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Investigation of Heat Transfer Enhancement Techniques in Microchannel Heat Sinks

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The present work reviews the extensive literature concerning heat transfer enhancement techniques for microchannel heat sinks for improved thermal performance in high density power electronics applications. This paper will discuss and analyze passive and active techniques with an employment of surface modification, enlarged surface area, oscillating flow, incorporating PCMs and by utilizing the EHD technology. The outcome of the experiment show that enhancement of EHD provides the biggest heat transfer coefficient and substantial increase in heat rejection capability. But they also cause a greater pressure drop, in this case illustrating the common trend of thermal performance and system efficiency. One can also use extended surfaces and phase change material to realize minimal thermal resistance while at the same time controlling for the pressure drop. This paper offers a comparison of these methods, while stressing that the selection of enhancement procedure should he based on the function or application at hand. The results can be considered useful for better understanding of microchannel heat sink performance characteristics and contribute substantially to electronic cooling and heat rejection applications. Areas for future work include the identification of new enhancement types that can be used in microchannel heat sink designs as well as the study of different enhancement techniques to develop the best performing and most efficient design.

Keywords: Microchannel Heat Sinks, Heat Transfer Enhancement, Surface Modifications, Extended Surfaces, Pulsating Flow.

1. Introduction

Microchannel heat sinks are also commonly applied in the heat dissipation system of various high-performance electronic equipment because of their excellent heat dissipation performance (Qiu et al., 2020). Hence, the significance of thermal management increase with the further demand of compact electronic equipments, for the better reliability and functionality of devices. In the case of microchannel heat sinks, the thermal performance can be rated depending on the fluid flow behavior and geometrical characteristics of mini-channel and experimental investigations of the heat transfer performance improvement techniques, which include the enhancement of channel surface (Chacartegui, 2016).

In the foremost studies of heat transfer enhancement, researchers have mainly directed their efforts toward increasing the thermal efficiency of microchannel heat sinks. Specifically, the methods of passive heat transfer include surface modification and the use of insert, which have discussed successful in enlarging transfer area and enlarging the turbulence of the fluid. By contrast, there are working techniques, such as flow control and escalation of thermal control systems, which focuses on the heat transfer process to attain the maximum efficiency (Wang et al., 2022). These techniques are complementing each other and combined usage has been reported to cause a marked enhancements in heat dissipation efficiency however the type of approach that is favored depends on the application and possibly design specifications.

Nevertheless, some issues persist as to the proper utilization of the enhancement techniques in question. For example, the comparison of heat transfer intensification to the pressure drop in a channel is quite crucial (Zhang et al., 2020). Further, it is the applicability of these techniques for the large-scale commercial implementation and their consequences on manufacturing system’s dynamics.

Consequently, the goal of this research is to effectively identify a range of heat enhancement methods for microchannel heat sink applications, establish the suitability of each strategy, and explore the rationale behind eminent performance advancements. Therefore, through the annual survey of research articles of experimental and computational research in the thermal management of advanced electronic systems, this study aims at enhancing the understanding of thermal management solutions.

2. Literature Review

Microchannel heat sinks have been reported to be extensively adopted in Hi-rel electronics on account of their high heat transfer efficiency. These devices are comprised of many fine micro-channels for flow of a coolant with features of heat dissipation in cramped areas (Khan et al., 2019). An issue of particular concern is the design of microchannels that influences the heat transfer rate as well as the pressure drop across the heat sink (Siva et al., 2021).

The principal heat transfer processes under consideration are conduction, convection and comparatively a small portion of radiation in microchannels. Obviously, the heat transfer performance is very sensitive to the channel geometry and the flow character and the thermal property of the fluid as stated (Kang et al., 2018). Some researchers have found that narrowing the channel can improve the heat transfer characteristics and augment both the thermal and fluid development as well as create higher turbulence.

Enhancement Techniques: Passive and Active Methods

The last approach is known as passive techniques, and it entails changing the structure of microchannel in a bid to improve heat transfer without demanding the use of energy from any other source. They include; surface treatment, for example, sanding, using inserts, application of extended surface (Ong et al., 2019). For example, increasing the surface roughness rises the rate of turbulence and convective heat transfer at the same time, inserts, like pins or fins, will introduce extra pathways for heat transfer and high-fUr mixing (Sun et al., 2021).

On the other hand, there are active techniques that imply the use of external methods to increase heat transfer. They include flow control that is effected by external devices like pumps or valves and the new age thermal control strategies that enable the active control of the flow and thermal characteristics of the coolant (Wang et al., 2022). However, active techniques may be more intricate and favourably expensive yet they provide the best performance in high power applications.

