Nat. Volatiles & Essent. Oils, 2021; 8(4): 2844-2857

A Review on the Development of Microscale Heat Transfer Enhancement Technique in Miniature Heat Sink

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Abstract

Different features have been added in course of system improvement which should be energy efficient, and these technologies made the system more efficient like it has become smaller in size, easy to transport, more convenient, and more effective. In their micro-scale inter-component fields, extremely miniaturized and embedded electronic systems frequently emit a significant amount of heat that, under some conditions, can contribute to the functional failure of the micro-device. This is the main reason for the improvement in the system such that the heat should be eliminated by providing some improved features in the system. Geometry improvement and working media alteration are used in the passive category, where heat transfer performance enhancement is mainly focused, and the characteristics which play the primary role in this phenomenon are discussed. Nusselt number and friction factor are an example of these characteristics which is responsible for fluid flow behavior and heat transferability of the system. There are several methods but in this article, the acoustic wave technique and pulsating inlet flow are considered for the active form of performance enhancement technique, which has recently been less studied. In general, the increase in heat transfer performance is improved by the addition of disrupted thermal boundary layers on fluid mixing.

Keywords: -Microchannel heat sink, Heat transfer, Nusselt number, Flow distribution, manifold, Cross-section

Introduction

Developments in micro-electro-mechanical systems have made it objectively practical to make the size smaller and have a very low volume of satellites through increasingly evolving space technologies. The main difficulty with this technological advancement is that extremely miniaturized and embedded electronic systems frequently generate excessive amounts of heat, for the required heat reduction, standard cooling systems are being pushed to their limits. In these applications, where the cooling medium is constrained to micrometer-scale channels, the system that deals with the fluid flow at micro sizes are frequently used. Flows are frequently found to be in a laminar flow regime, with a very sluggish and smooth flow field and a low Reynolds number, meaning that fluidic viscosity has a much bigger influence on flow than inertia, and hence cooling efficiency is severely constrained. As a result of this limitation, the installation of proper techniques for the transfer of heat in a system encounters at micro-scale flow is a must. Micro-scale heat transfer enhancement has recently become important in the fields of medical and biochemical engineering, apart from the system of mechanical engineering where the system is applicable. When the fluid has a very high viscosity and contained shear-sensitive materials, for example, the biomaterials of plants and animal cells are treated by blood oxygenators and bioreactors, it is critical to the flow character because it cannot sustain turbulence. So the use of laminar is the only way to achieve good mixing and efficient heat transfer characteristics [1].

The microchannel heat sink is mainly categorized into three types, the system which has a geometrical modification to improve its performance comes under the passive method while others are active methods in which additional effort is made by the compounding system to improve the performance of the system. In which they further categorized by the different approaches of these methods[2, 3].

Passive methods mainly focused on the geometrical modification and try to produce chaotic advection by modifying the flow path such that it produces obstruction in flow employing surface alteration, insert in the microchannel, surface extension, and providing additive to surface to increase performance and also changing fluid properties by Nanofluids. Theoretically, the process of transfer of heat is carried out by two potential modes of conductive and convective heat transfer with a flow having only one phase. The conductive part of heat transfer is mainly dependent on the area of cross-section of the part through which it is going to be conducted and the properties of fluid which further carry the heat from these surfaces should have better conductivity. But convective heat transfer process is regulated by the fluid flow and the flow behavior of the fluid. It can be better with turbulent advection and for these phenomena, the flow should be separated, bent, and extended to achieve the desired performance of heat transfer. Keeping these in mind often new micro heat exchangers are designed to provide heat transfer facilities employing either conductive method or convective method or combination of both the method whether of the passive or active form. In addition, to prevent hot spot generation due to uneven cooling behavior, it is critical to achieve thermal homogeneity and also get higher efficient heat transfer facilities.

