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Recent Advancements in Thermal Performance Enhancement in Microchannel Heatsinks for Electronic Cooling Application

Naga Ramesh Korasikha, Thopudurthi Karthikeya Sharma, Gadale Amba Prasad Rao and Kotha Madhu Murthy

Abstract

Thermal management of electronic equipment is the primary concern in the electronic industry. Miniaturization and high power density of modern electronic components in the energy systems and electronic devices with high power density demanded compact heat exchangers with large heat dissipating capacity. Microchannel heat sinks (MCHS) are the most suitable heat exchanging devices for electronic cooling applications with high compactness. The heat transfer enhancement of the microchannel heat sinks (MCHS) is the most focused research area. Huge research has been done on the thermal and hydraulic performance enhancement of the microchannel heat sinks. This chapter's focus is on advanced heat transfer enhancement methods used in the recent studies for the MCHS. The present chapter gives information about the performance enhancement MCHS with geometry modifications, Jet impingement, Phase changing materials (PCM), Nanofluids as a working fluid, Flow boiling, slug flow, and magneto-hydrodynamics (MHD).

Keywords: Microchannel heat sink (MCHS), Heat transfer enhancement, Jet impingement, Phase changing materials (PCM), Flow boiling, Slug flow, Magnetohydrodynamics

1. Introduction

Thermal management of electronic components is the major concern to make the efficient high powered energy system [1–3]. The modern researchers' attention is on the development of efficient heat exchanging devices for thermal management of electronic components [4, 5]. Miniaturization has a noticeable footprint on heat exchanger technology and which makes the heat exchangers as compact and efficient. The life and overall efficiency of a thermal energy system are highly affected by its heat exchanger's efficiency. The microchannel heat sink is an inventive and highly compact heat dissipating device, so it is the most suitable for the application of thermal management of electronics. The performance and the life span of the electronic component with high power density is highly dependent on its heat dissipation capacity [6]. The performance of an electronic component is enhanced

S.G. Kandlikar and W.J. Grande [7]	S.S. Mehendale et al. [8]
Conventional channels: $D_h < 43 \text{ mm}$	Conventional channels: $D_h < 46 \text{ mm}$
Mini-channels: $0.2 \text{ mm} < D_h < 3 \text{ mm}$	Compact passages: $1 \text{ mm} < D_h < 6 \text{ mm}$
Micro-channels: $10 \text{ }\mu\text{m} < D_h < 200 \text{ }\mu\text{m}$	Meso-channels: $0.1 \text{ mm} < D_h < 1 \text{ mm}$
Transitional channels: $0.1 \text{ }\mu\text{m} < D_h < 10$	Micro-channels: $1 \text{ }\mu\text{m} < D_h < 100 \text{ }\mu\text{m}$

Table 1.
The classification of the mini and microchannels.

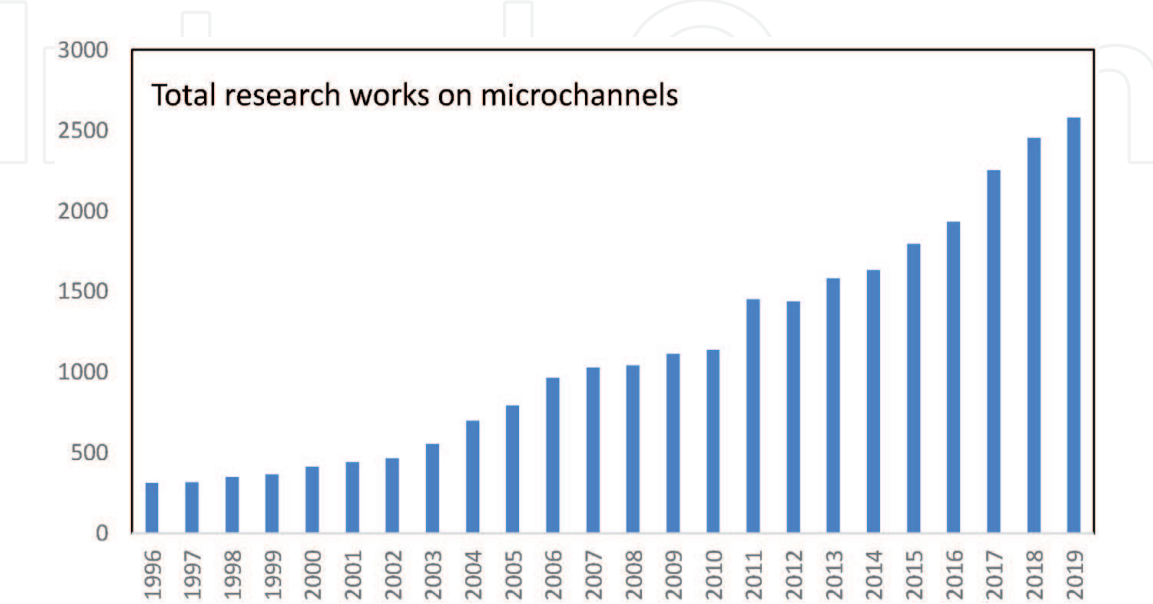


Figure 1.
The increment of studies performed on the micro-channels from the year 1996 to 2019 [15].

by providing an efficient heat absorbing device like MCHS. The MCHS is also used in many other applications like LED cooling, fuel cells, refrigeration, combustors, chemical industry and food industry, etc. Huge literature availability on MCHS indicates the capacity of this technology.

The categorization of the microscale channels is different from the conventional flow channels, and it is done by considering the channel’s hydraulic diameter. So many classifications are available from the literature. Many authors followed the classification given by S.G. Kandlikar and W.J. Grande [7] and S.S. Mehendale et al. [8], which is produced in **Table 1**.

The microchannel heat sink was first developed in 1981 for electronic cooling applications, which has rectangular cross-sectional channels made of silicon. In this study, the maximum thermal resistance of 0.09 0C/W was observed at the heat flux of 790 W/cm2 over the 1 cm2 area [9]. Since then, noticeable work has been done to improve the micro-channels’ fluid flow and heat transfer performance by improving the channel geometry, surface roughness of the channel, channel aspect ratio, working fluid and substrate materials, etc. The thermal resistance of 0.070 C/W was achieved for the MCHS developed for thermal management of the diode laser array manufactured by Indium phosphide (InP) [10]. The hydraulic diameter and aspect ratio of the channel was proved to be has a noticeable impact on the thermal and hydraulic behavior of the M [11].

Initially, few studies claimed that the conventional correlations and theories are not applicable for the micro and mini channels. Eventually, researchers cleared about these ambiguities and concluded that the inaccuracies in the microchannel dimensional measurements are the main reason for the deviation of the results produced from the conventional correlations. The uncertainties in experiments

were proved to be dominated by the uncertainties in the diameter measurement, which may cause the 20% deviation in the measurement of Poiseuille's number [12]. In this analysis, fRe (Poiseuille's number) data for microscale stroke flow showed negligible deviation from the macroscale stroke flow. 3% uncertainty in the channel width and channel height leads to the 21% uncertainty in calculating the friction factor [13]. The electric double-layer effect, entrance effect, and entrance effect are also possible causes for the deviation of pressure drop, apart from the measurements' errors. To find the possible inaccuracies and partial thermal in the MCHS, enhanced thermal characterization methods were developed [14]. **Figure 1** represents the increment of studies performed on the micro-channels from the year 1996 to 2019 [15].

2. Microchannel heatsink (MCHS)

The heat sink is a heat-absorbing device that takes heat from its surroundings by the various modes of heat transfer by using working fluids. Miniaturization makes the heat sinks as efficient and compact. MCHSs have fluid flow channels in the size of microns. MCHS application is found in the high-powered density energy system with less space availability. These applications include the computer components cooling (Storage devices, CPUs and GPUs, etc.) [16], thermal management of high power density electronic components (IGBTs) [17], cooling of fuel cells [18], diode laser arrays [19], and combustors [20], etc. Electronic cooling is the major application of the MCHS. **Figure 2** represents the schematic diagram of the transistor with a liquid-cooled heat sink.