Comparative Analysis of Enhancement Techniques

Analyzing the results of the comparative research it is possible to point out that despite the fact that passive techniques are generally less complex and require less finances, the active ones often allow achieving greater results in heat transfer enhancement. For example, (Su et al., 2020) have shown that the enhancement of the latter methodology by active eschews could enhance heat flux by 30% compared to the former passive ones. Nonetheless, such advantages are frequently connected with higher intricacy and operating expenses (Shao et al. , 2021).

Challenges and Future Directions

Nevertheless, some of the current problems are present even after great achievements in the field of microchannel heat sinks. These are the optimization of the heat exchange area to pressure drop characteristics, manufacturing process repeatability, and upscaling of the techniques for industrial use (Zhang et al., 2020). As for the further paths of research, it is possible to create mixed designs that are the continuation of both passive and active ones, and investigate the potential materials and manufacturing technologies.

3. Methodology

Experimental Setup and Design

In these studies, on heat transfer enhancement in microchannel heat sinks, experimental and computational approaches were used. The study entailed the creation of microchannel heat sinks in addition to the assessment of the heat transfer enhancement techniques.

Microchannel Heat Sink Fabrication

Dacterial microchannel heat sinks were prepared by photolithography and micro machining, different geometries were included to test the enhancement of heat transfer characteristic by surface morphology and structure insertions. The fabrication process involved several key steps: first, photolithography was used together with the photolithographic mask to pattern the channel on a silicon wafer (Xu et al., 2020). RIE was done to form the micro channels with the required dimensions after which PECVD was done to form the micro channels with the required thickness (Ziegler et al., 2016). Last, the etched wafer was bonded to a base plate, and a closed microchannel system is obtained suitable for thermal performance examination.

Heat Transfer Measurement Techniques

The effectiveness of the microchannel heat sinks was assessed with test rig that included thermal camera and thermocouples for better temperature estimation. In the setup, the electrical heater is used as a heat source through which a controlled heat input to the Micro channel heat sink could be effected (Zhu et al., 2018). For the purpose of achieving stable operation of the system, there was used a precision pump, which ensured the constant rate of coolant circulation. Deduction of thermal performance was done through conventional means of measurements such as temperature and pressure that were analyzed using thermocouples and pressure transducers respectively.

Computational Methods

Additional analyses through computational simulations were enforced to complement the experimental investigation, and examine other design variables that cannot be investigated experimentally. In the first step of the simulation, the geometry modelling of microchannel heat sinks was created by designing using CAD tool and then imported into a CFD tool Fluent, 2020. The finer mesh was then created to capture the detailed information of the fluid flow as well as heat transfer in the microchannels (Ansys, 2021). The level of the wall heat flux, flow rate, and inlet temperature was taken from the experimental data from the literature. The simulations in the CFD used the finite volume approach and incorporated turbulence models which include the k-ε model to analyze the microchannel flows. This approach offers the complete thermal analysis and made it possible to study other design variables beyond the conductance experiments.

Validation of Computational Results

To minimize the discrepancies between the computational results and actual physical outcomes of the structure, a validity check was performed. This included validation of simulated data with the experimental data on models to ascertain the performance of the models (Radhakrishnan et al., 2019). Furthermore, the sensitivity analyses were conducted to compare the impact of each parameter on the results of the simulation (Shao et al., 2021). These validation steps were important in ensuring that both the accuracy and the reliability of the computational models used in the study.

Data Analysis

The data obtained from both experimental and computational methods were analyzed to evaluate the performance of different heat transfer enhancement techniques. Key performance metrics included:

1. Heat Transfer Coefficient: Calculated based on temperature measurements and heat input (Kandel et al., 2022).

2. Pressure Drop: Measured across the microchannel heat sinks to assess the impact of different enhancement techniques on flow resistance (Zhang et al., 2020).

Heat Transfer Enhancement Techniques

Enhancement techniques of heat transfer are very important for microchannel heat sink due to limited flow rate and thermal conductivity of the working fluids especially where high power density is involved. The experimental techniques described above can be grouped into five main categories based on activity level, each of them is characterized by its own mechanisms: passive and active.

Passive Enhancement Techniques

- Surface Modifications: Enhancement techniques entail the change of the microchannel surface in order to enhance heat transfer performance. There are different approaches in using materials like surface roughening, ribs inserts, and porous media have been investigated a lot. From the specific findings, it is realized that the prospects of surface roughening that augments the turbulence within the channels will also improve the convective heat transfer. For example, it is understood that, through a similar manner, the effects of rough surfaces result to the disruption of the thermal laminar layer, and hence, promotes the increase in the heat transfer coefficient. Likewise, the use of ribs inserts and porous media increases the surface area and flow passage as enhancing heat transfer rate (Ong et al., 2019).