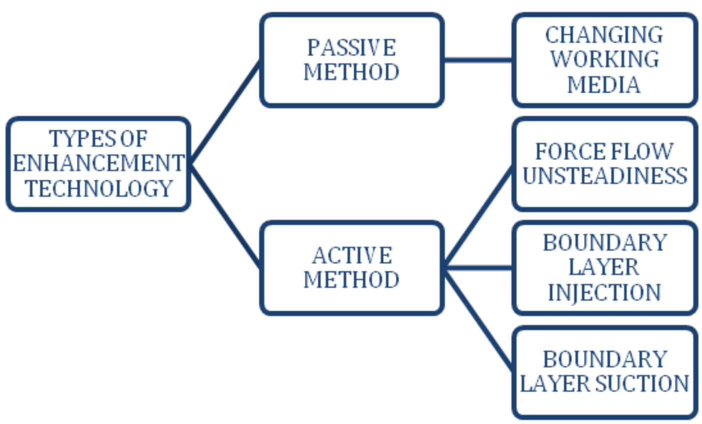

Figure 1 Types of Methods used for Heat Transfer Enhancement in a Microchannel.

Next, we comprehensively study the methods of heat transfer enhancement widely used in low Re number microfluidic systems, both passive and active methods. Second, that fluid that can be used as cooling fluid in miniature heat sinks the measurement of different non-Newtonian fluids characteristics is a very useful subject for future in the medical field. Some fluids, like pseudo-plastic fluid and viscoelastic fluid, are used as a passive cooling method.

Passive Method

The primary objective is to stimulate the micro-channels erratic advection, optimize the contact area between hot fluid flow field and cold fluid fields, improve coolant conductivity, and so on, to facilitate the transmission of heat through conduction as well as convection. The passive methods of heat transfer improvement strategies from each way are overviewed in this section as follows.

Geometrical Modification

Manipulation of flow by changing geometric configurations is very efficient in the creation of effective micro-scale heat transfer enhancement. The basic model that is simple rectangular, as well as trapezoidal and circular channels, are considered as a base model and complex geometrics are demonstrated concerning those. Previously, a series of equations that can be used to forecast the efficiency of heat transfer in a straight microchannel is evaluated[4].

The cooling systems in which direct MCHS were not able to satisfy the requirements in the face of the difficulty of the increasing strength and the enormous amount of heat which is produced by the system. Therefore, a significant number of innovative geometry of micro-channel have been developed with structural designs having some complexity.

The most recent geometric changes use two approaches: internal constructions are added, and inlet design, as well as outlet design and header designs, are improved. Injecting structures for internal changes, destabilizing/restarting the formation of the boundary layer, generating secondary flow, and generating unstable flow movements are all common strategies for scaling up the contacting surface area and therefore boosting the efficiency of micro-scale heat transfer.

To the full understanding of the source, thermal and hydraulic performance of heat exchangers, regardless of the achievable Thermal homogeneity or overall efficiency, is a function of the characteristics of flow motion. To ensure effective heat transfer, improved flow distribution is also of critical importance. Flow mal-distribution for heat transfer is unwanted and disadvantageous, leading to local overheating and system failure. The so-far studies of the insertion of internal structures primarily considered the action of the flow of fluids and related characteristics of transfer of heat in the micro-scale heat exchangers or the total heat transfer performance of complicated miniature heat sinks. Although, there is not much comprehensive research on the comprehension of the complicated flow characteristics that cause the mal-distribution of flow yet. In a broad sense, several variables will cause the flow maldistribution; geometry of the inlet as well as outlet header, differences in size among the channels, characteristics diameters such as the hydraulic diameter of channels, faulty multiple design modifications of the channel, and variation in the viscosity of the stream, among others [5, 6].