Fabrication of MCHS is the biggest hurdle to perform the experimental investigations. Laser cutting [22], dry and wet etching [23–25], micro-cutting [26], and ultrasonic micro-machining [27] are very expensive fabrication methods for MCHS. Most of the researcher's attention is on developing a new low-cost manufacturing method with good surface characteristics. Kaikan Diao, Yuyuan Zhao [28] studied the performance of the sintered Copper microchannel manufactured by a low-cost fabrication method. This study proved that the pressure drop in the sintered copper microchannel was higher than the microchannel machined conventionally and noticeably lower than the porous Copper microchannel fabricated by the Lost carbonate sintering method (LCS). Ivel L. Collins et al. [29] performed the direct-metal-laser-sintering

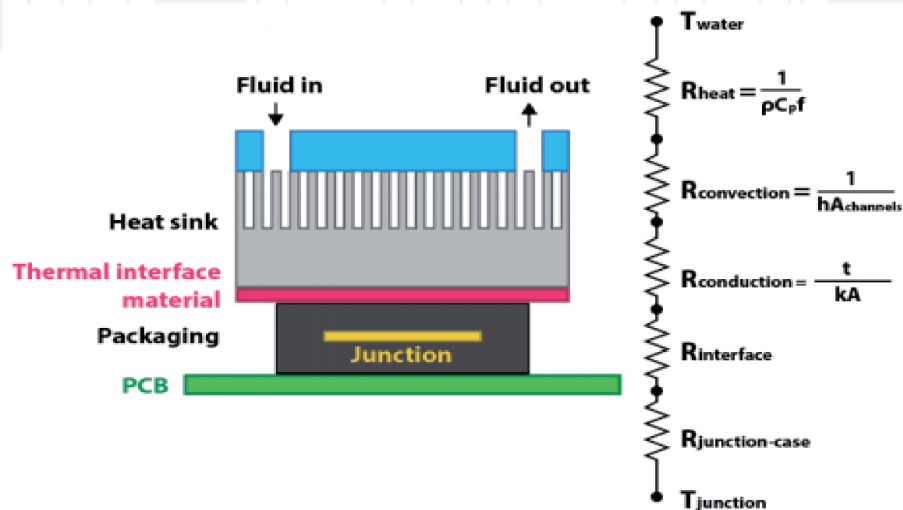


Figure 2.
Schematic diagram of the transistor with liquid-cooled heatsink [21].

method (DMLS) for manufacturing of two MCHS models, PMM (permeable membrane MCHS) and MMC (manifold MCHS) heat-sinks shown in **Figure 3**. The analysis method implemented for the study of MCHS is also plays a key role in the accuracy of the study. Initially, researchers and scientists depended on expensive experimental methods only for their research but the development of numerical methods has upturned the studies on microfluidics. Novel computational fluid dynamic (CFD) techniques have been developed for accurate analysis of the MCHS. 3-dimensional simulation models give an accurate result than 2-dimensional simulation models but computational time is less for a 2-dimensional model. Similar outcomes were found in the 2D and 3D simulation model studies conducted on the

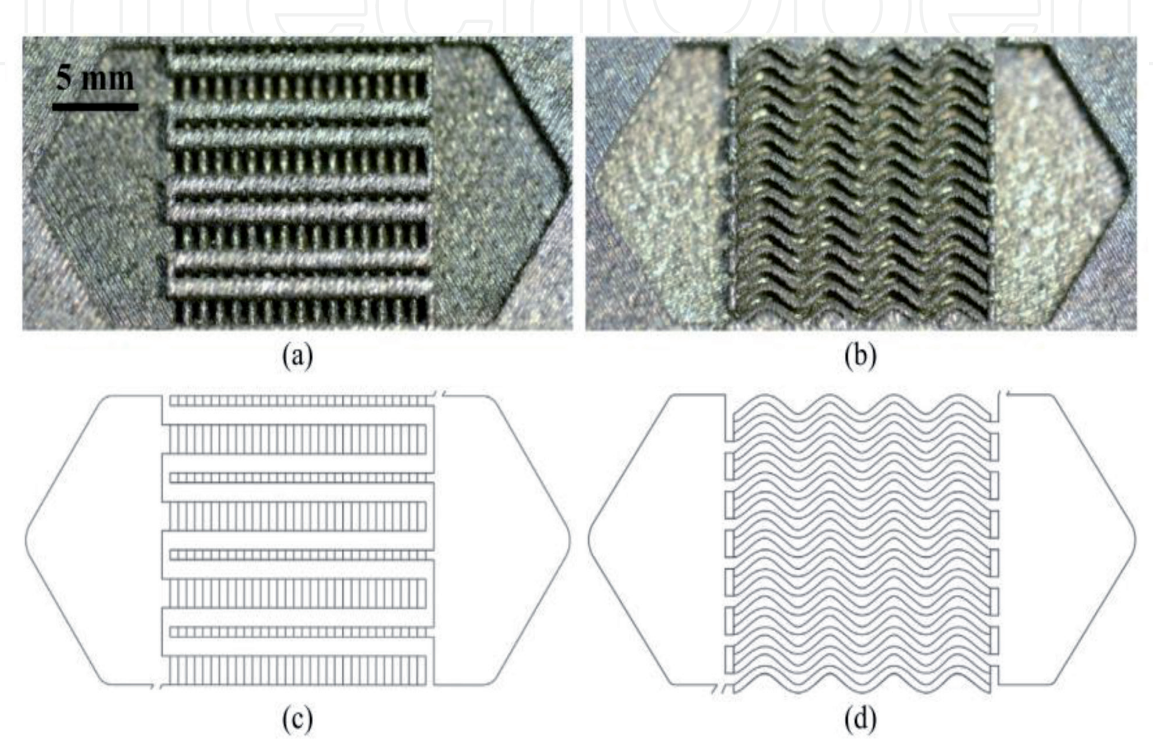


Figure 3. Images of the (a, c) manifold MCHS and (b, d) permeable membrane MCHS [29].

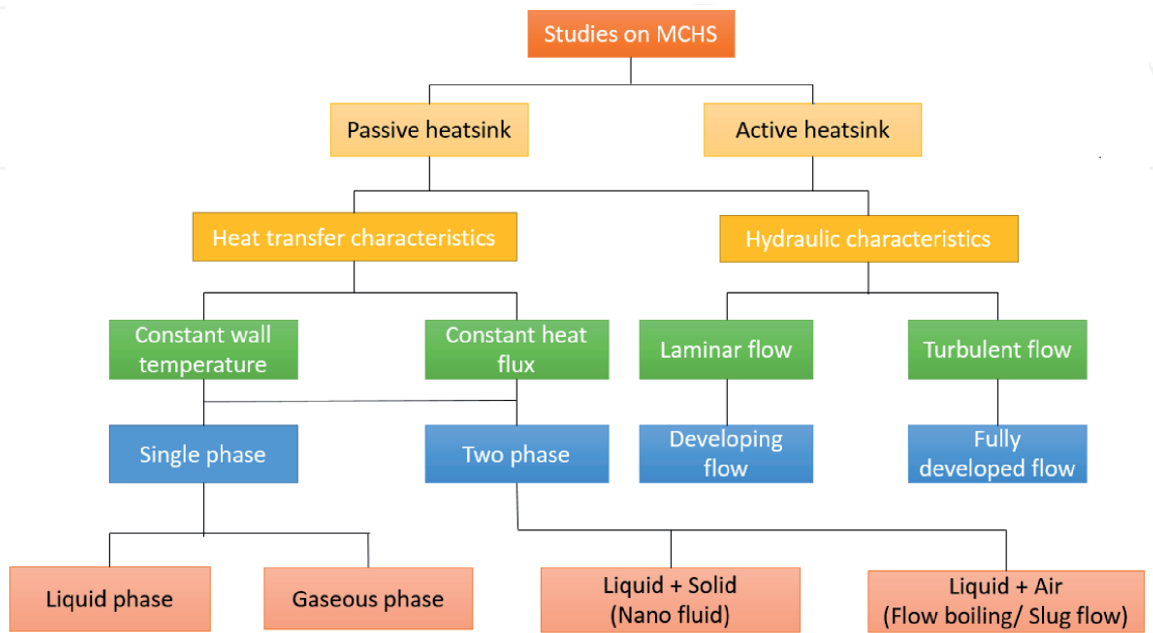


Figure 4. Schematic of various studies on micro-channel heatsinks (MCHS) [15].

microchannel fluid micro-mixing [30]. S. A. Si Salah et al. [31] implemented the control-volume FEM (CVFEM) to study microchannel flow, which has the advantages of both finite element method and the finite volume method. The slug flow in the microchannel of serpentine shape was studied using a Coupled-level-set and volume of fluid (CLSVOF) method, which accurately predicted heat transfer and fluid flow performance liquid-liquid 2-Phase flow [32]. J. Rostami and A. Abbassi [33] implemented the Eulerian-Lagrangian method to analyze the Al_2O_3 -water fluid flow in the wavy channeled heat sink. Shuzhe Li et al. [34] and Zhibin Wang et al. [35] were also used the coupled level set and volume of fluid method for their study on coalescence between the moving liquid and the droplets in the microchannel. A flexible coupled-level-set and volume of fluid (flexCLV) method [36], Lattice Boltzmann method (LBM) [37, 38]. The coupled LBM [39] was also implemented for the accurate prediction of complex problems. **Figure 4** shows the schematic of types of studies performed on the microchannel heat sinks.

