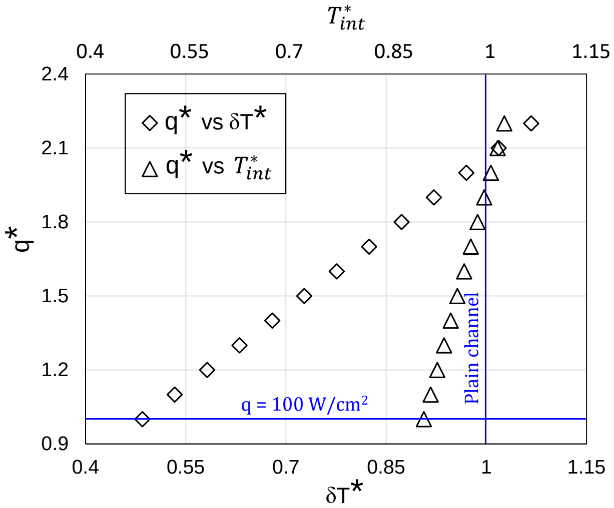

Figure 3: Comparative temperature analysis of the suggested novel MCC with the plain channel

4.2 Effect of microstructured wall

Efforts have been made to investigate the fluid flow characteristics, and heat transfer performance of microchannel heat sinks (MCHS) with micro-structures (micro-pillar and micro-ribs). In the first analysis, the performances of MCHS with micro-pillars are compared with the various arrangements of micro-ribs. The higher heat transfer coefficient, and lower average sink temperature are achieved for the microchannel with micro-ribs located at the bottom surface of the channel. The rise in pressure drop in the channel due to the presence of micro-ribs is also lower than the presence of micro-pillars. In the second analysis, the effect of various cross-sections of micro-ribs (located at the bottom surface) has been investigated. The heat transfer performance, and the pressure drop across the channel depend on the cross-section of the ribs. Based on the performance parameters microchannel heat sink with aerofoil and reversed aerofoil micro-ribs are found to be the best configuration among others. From the final analysis, it is noted that the heat transfer enhancement by the ribs is significant when they are placed at the upstream half of the channel. It is also noted that the aerofoil ribs enhance the heat transfer and reverse aerofoil ribs recover the pressure drop. Based on these two observations a novel arrangement of micro-ribs has been proposed with twelve aerofoil ribs at the upstream half and twelve reversed aerofoil ribs at the downstream half. The suggested novel heat sink reaches the performance of the plain channel when the heat flux becomes nearly twice as shown in Fig. 3. $T_{int}*$ and $\delta T*$ is the normalized average interface temperature and difference between the maximum and minimum temperature respectively. q* is is applied heat flux normalized by $100 W/cm^2$.