The re-entrant cavity is used to induce the flow vortices. Implementation of re-entrant cavity causes interruption in the thermal boundary layer along the fluid flow stream in the channel Xia et al. [7-10] In a sequence of micro-channels with different types of shape of re-entrant cavities as shown in Fig. 2, fluid flow behavior and heat transfer is numerically studied, including triangular shape cavity, balanced fan-shaped cavity and offset fan-shaped re-entrant cavities. Studies of the influence of geometrical modification parameters on the characteristics of flowing fluid and the performance of heat transfer helped them define the ideal re-entrant form for MCHSs. Concerning the phenomena which are the main cause for achieving better performance in thermal characteristics, it was found that the re-entrant cavity provides vortices development in the re-entrant cavity and also periodically redevelopment of the thermal boundary layer at the surface along the constant cross-section of the channel[7], the jet introduction is provided to disturb the boundary layer and same things we can achieve through throttling effect in both cases the surface heat transfer is improved[8].

The numerical and experimental analysis is done to find out the effect of periodic expansion–constriction cross-sections in microchannel heat sink as shown in **Figure 2**. the averaged Nusselt number can be improved to double as compared to the straight channel.

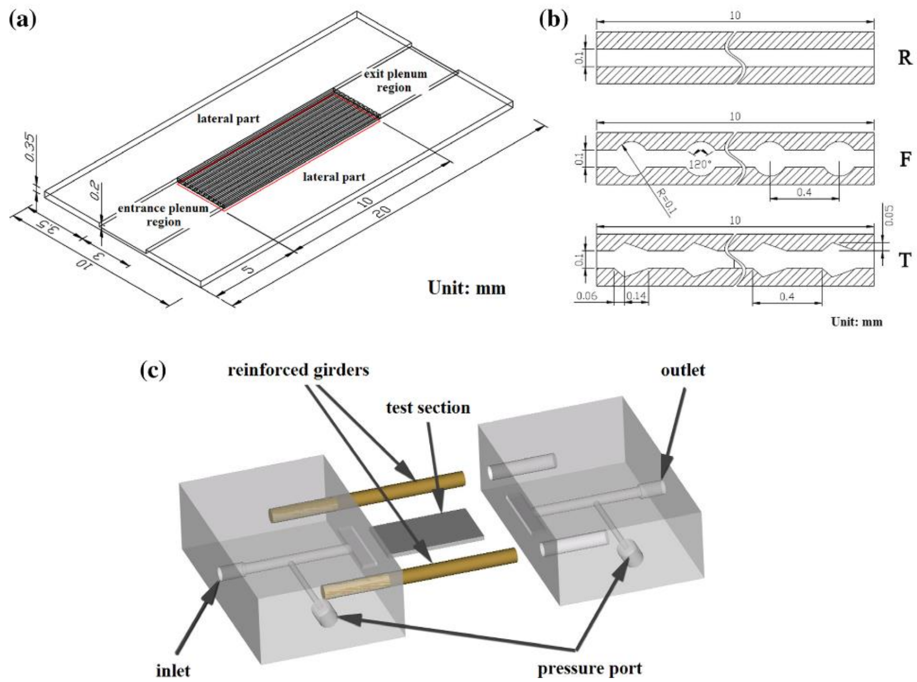

Figure 2 (a) Structure of heat sink (b) size of heat sink (c) packaging of the system.[10].

However, for re-entrant cavities, the compound rise may enhance the value of pressure drop additionally[10]. When compared to straight channels, introducing cavities in micro-channels could improve heat transfer while lowering pressure drop [11]. To suppress heat transfer, which is slipped over the cavity can affect the conduction and also reduce viscosity drastically [12]. The detailed experimental research into MCHSs with cavities having a shape of a fan that is fan shape cavities was performed based on the above evidence (FSCs). This structure was planned and configured for the performance of heat transfer in a different perspective, for example, the degree of deviation, the degree of coincidence, and the variation in the distribution of fan shape cavities. Therefore, it is evident from the above-mentioned studies that re-entrant cavities introducing technology are very common and can meet a very higher efficiency in terms of heat transfer improvement.