3. Thermal performance-enhancing techniques

It is clear from the studies in the literature that MCHS has an eminent future in the field of thermal management of electronic equipment. The work performed on the micro-channel heat sink by Tuckerman and Pease [9] attracted the researchers towards the MCHS. Researchers and scientists have been working on MCHS to develop new ways to enhance heat transfer in micro-channels. The details of the few thermal performance-enhancing techniques developed for MCHS are produced in this section.

3.1 Geometric improvements

The microchannel geometry has a major impact on its heat transfer and fluid flow performance. The improvement of the microchannel geometry is a possible technique to decrease the pressure drop with a significant increase of the heat transfer. Various cross-sectional shapes of micro-channels used for the analysis are presented in **Figure 5**. Microchannel with a Trapezoidal-shaped cross-section has a good thermal performance than the rectangular channel [41]. The effect of the different parameters like aspect ratio (AR) [42], hydraulic diameter, channel spacing [31], channel width, channel height, etc., on the heat transfer behavior of microchannel, were also studied.

An experimental analysis performed on the rectangular microchannel with the working fluids FC770 and water proved that the critical Reynolds number (Re) increases to 2400 from 1700 with a reduction of aspect ratio (AR) to 0.25 From 1 [43]. The reduction of friction factor with increasing the AR was also noticed initially, and then it started increasing. The increase of both the Nusselt number (Nu) and the pressure loss with the channel height reduction was observed in the numerical study on MCHS with transfer channels [44]. The flow channel size shows a noticeable effect on the hydraulic performance as it was decreasing from the macro scale to the micro-scale. The effect on the hydraulic behavior of the microchannel was negligible as the space between the micro-channels decreases from 50 μm to 0.5 μm [31]. The Nu and Poiseuille number are found to be raised with rising the AR and side angle [45].

Some studies on MCHS have introduced the ribs, internal fins into the flow channels and changes the shape of the passage so that the area of heat transfer increased. A considerable decrease of pressure drop was noticed when the rectangular-shaped ribs and the sinusoidal cavities are provided to the MCHS [46]. In the various category of offset ribs on the channel sidewalls, the best performance was observed with the forward triangular ribs and the rectangular ribs showed the worst behavior at the Re

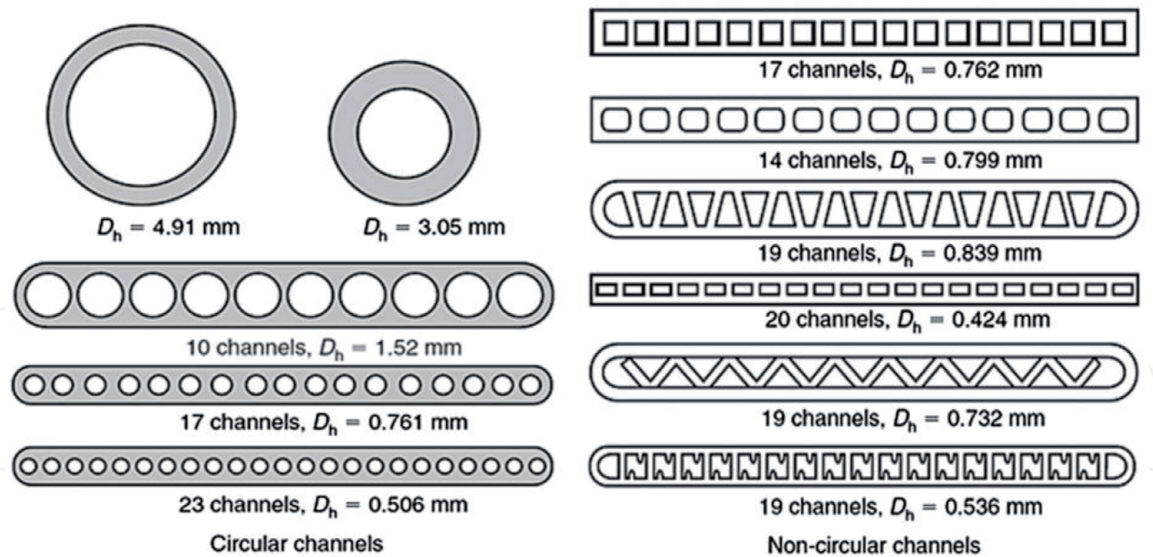


Figure 5.
Various cross-sections of micro/mini channels used for studies [40].

less than 350 [47]. The increase of heat transfer was also observed by providing the internal fins with the increase of pressure drop, as a cumulative effect, the microchannel performance was increased. The proximity from the wall of the large row of pin fins showed the greatest effect on the velocity field, distribution of flow, temperature distribution, and streamline structure. As the gap between the pin-fins increases, the heat transfer is noticed to increase first and then decrease. The fin structured microchannel with equal gap and diameter shows better thermal performance [48]. A schematic model of finned MCHS is produced in **Figure 6**. The effect of proximity from the sidewall on the thermal performance is represented in **Figure 7**.

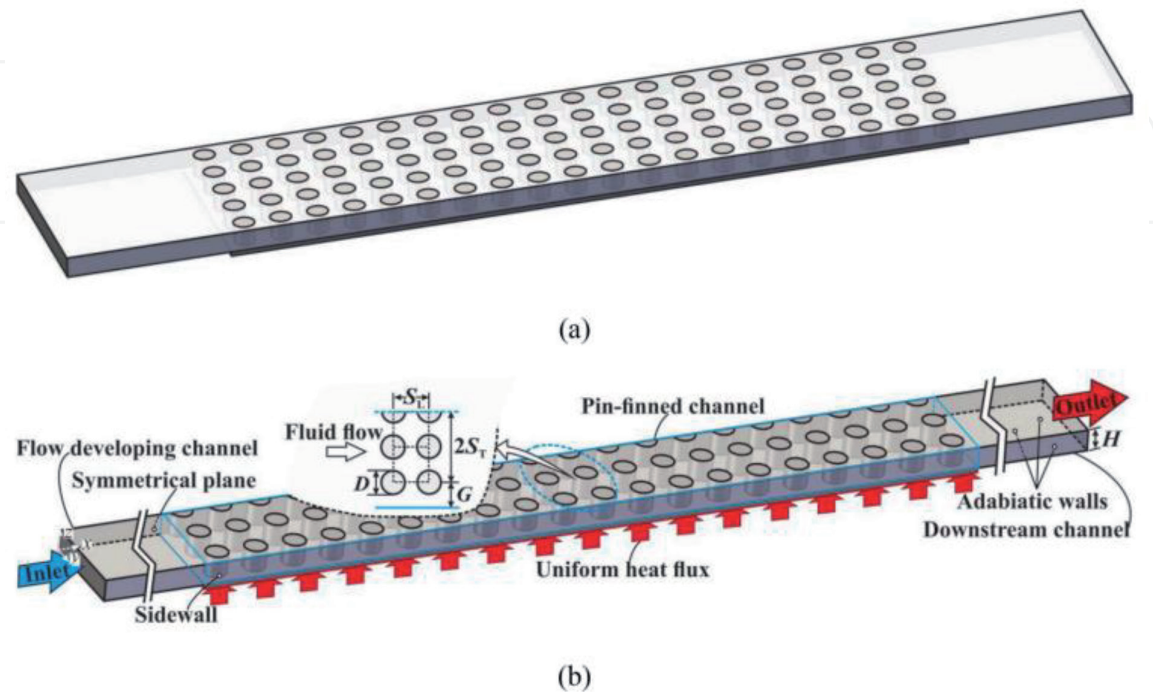


Figure 6.
Schematic model of finned MCHS, (a) physical model and (b) boundary conditions [48].