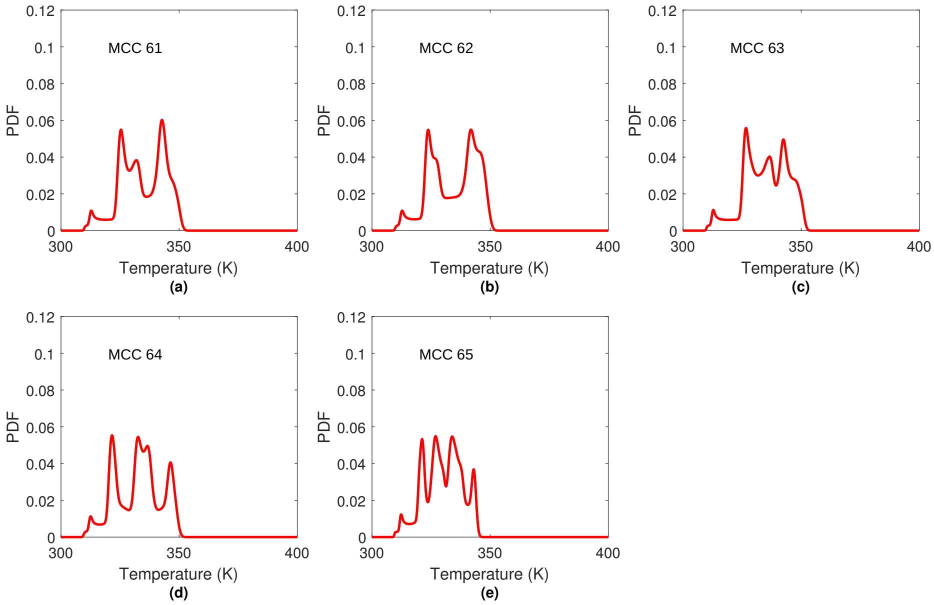

Figure 4: Probability density function of the temperature of analysis 3

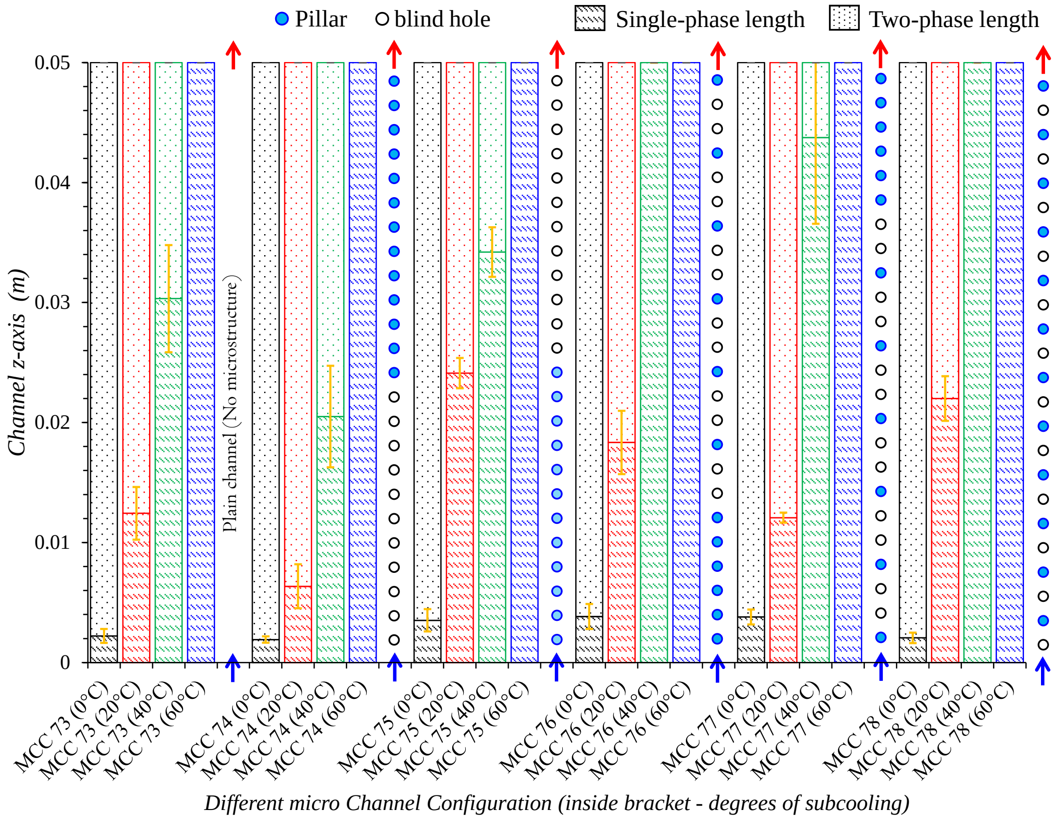

Figure 5: Length of single and two phase flow

4.3 Effect of variation of the flow passage

This portion of research work deals with the investigation of the effect of variation of the area of the cross-section area of the microchannel on its thermohydraulic performance. The study has been performed through a sequence of three analyses. In the first analysis, the effect of the gradual variation of the cross-section area has been investigated. From the inlet, the channel cross-sectional reduces along the length of the channel and increases. In this detailed analysis, the location of the minimum cross-section area (throat) varies from 0% to 100% of the channel length. It is observed that the effect of the angle of divergence on the pressure drop is more than the converging angle. None of the cases achieves OPI greater than 1. In the next analysis, the effect of sudden contraction and expansion is thoroughly discussed. The pressure reduces instantaneously with a significant magnitude as the flow passes through sudden contraction and increases gradually as it passes through sudden expansion. The rate of pressure recovery in sudden expansion depends on the ratio of the maximum cross-section to the minimum cross-section. It is also observed that the thermohydraulic performance of the microchannel improves when the upstream and downstream part of the channel with cross-section L (cross-sectional area is $0.55 \times 0.4\ mm^2$) is connected by a significant length of the channel with cross-section S (cross-sectional area is $0.25 \times 0.4\ mm^2$). From these observations, the third analysis is planned by dividing the channel length into multiple number of section with alternative cross-sectional area L and S. The heat transfer performance increases with more number of such divisions are done. However, the pressure drop for such cases increases drastically with the increase in Re. The overall performance index for the microchannels with two sections with cross-sectional area L connected by a cross-sectional area S (the section with cross-sectional area S is shifted towards upstream) is maximum than all other cases. Fig. 4 shows the probability density function of temperature of the considered microchannel configurations. An effort also has been made to improve the heat transfer performance of microchannel heat sinks by incorporating the transverse channels without incurring any penalty in terms of pressure drop. The presence of transverse channels enhances heat transfer performance by disrupting and regenerating the boundary layer. Additionally, the average temperature of the bottom surface decreases as the number and length of transverse channels increase. The inclusion of a sudden expansion in the cross-sectional area before the transverse channel contributes to improved heat transfer rates. Conversely, reducing the channel flow passage after the transverse channel enhances the rate of heat dissipation and increases the pressure loss. The transverse channel aids in pressure recovery.

4.4 Effect of pillars and blind holes under flow boiling condition