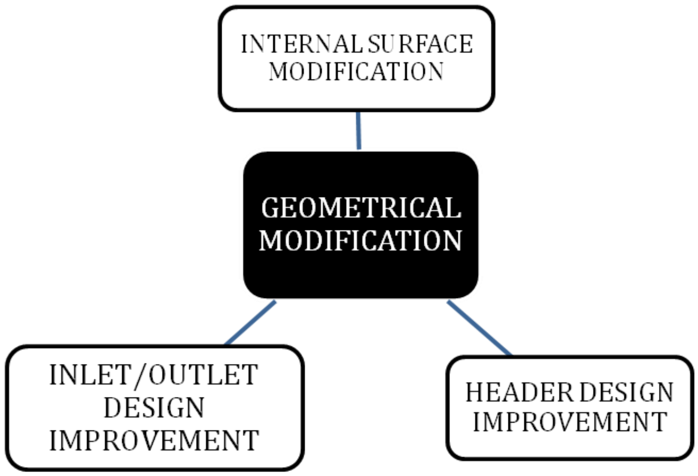

Figure 3 Types of Geometrical Modifications.

In addition to re-entrant cavities, another option is to implant fin cores to increase surface area such that effective heat transfer area becomes more, to achieve it some different types of fin introduced called louvered fin and strip fin which provide periodic changes in the direction of flow and the heat transfer is increases due to mixing of hot coolant with cold coolant, the boundary layer disruption also plays a key role in heat transfer enhancement [13].

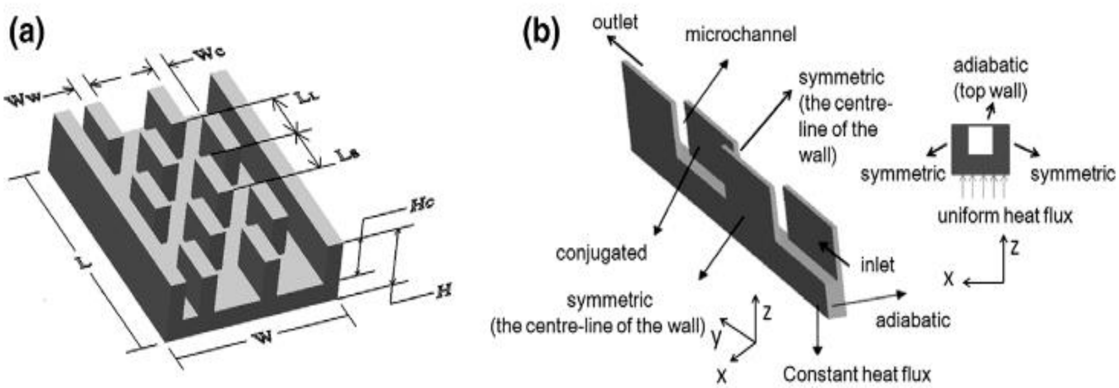

Figure 4 Schematic Diagram of (a) Offset Strip-fin (b) Computational Domain [13].

Pin-fins are also very important in terms of heat transfer performance enhancement[14] and different types of corrugation like wavy channels as shown in **Figure 5**, among others [15]. The study of forced airflow in a wavy channel having a low Reynolds number was carried out and it has been found that the disrupted regularly on the fin floor, creating recirculation areas where strong local heat transfer is accomplished. In addition, increasing fin density is not always prudent, as due to the narrower inter-fin flow area, recirculation is confined and further intensity of recirculation is decreased.

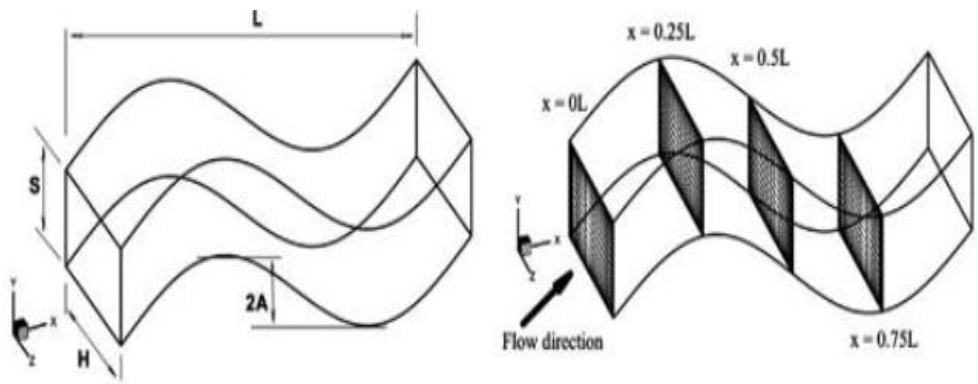

Figure 5Geometry of Three-Dimensional Sinusoidal wavy-Plate-fin. [15].