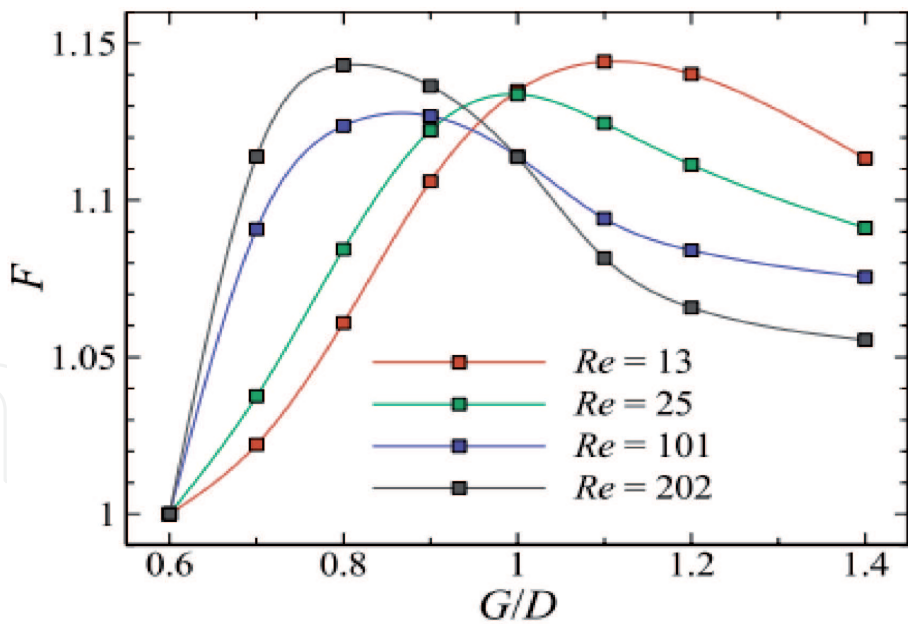


Figure 7.
The influence of proximity from the sidewall on the thermal performance of MCHS [48].

The large heat transfer (HT) enhancement was found in the periodically converging and the diverging and periodically expanded and constrained MCHS. 46.8–160.2% improvement in HT was noticed in the converging and the diverging MCHS (**Figure 8**) [49]. 50–117% improvement of heat transfer was found in the periodically expanded and constrained MCHS (**Figure 9**) in the range of Re from 150 to 820 [50].

An experimental study on periodic jetting and throttling MCHS (**Figure 10**) has concluded that the mean temperature and maximum temperature in the throttling



Figure 8.
Physical model of periodic converging–diverging microchannel [49].

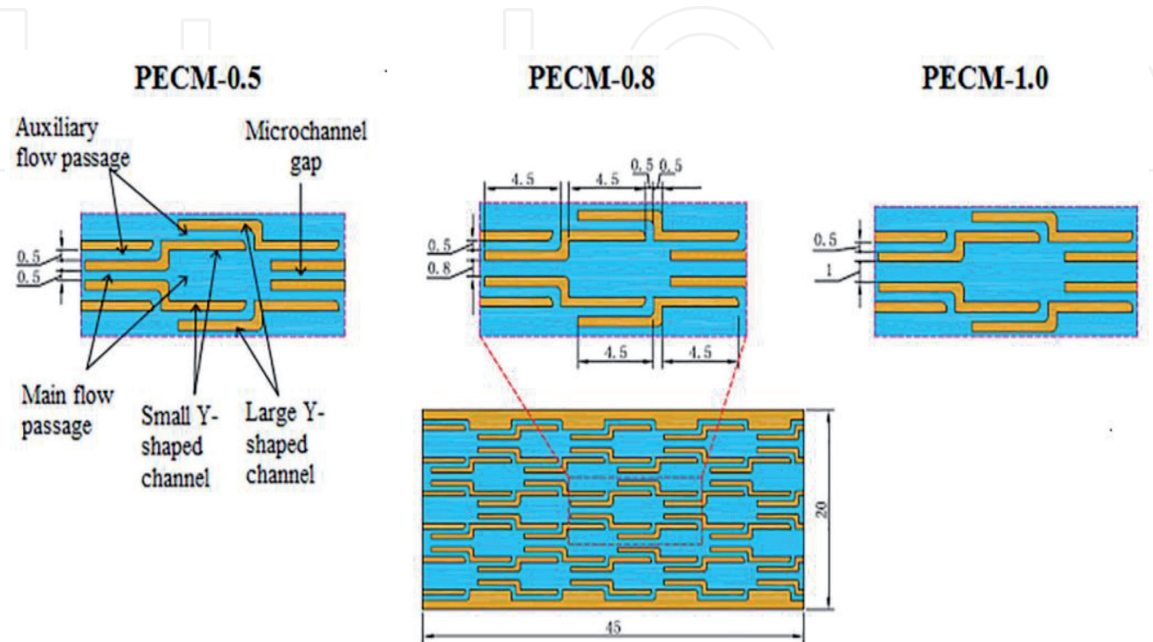


Figure 9.
Design of the periodic expanded and constrained MCHS [50].

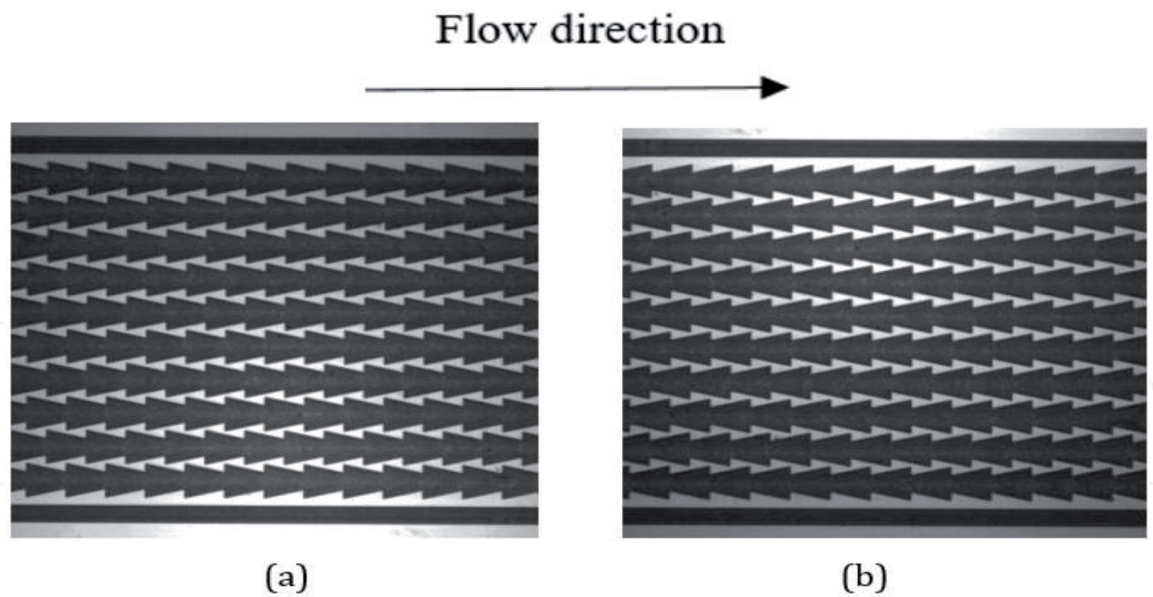


Figure 10.
Physical model of (a) jetting MCHS (b) throttling MCHS [51].

MCHS are less than the jetting MCHS with huge pressure loss [51]. The heat transfer rate in the trapezoid cross-sectional MCHS with grooved structure was noticed to be improved by 28% because of the breaking and regeneration of the thermal and hydrodynamic boundary layer [41].

Huan-ling Liu et al. [52] developed new annular MCHS designs, MRNH and MRSH presented in **Figure 11**, and concluded that the consistency of the substrate temperature of the interleaved structure was better than the sequential structure. The increase of the total thermal resistance was noticed with rising the slant angle in the MRSH design. The variation of the average Nu with the pumping power is represented in **Figure 12**.