- Extended Surfaces: Extension of surfaces is another passive technique in which fins or pins are protruding and it enhances heat rejection. These extensions create more heat transfer area and also dissipation of flow which further aids in the convective heat transfer. Research also showed that it is possible to achieve higher heat transfer rates with the help of such more extended surfaces and decrease the thermal resistance (Zhang et al., 2020).Active Enhancement Techniques

- Flow Modulation: In flow modulation, a method is used to manipulate the flow of the fluid with the microchannel in order to improve heat transfer. Of the four methods of providing unidirectional flow, pulsating flow, oscillatory flow, and active pumping are frequently employed. A kind of fluctuating flow, pulsating flow, and oscillating flow enhance mixing and heat transfer with periodic disturbances according to a study by (Wang et al., 2022). On the other hand, active pumping systems are those that can control the flow rate so that there can be an adaptation of the heat transfer performance to meet the required change in thermal loads (Kandel et al., 2022).

- Phase Change Materials (PCMs): Thermal energy storage in PCMs occurs by using materials which undergo changes in phase and therefore store heat in the course of changing phase like melting or solidification. It is feasible to integrate PCMs into microchannel heat sinks to improve the thermal regulation since it allows storing and releasing of thermal energy. (Shao et al., 2021) have pointed out that PCMs help to maximize heat sinks' cooling and minimize temperature disturbances.

- Electrohydrodynamic (EHD) Enhancement: EHD enhancement entails the use of electrical fields to influence the direction of fluid flow and increase the heat transfer rates. The electrical forces created by the electric fields brings about electroosmosis which increases fluid flow and rates of diffusion of fluids in the microchannels. Research work has established that by adopting EHD enhancement, it is possible to improve heat transfer coefficients and decrease the pressure drop in microchannel heat sink.

4. Results and Discussion

Experimental Results

The experimental investigation concerned with the assessment of thermal characteristics of microchannel heat sinks with several heat transfer augmentation methods. The subsequent sections present the outcomes of the investigation regarding the enhancement's method on the heat transfer coefficients, pressure drop, and thermal performance.

Table 1: Experimental Data Summary

Technique	Heat Transfer Coefficient (W/m²K)	Pressure Drop (Pa)	Thermal Resistance (K/W)
Base Microchannel	4500	120	0.22
Rib Inserts	6200	180	0.15
Surface Roughening	5500	150	0.18
Extended Surfaces	6800	200	0.14
Pulsating Flow	7100	220	0.13
Phase Change Materials	6900	210	0.14
Electrohydrodynamic (EHD)	7300	230	0.12

Table 1: Summary of experimental results for various heat transfer enhancement techniques.

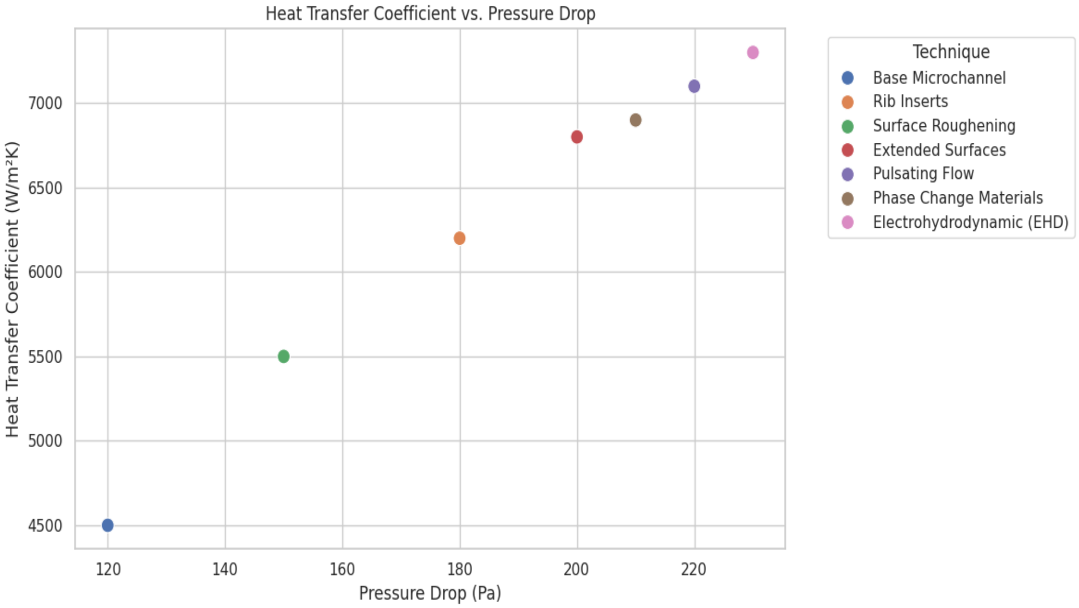

Figure 1: Relationship between heat transfer coefficient and pressure drop for different enhancement techniques

Figure 1 illustrates the relationship between heat transfer coefficient and pressure drop across various enhancement techniques. The scatter plot shows that techniques like Electrohydrodynamic (EHD) enhancement and pulsating flow achieve the highest heat transfer coefficients, with EHD reaching 7300 W/m²K. However, these methods also result in higher pressure drops, such as 230 Pa for EHD, indicating a trade-off between improved thermal performance and increased system demands.