Besides fins, the offset ribs for MCHSs [16], the following two uses are often considered and frequently mounted on the sidewalls of two opposite channels: to create the channel having cross-sectional as converging-diverging type introduced [17]; and it is also provided to use as a baffle [18-21]. Some open-cell foam metal also introduces that employing strip metal foam attached to the copper plate, the best heat transfer effect can be reached at an air velocity of 1.33 m/s and an optimal proportion of 1:1.6 in terms of power consumption [22]. And some different work on baffles is also done [23]. Chai et al. [16] introduced offset ribs which are in varying shapes. They created five distinct types of these ribs as shown in **Figure 6** and their computational results revealed that the produced boundary layer disturbance, secondary flow generation, and offset ribs would all contribute to significant heat transfer augmentation at the expense of high-pressure drop. For the various offset ribs tested, the thermal efficiency assessment requirements (TP) are around 1.02–1.48.

In total, for such systems, heat transfer enhancement was obtained. However, to discover the best configuration, it's necessary to understand how the geometry of channels, the size of the system, and the density of the fluid affect heat transfer for various types of internal structures. To understand the above results, the flow behavior is, of course, essential. Moreover, since current experiments are typically based on a particular type of structure, it is often difficult to say which one is the best one. For industrial applications, a thorough investigation and distinction between the uses of various types of internal systems would be very necessary and beneficial. To obtain a uniform flow distribution, temperature uniformity is required, which can be achieved by achieving either a larger width ratio or a smaller area ratio. However, if we see in terms of flow mal-distribution, it is more in either at inlet position or outlet position and header. When fluid flows from the inlet to exit in a micro-channel heat sink, the manifold is the region responsible for fluid allocation and convergence. The flow distribution along the channels is maintained in the region of the manifold. As a result, the manifold's design has a significant impact on the distribution of flow in microchannel heat sinks [24]. Different kinds of manifold inlet and manifold outlet flow arrangements and design of header were examined by the various researchers (including manifold shape and size) [25, 26]. The lower value of the ratio of the manifold area, the greater the uniform distribution of flow, they stated.

Kim et al. Compared to rectangular and trapezoidal headers, it has been seen that triangular headers produce improved flow distribution [27]. To conduct more thorough research, the impact of multiple header construction and inlet, as well as outlet configurations of maldistribution of flow in a microchannel heat sink, was considered. Because their header shape analysis suggested that a triangular inflow header increases flow propagation, they statistically analyzed many configurations by varying the header form, header size, and inlet and outlet positions as shown in **Figure 7**. An outlet header with a trapezoidal form, on the other hand, provides a more homogeneous flow distribution. According to the findings, flow propagation for C-type flow setups provides satisfactory performance and worse for V-type flow setups in terms of inlet and outlet. The induced flow separation and also the recirculating bubble, both occurred in the header provided at the inlet and the main cause behind it is the flow mal-distribution in between the channel wall. This attributes to the heat transfer effect occurring in their microchannel heat sink [28].