Some of the researchers [53–55] investigated the effect of the channel surface-roughness on the thermal performance of MCHS. Their work disclosed that the HT in MCHS was augmented for rough-surfaced channels and its effect is very significant at high Re. Yan Ji et al. [56] analyzed the low Knudsen number (Kn) gas

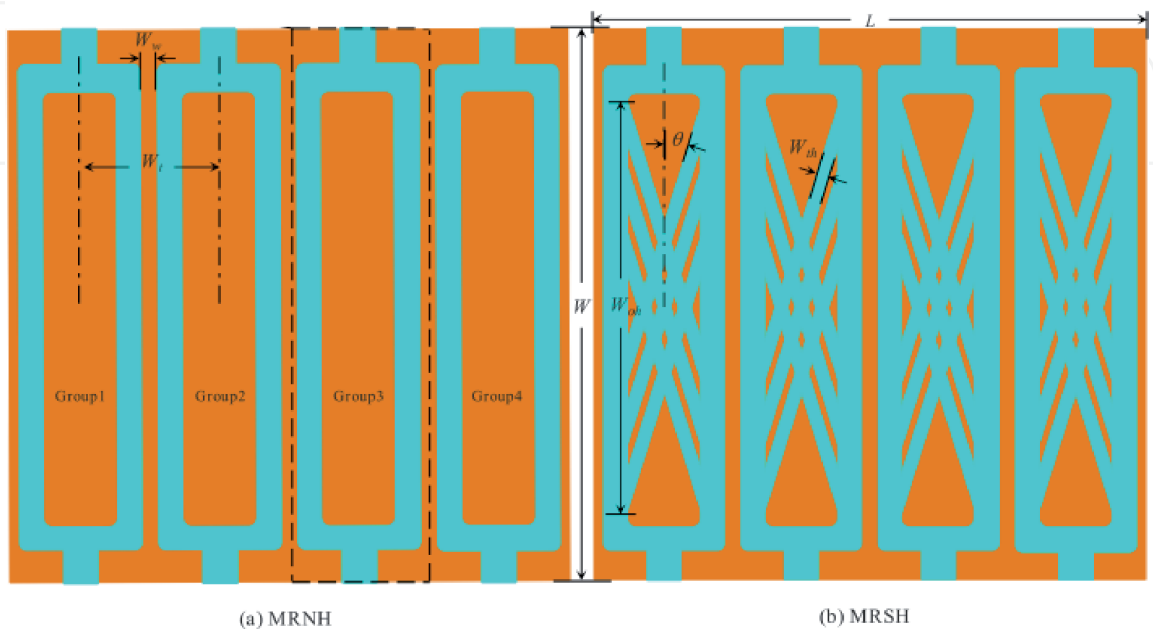


Figure 11.
Schematic design of MCHS, (a) MRNH (b) MRSH configuration [52].

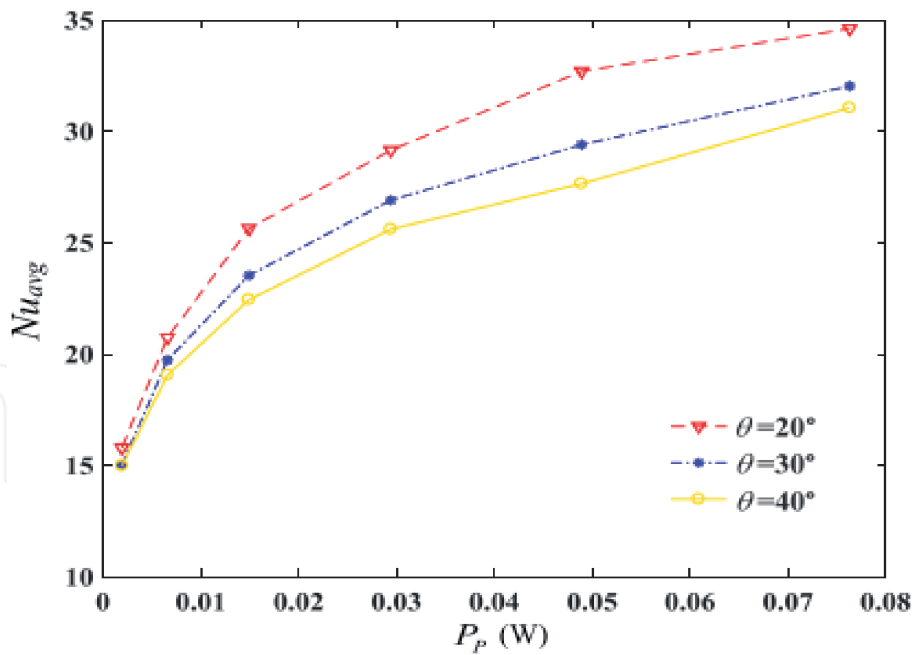


Figure 12.
The variation average nu with pumping power at three slant angles [52].

flow in rough channels and observed a decrease of local heat flux with increasing the relative roughness for rarefied and compressible flow. The variation Nu with the roughness is shown in **Figure 13**.

Secondary flow in MCHS is an effective method to reduce the pressure drop, which is a major limitation in the above-discussed models. One of the secondary flow MCHS models is shown in **Figure 14**. The maximum enhancement in heat transfer in secondary flow MCHS was obtained by optimizing the ratio of the parameters of secondary channel width to the main channel width (α), the ratio of secondary channel half-pitch to the main channel width (β), and tangent value of the angle of the secondary channel (γ) [57].

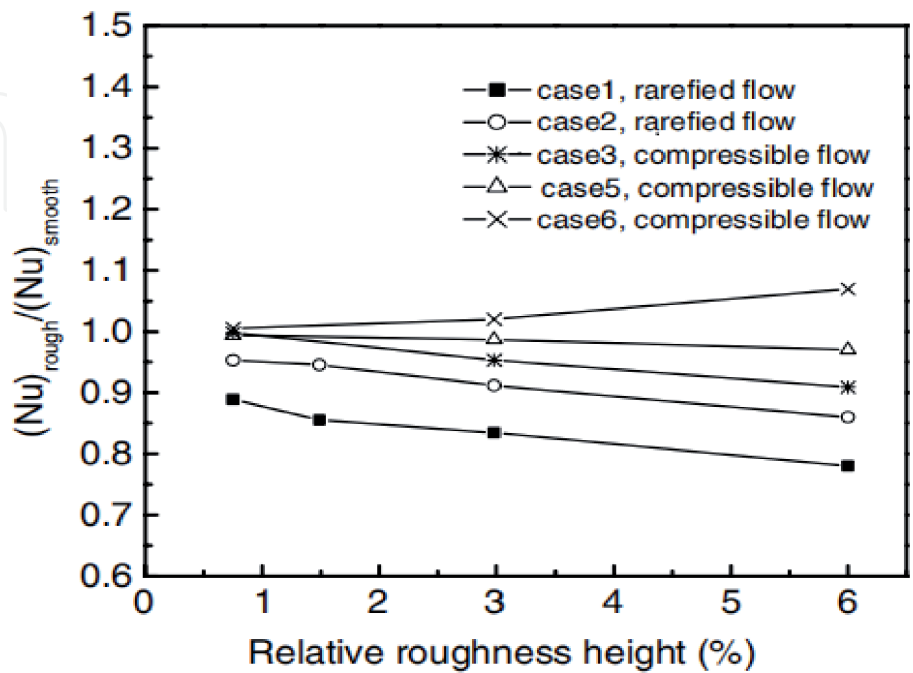


Figure 13.
Variation of nu with the relative roughness [56].

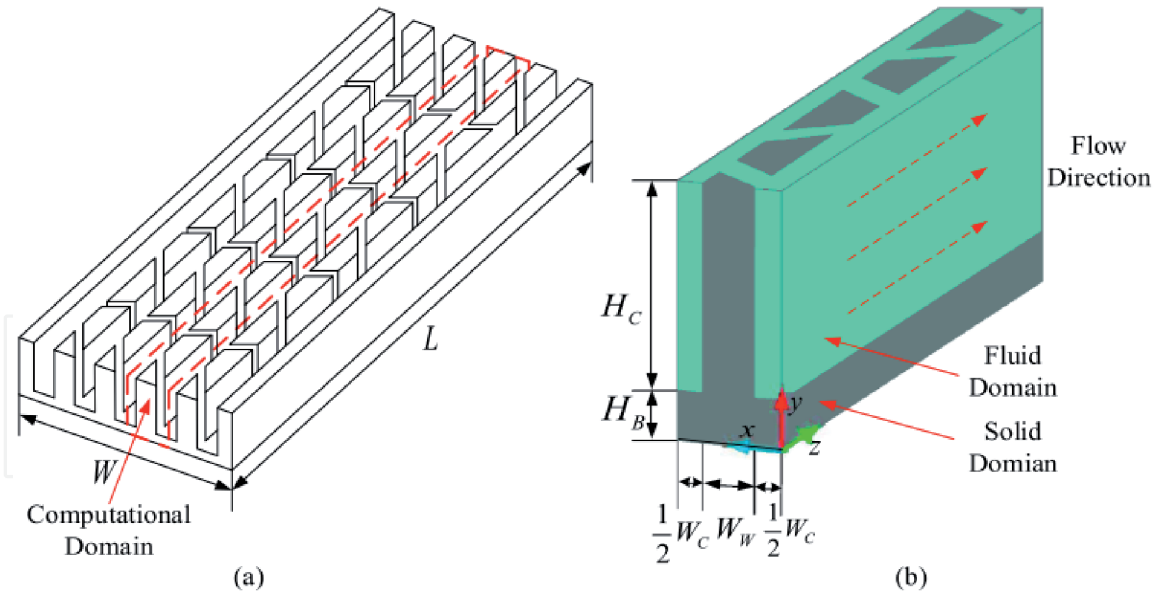


Figure 14. Design of (a) secondary flow MCHS (b) computational domain [57].