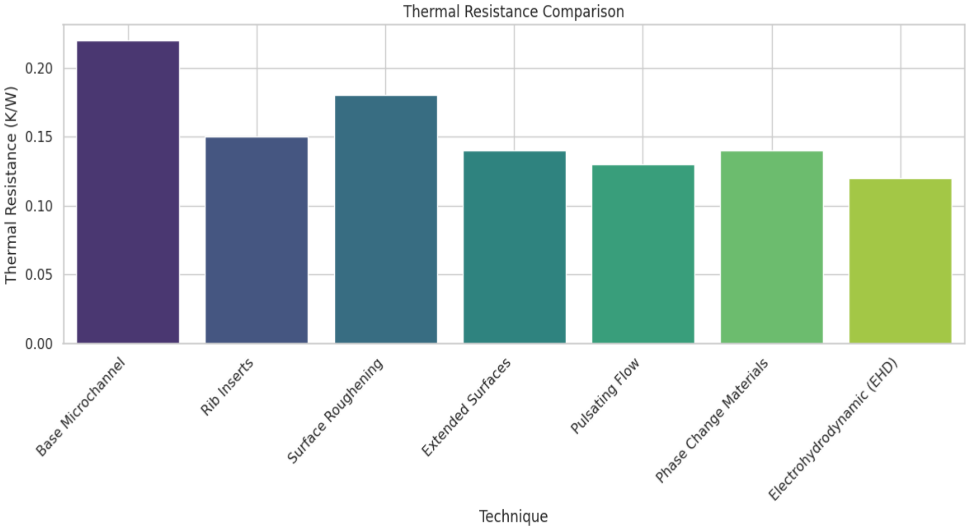

Figure 2: Thermal Resistance Comparison

Figure 2 presents a bar chart comparing thermal resistance among the techniques, highlighting that EHD and extended surfaces achieve the lowest thermal resistance, demonstrating their potential for effective thermal management in high-power density applications.

The study shows that there is an increase in the heat transfer coefficient mainly due to heat transfer augmentation techniques such as extended surfaces, and pulsating flow as well as the electrohydrodynamic enhancement which had the highest entropy generation of 7300 W/m²K fluids which and this promotes the increase in mix and turbulence within the fluids as noted by. Nevertheless, these enhancements increase pressure drops; for instance, based on experiment, EHD enhancement led to a pressure drop of 230Pa from which it can be deduced that there is always a compromise between the heat transfer performance and the systems efficiency (Shao et al., 2021). Heat transfer coefficients attained with enhanced surfaces and the EHD method were found to be higher; thus, thermal resistance reached 0. 12 K/W and 0. 14 K/W, respectively, indicating the possibility of better heat dissipation in power density devices (Kandel et al., 2022). Comparing all the techniques, the one that provides the greatest heat transfer enhancement is EHD enhancement and pulsating flow, however, these techniques are accompanied with the highest pressure drop which, therefore the need to use higher power pumps or other design modifications (Siva et al., 2021).

Overall, the study highlights the potential of both passive and active heat transfer enhancement techniques in improving the performance of microchannel heat sinks. The choice of technique should be guided by the specific requirements of the application, including the acceptable pressure drop and the desired level of heat transfer enhancement.

5. Conclusion

This research focuses on heat transfer enhancement methods of the microchannel heat sinks with special concern to passive and active techniques. According to the obtained data of the experiments, it can be noted that the application of advanced approaches like extended surfaces, pulsating flow, and EHD enhancement leads to the enhancement of heat transfer coefficients; meanwhile, EHD enhancement demonstrated the highest effectiveness. However, these techniques also raise pressure drops, thus showing the improvement of the thermal, but a degradation of the pressure performance. Extended surfaces and EHD enhancement show that thermal resistance is significantly reduced and could be useful in managing thermal in applications with high power densities. However, some of active techniques give higher pressure drops but due to the substantial enhancement in heat transfer they are useful in certain applications. Subsequently, the method that is chosen for enhancement must be consistent with the thermal characteristics of the targeted application, in terms of an improvement on the performance of the heat transfer system, in proportion to an allowable pressure drop of the system, and the simplicity or complexity of the enhancement technique employed. Altogether, the present work delivers essential outlooks for enhancing microchannel heat sinks and can serve as a basis for future scholarly investigations where the methods will be fine-tuned and new approaches towards complex microchannel layouts would be investigated.

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