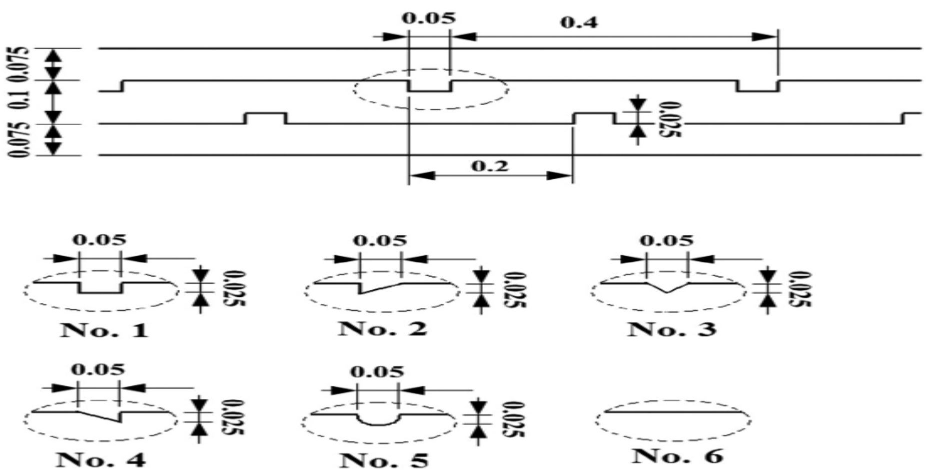

Figure 6 Offset ribs Structure with Dimension [16].

Various designs were taken for further investigation, with a focus on how different positions of the inlet as well as an outlet, different shapes of the header, and different shapes of the cross-section of channel influence flow behavior of fluid and efficiency of heat transfer within microchannel heat sinks. As they defined fluid flow through flow branches interactions and the friction generated by the wall of header in the system. In terms of their influence on changing shape, rectangular headers give better flow distribution uniformity than the trapezoidal header and triangular headers. In contrast to the header form effect, microchannel heat sinks which have offset cavities of fan-shaped and re-entrant cavities of triangular shape had a higher influence intensification of heat transfer than standard rectangular microchannels. The additional drag created by the effects such as jetting effect and throttling effect, triangular re-entrant cavities generated secondary flow, the extra disturbances around those re-entrant cavities and the extra jetting and throttling effect by those re-entrant cavities for this, the laminar flow boundary layer is disrupted and redeveloped by nature, thereby maximizing the performance of heat transfer in this micro-channel heat sinks. It is observed on the ground of the entire analysis that the triangular inlet header will achieve a uniform distribution of flow. It is also proven that they are a safer alternative. More specifically, in practical applications, the inlet position as well as outlet position, the configuration of header design, and microchannel form should be configured simultaneously to achieve greater efficiency of heat transfer [29]. Apart from the foregoing, the structure optimization of multiple micro-channel optimizations reduced flow mal-distribution by some researchers [30-32].

Microchannel with perforated baffle and also with the perforated wall which heat transfer ability can be considerably increased with a pressure drop penalty, and the thermal performance evaluation criterion value is always greater than unity. When perforated baffles and punching holes in the channel walls are added to a typical heat sink, the maximum temperature of the substrate can be decreased by 17.8 K [33].

Because of its short duration flow in the channel, the manifold structure enables to spread of the flow by rotating numbers of inlets and outlets significantly decreasing the pressure drop while at the same time due to thermal boundary layer disruption, the intensity of thermal efficiency increases significantly. The best heat transfer efficiency of the MMC heat sink was found to be achieved with a 3:1 ratio as the manifold input to outlet length [31].In the tailored heat sink of self-similarity, tapered intake plenums, and inlet manifolds were utilized. They used numerical simulation to compare the thermal efficiency of a Self Similarity Heat Sink to that of an improved one. They discovered that flow distribution and heat transfer efficiency are governed by the height of the overflow channel rather than its breadth and length. The convectional SSHS's rectangular intake plenum and inlet manifold channel have been adjusted for tapered ones, resulting in flow mal-distribution mitigation. Temperature control homogeneity is possible with the pre-set SSHS, which prevents the microchannel from interrupting the hot spot, the current microstructure, on the other hand, might increase flow resistance [34].