A novel MCHS model namely, permeable membrane MCHS (PMM) and manifold microchannel heatsink (MMC) manufactured by Direct metal laser sintering method using an aluminum alloy was studied experimentally and noticed the better performance of the PMM heat sink [29]. **Figure 3** shows the images of PMM and MMC heat sinks.

3.2 Jet impingement arrangement

A microchannel heat sink with a jet impingement arrangement is an active heat sink with high heat transfer coefficients. Jet impingement in the flow of a fluid using liquid coolants produces very high heat transfer coefficients and it is more significant in the stagnation region [58–60]. Substantial work has been performed on the jet impingement, with various working fluids, at various nozzle configurations, standoff distances, and lengths. Jet impingement in heat sinks shows uniform temperature distribution for both micro-scale and macro-scale applications. Microscale jet impingement is most suitable for dissipating the heat from high-powered electronic systems [61]. Hybrid MCHS with micro jet impinging developed for photovoltaic solar cell cooling was enhanced the solar cell electrical efficiency by 39.7% [62]. The numerical study conducted on the hybrid MCHS with a slot-jet module and various channel cross-sections revealed that the trapezoidal channel shows the better cooling effect [63]. The decreasing order of the pressure drop in the various channels at the fixed flow rate was circular cross-section, a trapezoidal cross-section, and rectangular cross-section. The rectangular channel was not favorable for impingement jet to produce vorticities, so it has a low-pressure loss. Afzal Husain et al. [64] modeled a new hybrid MCHS with impingement and pillars (**Figure 15**). It was noticed that the MCHS model with the low jet pitch to diameter ratio produces a greater heat transfer coefficient. The hybrid MCHS design with the ratio of standoff (distance between jet impingement surface and nozzle exit) to the diameter of the jet close to 2 and 3 results in low thermal resistance and pumping power.

P. Naphon et al. [65] applied the ANN model (**Figure 16**) of the Levenberg–Marquardt Backward propagation (LMB) training algorithm and Computational

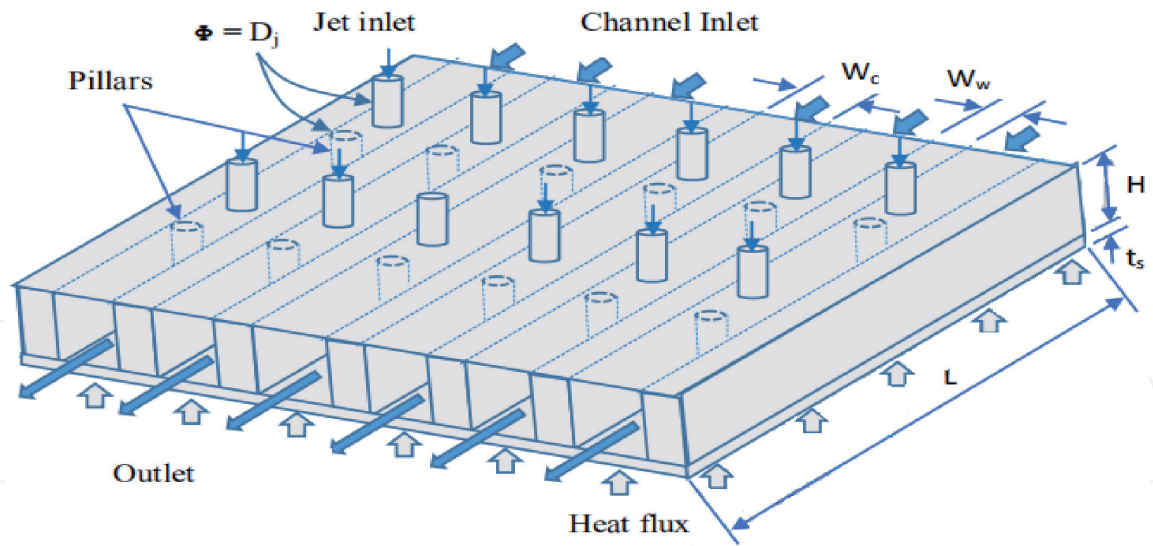


Figure 15.
Schematic model of the hybrid MCHS with pillars and jet impingement [64].

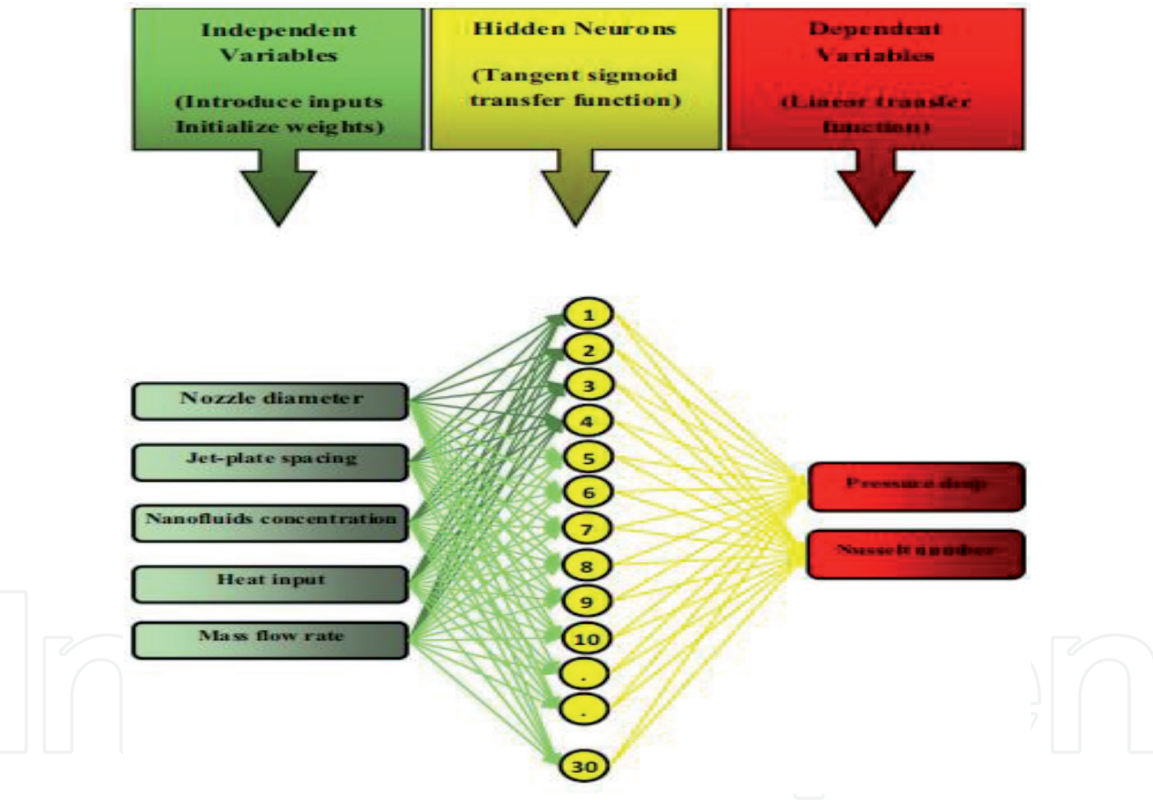


Figure 16.
Optimal ANN model proposed by P. Naphon et al. [65].

fluid dynamics to study the jet impingement of Nanofluids in the MCHS. The maximum deviation of the predicted results from the measured data was found to be 1.25%. With increasing the nozzle level, the heat transfer from the heat sink module to Nanofluid was tended to decrease, which causes the high fins tip temperature. Generally, there are two different jet impingement arrangements: the free-surface and submerged jet-arrays [66]. The schematic model of the free surface and submerged jet arrays are produced in **Figure 17**.
The heat transfer was also enhanced effectively by introducing various shapes of dimples on the HT surface with impinging jets [67]. Convex dimple arrangement