Finally, efforts have been made to study heat transfer and fluid flow performance of a microstructured microchannel heat sink under flow boiling conditions. Initially, five different configurations of micro-pillars and blind holes have been considered and their performance has been studied for saturated inlet conditions. Next, keeping the heat flux constant, the inlet subcooling is varied. At the last, keeping inlet subcooling as constant as $60^O C$, the input heat flux has been varied. From the first two analyses, it is found that the blind holes act as nucleation sites throughout the channel and the pillars delay the boiling by accelerating the flow near upstream. The pressure fluctuates due to the passage of vapor bubbles intermittently through the small opening between the pillars and the channel wall. If more pillars are located in the two-phase zone, more fluctuation is observed. It is also observed that the heat transfer and fluid flow characteristics of the microchannel heat sink strongly depend on single-phase and two-phase length (shown in Fig. 5) which is affected by the arrangement of microstructures. From the last analysis, it can be seen that with the degree of subcooling $60^{O}C$, MCC 75 (12 pillars upstream and 12 blind holes downstream of the channel) experiences the maximum heat transfer coefficient and minimum pressure drop. Therefore, it can be said that the performance of MCC 75 is optimum under these conditions among the selected microchannel configurations.

5 Conclusions

The findings of the present research work are summarized as follows.

- The blind holes marginally enhance the heat transfer performance and reduce the pressure drop. MCHS with circular blind holes achieved a higher heat transfer performance than the oval cross-sectional blind holes.
- For higher heat transfer performance, the pillars should be distributed throughout the channel length and more pillars should be located near the channel inlet.
- The gradual variation in the cross-sectional area of the channel helps to reduce the pressure drop. The pressure drop in a microchannel with reversed aerofoil pillars attains a lower value than others. MCHS with elliptical cross-sectional pillars achieved a higher overall performance index.
- The microchannel with micro-ribs positioned at the bottom surface achieved a lower heat transfer coefficient, lower average sink temperature, and lower pressure drop.
- MCHS with aerofoil and reversed aerofoil micro-ribs stand out as the best based on its performance parameters. The novel micro-rib arrangement is proposed, consisting of twelve aerofoil ribs at the upstream half and twelve reversed aerofoil ribs at the downstream half.
- The heat transfer coefficient and pressure drop increase as the number of sudden contractions and expansions increases.
- The presence of a transverse channel increases heat transfer performance without a significant increase in the pressure drop.

- The analyses reveal that the blind holes serve as nucleation sites in the channel, while the pillars delay boiling by promoting accelerated flow near the upstream region.
- A higher heat transfer coefficient is achieved when the upstream and downstream stations are occupied by pillars and blind holes respectively under flow boiling condition.