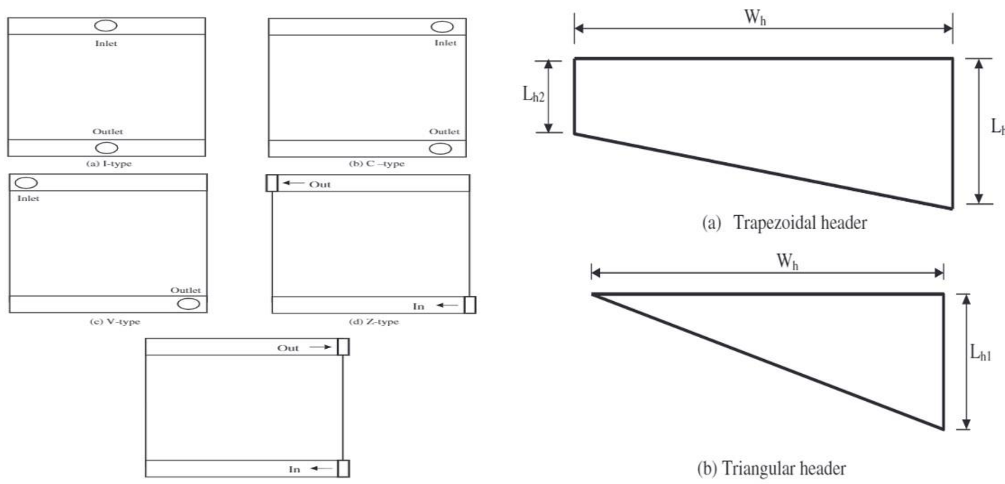

Figure 7Schematic diagram of micro-channel with (1) Different inlet-outlet configurations (2) different header shapes[28].

Working Medium Modification

In micro heat exchangers, changes in working media, as well as changing microstructures, help to improve the fluid flow behavior and performance of heat transfer such as efficiency. Different types of working fluids have been utilized in microchannels in the past, with liquid coolants being preferred for MCHSs over coolants which are in gaseous form due to their better thermal conductivity [35]. Generally, coolants of Newtonian liquid with low heat conductivity, such as water, tar, and organic compounds, make gaining higher performance impossible. To ensure adequate transfer of heat and solve the limits of standard coolants of liquid form, changes to the working medium have been made. On the one hand, newly discovered Nano-fluids with unparalleled agility of suspended nanoparticles have emerged as a possible substance for the next-generation heat transfer medium to address the poor thermal conductivity of traditional coolants due to their anomalous thermal conductivity (K_n) enhancement property. [36-38].

Nano-Fluid

Nanofluids are liquid dispersions with particle or liquid suspension of particle, diameters of less than 100 nanometres while thermal conductivities are hundreds of times higher than base liquids. They outperform other materials in terms of thermal conductivity, as well as long-term stability and rheological qualities. Several factors influence the thermal conductivity of Nanofluids (k_n), including nanoparticle diameter, substance, volume fraction, and fluid bulk temperature. In general, a coolant with Nanofluids enhances the heat transfer coefficient (h) by increasing the thermal conductivity. Nanoparticles in working media have recently piqued interest as a means of improving micro-scale heat transfer performance.

The thermophysical properties of Nano-fluids consisting of various nanoparticles and basic liquids, such as particles of copper oxide which suspended in water, are of particular interest to most researchers [39-44], and particles of aluminum oxide which is suspended in water[45-47]and on the efficiency of heat transfer in micro heat exchangers employing the aforesaid Nano-fluids as working fluids. According to research, $Al2O_3$–water Nanofluid has been included in a larger microchannel heat sink, and its hydrodynamic activity, as well as thermal activity, has been investigated numerically and experimentally. They also observed a link between the average Nusselt number and factors like Reynolds number, volume percent, and shape and size of nanoparticles in microchannel heat sink having a more complex structure [43]. Nguyen et al. considered $Al2O_3$-water as a fluid that is used for Cooling microprocessors or other electronic components with Nano-fluid in a closed device. Their findings also showed that adding nanoparticles to distilled water improves convective heat transfer and that particle sizes less than a micron can achieve better efficiency of convective heat transfer [46].