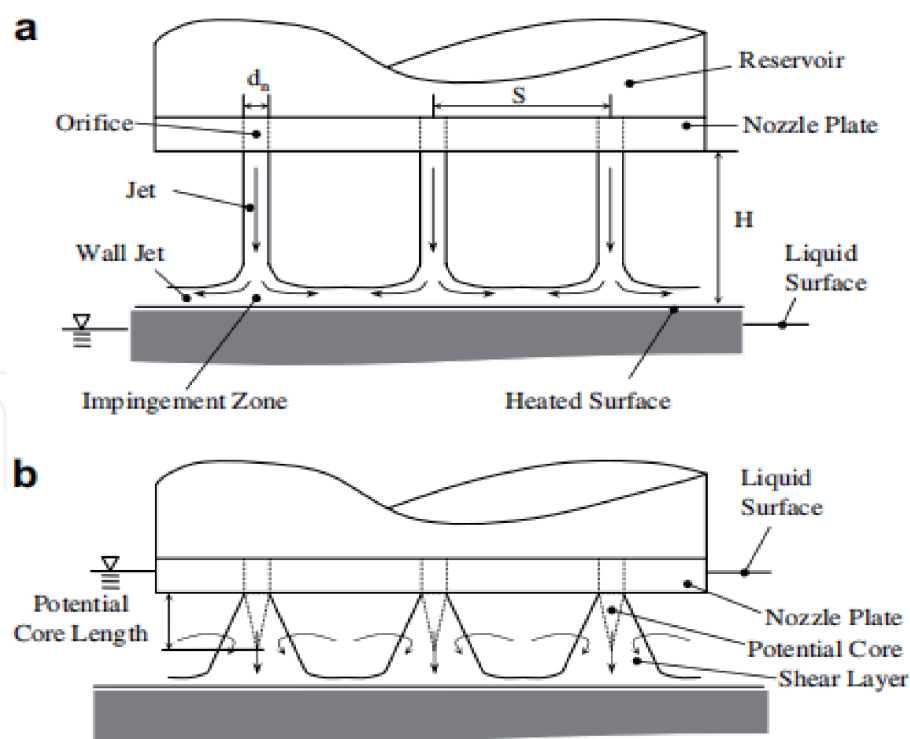


Figure 17.
Schematic model of (a) free-surface jet-arrays and (b) submerged jet-arrays [66].

has superior overall performance among the three arrangements studied and it has a high heat transfer rate and lowest pressure loss. The single nozzle with a convex dimple arrangement is presented in **Figure 18**.

3.3 Nanofluid as the working fluid

Thermo-physical properties of the Nanofluids are superior among various working fluids, so which are suitable for high heat transfer applications.

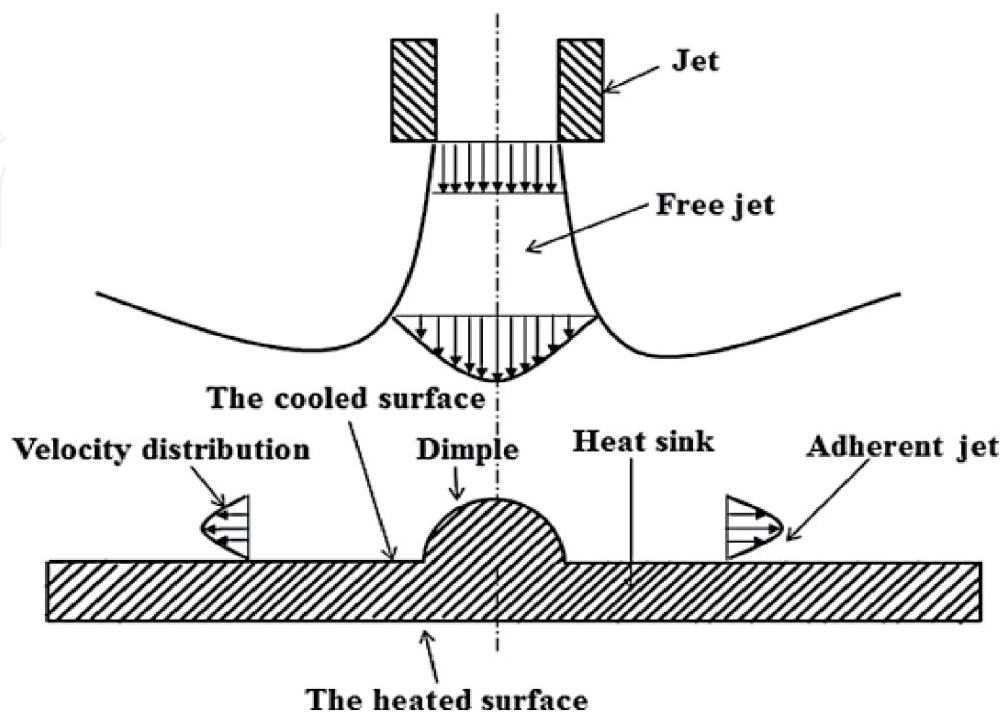


Figure 18.
Schematic diagram of single nozzle with convex dimple arrangement [67].

Significant research has been done on MCHS with Nanofluids using experimental and single and multi-phase CFD models. Multi-phase methods are noticed to be more precise compared to the single-phase numerical methods [68]. The inaccuracy of the 2-phase mixture method and the 1-phase methods for 1% Nanofluid compared to the experimental results were found to be 11.39% and 32.6% respectively [69].

Ayoub Abdollahi et al. [70] proved that the water-based SiO₂ Nanofluid has the best performance among the four water-based SiO₂, CuO, Al₂O₃, and ZnO Nanofluids. In a similar study conducted on the hexagonal channeled MCHS using various water-based Nanofluids, it was observed that Al₂O₃-water Nanofluid has the highest heat transfer coefficient [71]. The analysis on CuO-Water Nanofluid flow in trapezoidal channeled MCHS proved that the thermal performance of heat sink

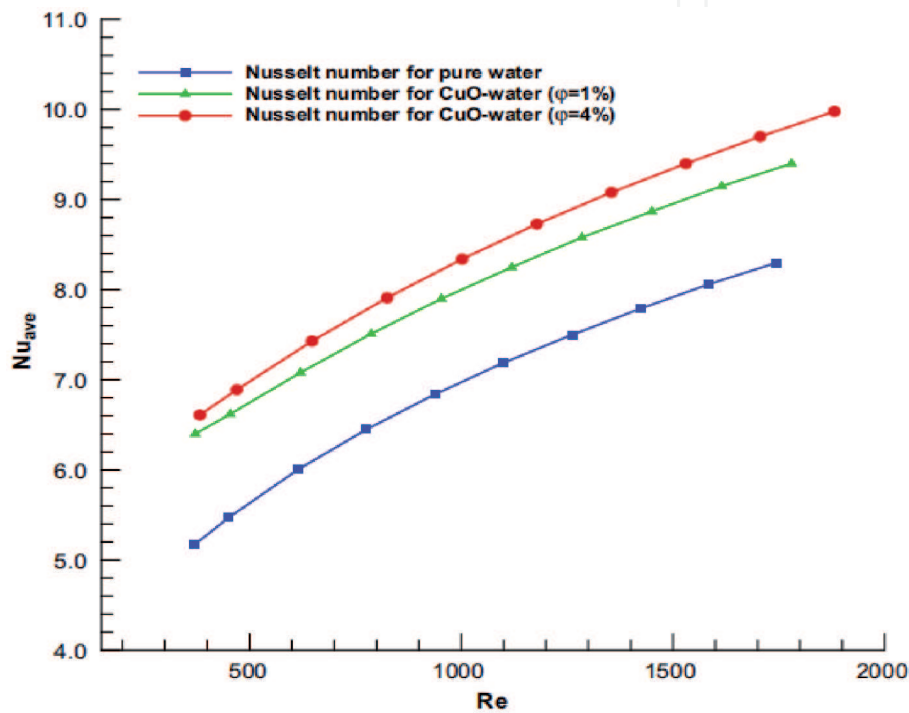


Figure 19.
The variation of average nu with Reynolds for various nanofluid volume fractions [72].