6 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction

(b) Chapter 2: Effect of pillars and blind holes

(c) Chapter 3: Effect of microstructured wall

(d) Chapter 4: Effect of variation of the flow passage

(e) Chapter 5: Effect of pillars and blind holes under flow boiling condition

(f) Chapter 6: Conclusion and Future Scope

7 List of Publications

The followings are the publications based on the thesis

Refereed Journals

- Rajalingam A and Shubhankar Chakraborty, Effect of micro-structures in a microchannel heat sink–A comprehensive study, *International Journal of Heat and Mass Transfer*, 154, 119617, (2020).
- Rajalingam A and Shubhankar Chakraborty, Effect of shape and arrangement of micro-structures in a microchannel heat sink on the thermo-hydraulic performance, *Applied Thermal Engineering*, 190, 116755, (2021).
- Rajalingam A and Shubhankar Chakraborty, Estimation of the thermohydraulic performance of a microchannel heat sink with gradual and sudden variation of the flow passage, *International Journal of Heat and Mass Transfer*, 190, 122776, (2022).
- Rajalingam A and Shubhankar Chakraborty, Microchannel heat sink with microstructured wall—A critical study on fluid flow and heat transfer characteristics, *Thermal Science and Engineering Progress*, 38, 101613, (2023).

- Rajalingam A, and Shubhankar Chakraborty, Fluid flow and heat transfer characteristics of a microstructured microchannel heat sink under flow boiling condition, *International Journal of Heat and Mass Transfer* (Submitted).

Conference

- Rajalingam A and Shubhankar Chakraborty, Effect of the transverse channel on the performance of microchannel heat sink, *26th National and 4th International ISHMT-ASTEF Heat and Mass Transfer Conference*, Accepted, (2023).

References

1. **Ali, A. Y.**, **E. M. Abo-Zahhad**, **H. I. Elqady**, **M. Rabie**, **M. Elkady**, **S. Ookawara**, **A. El-Shazly**, and **A. Radwan** (2021). Thermal analysis of high concentrator photovoltaic module using convergent-divergent microchannel heat sink design. *Applied Thermal Engineering*, **183**, 116201.

2. **Chai, L.**, **L. Wang**, and **X. Bai** (2019). Thermohydraulic performance of microchannel heat sinks with triangular ribs on sidewalls–part 2: Average fluid flow and heat transfer characteristics. *International Journal of Heat and Mass Transfer*, **128**, 634–648.

3. **Deng, D.**, **L. Chen**, **X. Chen**, and **G. Pi** (2019). Heat transfer and pressure drop of a periodic expanded-constrained microchannels heat sink. *International Journal of Heat and Mass Transfer*, **140**, 678–690.

4. **Ghaedamini, H.**, **P. Lee**, and **C. Teo** (2013). Developing forced convection in converging–diverging microchannels. *International Journal of Heat and Mass Transfer*, **65**, 491–499.

5. **Hajji, H.**, **L. Kolsi**, **K. Ghachem**, **C. Maatki**, **A. K. Hussein**, and **M. N. Borjini** (2021). Numerical study of heat transfer and flow structure over a microscale backstep. *Alexandria Engineering Journal*, **60**(3), 2759–2768.

6. **Jia, Y.**, **G. Xia**, **Y. Li**, **D. Ma**, and **B. Cai** (2018). Heat transfer and fluid flow characteristics of combined microchannel with cone-shaped micro pin fins. *International Communications in Heat and Mass Transfer*, **92**, 78–89.

7. **Jung, K. M.**, **A. Krishnan R**, **U. Kumar G**, and **H. J. Lee** (2021). Experimental study on two-phase pressure drop and flow boiling heat transfer in a micro pin fin channel heat sink under constant heat flux. *Experimental Heat Transfer*, **34**(2), 162–185.

8. **Li, Y.**, **G. Xia**, **D. Ma**, **Y. Jia**, and **J. Wang** (2016). Characteristics of laminar flow and heat transfer in microchannel heat sink with triangular cavities and rectangular ribs. *International Journal of Heat and Mass Transfer*, **98**, 17–28.

9. **Li, Y.**, **G. Xia**, **D. Ma**, **J. Yang**, and **W. Li** (2020). Experimental investigation of flow boiling characteristics in microchannel with triangular cavities and rectangular fins. *International Journal of Heat and Mass Transfer*, **148**, 119036.

10. **Qidwai, M. O.** and **M. M. Hasan** (2019). Effect of variation of cylindrical pin fins height on the overall performance of microchannel heat sink. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 0954408918821777.

11. **Yadav, V.**, **K. Baghel**, **R. Kumar**, and **S. Kadam** (2016). Numerical investigation of heat transfer in extended surface microchannels. *International Journal of Heat and Mass Transfer*, **93**, 612–622.