Non-Newtonian Fluid

The fundamental difference between Newtonian fluids and non-Newtonian fluids is the latter's nonlinear rheology, which affects the pattern of flow significantly. Shear or time-dependent viscosities are common in non-Newtonian fluids, resulting in a non-linear connection of shear stress with shear rate [48].

The heat transfer from non-Newtonian power-law fluids into fully formed laminar flows between fixed parallel plates was studied theoretically. For shear-thinning and thickening fluids, the effect of viscous dissipation and the proportion of heat flux at the boundary was taken into account. With a square cylinder submerged, this problem was numerically solved in static power-law fluids. In shear-thinning fluids, they were able to obtain HTE, which was also boosted by 100% under the correct conditions. The flow has a 30–40% detrimental influence on heat transmission in shear thickening circumstances, depending on the index n [49].

Four alternative flow control microstructures were used to describe the heat transport of CMC aqueous solutions. Their findings reveal that heat transmission is stronger in fluids with maximal velocity and low viscosity due to increased mixing between the main flow and near-wall flow[50].

The consequences of its effect of viscoelastic on micro-scale transfer of heat are examined for another non-Newtonian fluid with viscosity and elasticity. It has a significant and beneficial impact on the heat transfer process. This innovative technology has sparked a lot of interest in recent years since it eliminates the low Reynolds number restriction for excitation turbulence and allows for simpler and less expensive fabrication techniques than structural alteration. Nonlinear inertial and elastic effects occur in viscoelastic fluid flow, although they do not have to coexist [51].

Active Method

Parts of active methods require extra energy to act or create a motive force. There are various active approaches available, acoustics system provided to help disturb boundary layer [52], pulsating inlet help to create redevelopment of new boundary by eliminating old one [53, 54], electro-hydrodynamics (EHD) provide additional energy to disruption[55, 56], electro-kinetics (EK) provides support to enhance the performance[57, 58], and magneto-hydrodynamics (MHD) used to provide the same effect as above one [59, 60]. Heat transmission can be improved by forcing temporal pulsing cross-flows via a primary pipe. Pulsing flow, such as pulsating inlet flow and channel geometric wavy structure, can be time and space-dependent [61].

Conclusions

Microfluidic cooling has a lot of potentials, and there has been a lot of study and application advancement on both passive as well as active heat transfer improvement approaches over the last few decades. The following are some key concluding remarks based on the literature discussed here:

- The heat sink geometry is crucial for increasing the microchannel system's efficiency. Average temperature, pressure drop, heat transfer coefficient, Nusselt number, and flow and temperature uniformity are all important factors that can be altered by thermo-hydraulic efficiency.
- The header configuration and manifold inlet/outlet arrangement all play a role in maintaining better fluid flow behavior in the microchannel heat sinks. As a result, reducing flow mal-distribution by adjusting the inlet/outlet configuration and header architecture will increase delivery uniformity of microchannel heat sink.
- Fluids of Non-Newtonian behavior, particularly pseudo-plastic fluids and viscoelastic fluids, can improve the efficiency of heat transfer when Reynolds numbers are low. This area of heat transfer amplification technologies will be an attractive topic for biological and medical field applications in the coming times.

- The pulsing input flow and the acoustic wave are the active methods in this analysis. Due to flow instability, it is supplied to the heat transfer fluid for pulsing inflow to disturb or break the thermal boundary layer in the laminar flow. The mechanism that controls the thermal efficiency of the acoustic wave is currently unknown.

This study considers two aspects of passive methods: changing the working medium and changing the geometry. In some cases, the HTE process is caused by increasing contact surface area, halting boundary layer formation, or adjusting geometry to improve flow propagation. The HTE approach of working medium modification, on the other hand, principally leverages the working media's characteristics to increase heat conductivity or produce flow instability. The two active techniques explored in this study are pulsating inlet flow and acoustically induced vibrations. By breaching thermal boundary layers and altering the overall convective heat transfer rate, pulsating inlet flow can improve heat transfer efficiency.

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