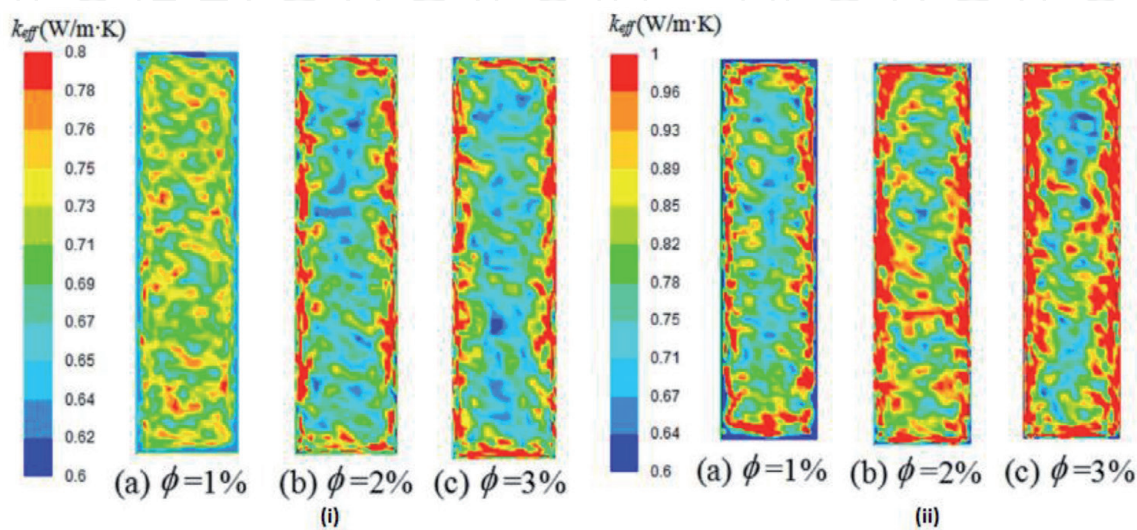


Figure 20.
Distribution of nanofluid thermal conductivity at the outlet with various mass Flux (i) 0.0001 kg/s, (ii) 0.0003 kg/s [75].

was enhanced by increasing the Nanofluid volume fraction with a penalty of high pumping power [72]. The variation of Average Nu with the Reynolds number (Re) is shown in **Figure 19**.

The numerical investigation on the Nanofluid-based triangular and trapezoidal grooved MCHS revealed that the water-based Al_2O_3 Nanofluid was the best coolant for the trapezoidal grooved MCHS [73, 74]. In a numerical study conducted on Al_2O_3 -water Nanofluid-based MCHS, the rise of Nanoparticles' concentration at the walls and non-uniform distribution of thermal conductivity was observed with increasing Discharge [75]. **Figure 20** shows the distribution of the Nanofluid thermal conductivity at the outlet.

Few studies used the advantages of both the geometries and the Nanofluids in the MCHS. Water-based Diamond Nanofluid has the best performance among the various Nanofluids used in the analysis of the wavy channeled MCHS [76]. M.M. Sarafraz et al. [77] witnessed a 76% improvement in the heat transfer performance of MCHS with a 20% increase in the pumping power at the Re higher than 1376. The variation of the Nu obtained from the experiments and existing correlations is shown in **Figure 21**.

The efficiency of an energy system can understand by finding its entropy generation. Some studies investigated the entropy generation of the MCHS to analyze its performance using various working fluids. In the first and second law thermodynamic analysis of offset strip-fin MCHS with CuO Nanofluid as coolant, it was found that the thermal characteristics of the MCHS improved with Re but the frictional entropy generation was also increased [78]. The rate of entropy generation of MCHS in the flow direction concerning the number of fins is presented in **Figure 22**.

3.4 Magneto-hydrodynamics (MHD) influence

MHD is an interdisciplinary subject that has been used in various engineering problems like the design of MHD pumps and flows meters and cooling of nuclear reactors etc. In the field of microfluidics, MHD pipping is very favorable because of its uncomplicated design and less power consumption [79–82]. In the starting, conventional heat

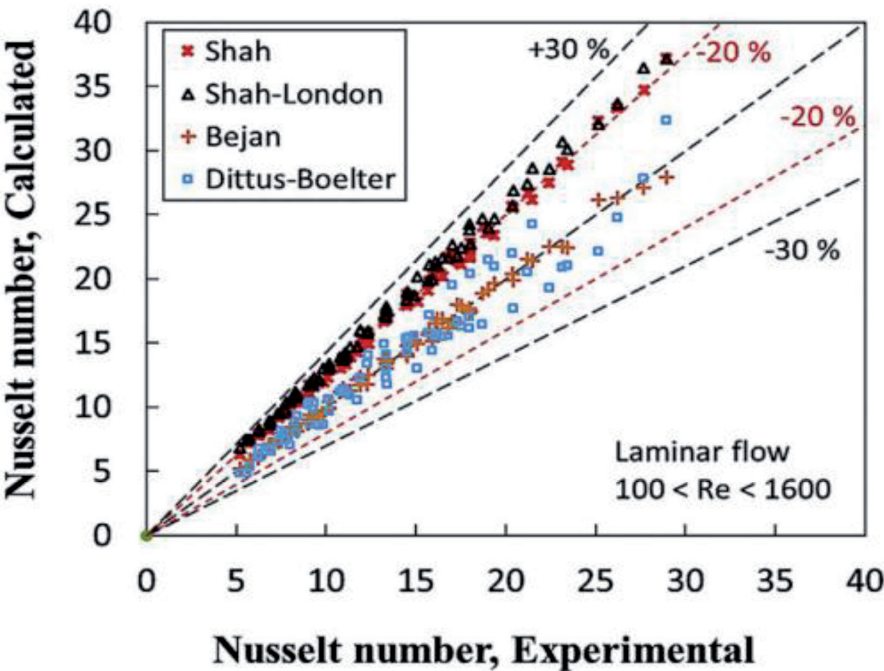


Figure 21.
The variation of the nu obtained from the experiments and existing correlations [77].

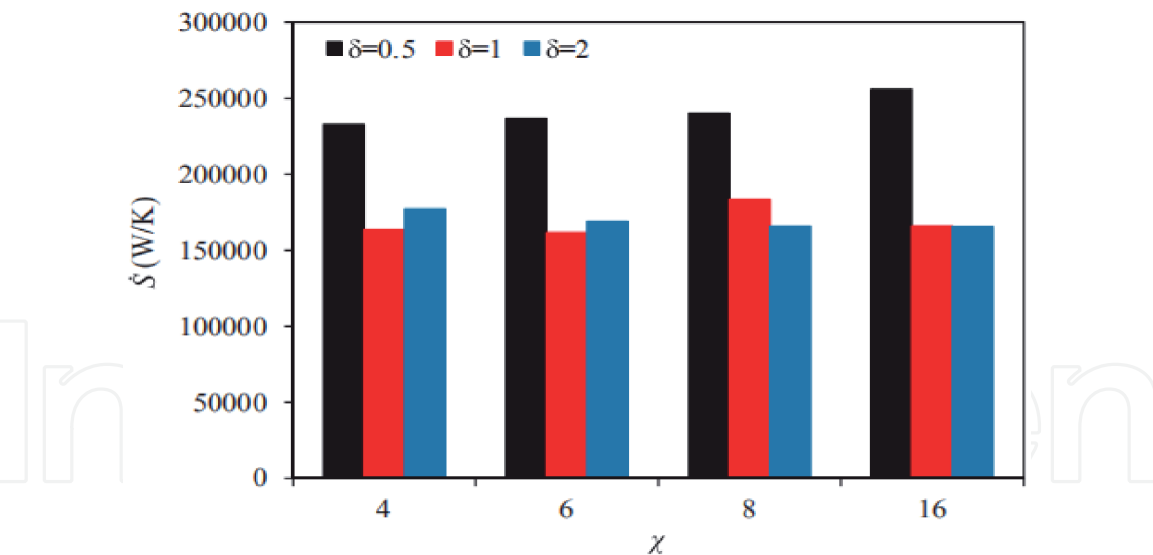


Figure 22.
The entropy generation of MCHS in the flow direction with the number of fins [78].

exchangers with magnetic fluid are investigated to know its performance by applying it. The proportionality of friction factor and Nusselts number with the applied magnetic field was noticed in the study of the MHD effect on circular tube flow of Fe_3O_4 -Water Nanofluid [83]. Variation of Nusselt number with Magnetic field effects is presented in **Figure 23**. The working fluid velocity was observed to be reduced with Lorentz force generated because of magnetic flux applied. The increase of the local heat transfer coefficient was witnessed experimentally when an external magnetic field was applied to the W-40 (magnetic Nanofluid) flow in a rectangular duct [84].

Few research studies about the MHD effect on micro-channels noticed the improvement of their hydraulic and thermal behavior. The decrease of the gradient of velocity at the wall with a rise in the index of Power-law flow was observed in the flow of non-Newtonian fluid flow in a microchannel under a transfer magnetic field [85]. The increment of the gradient of velocity near the wall and reduction of maximum velocity was found with the rising Hartmann number. The increase in the Joule heating and the viscous dissipation was observed to decrease the Nusselt number. Chunhong Yang et al. [86] studied the thermal behavior of an incompressible MHD flow in a rectangular microchannel by taking the combined influence of the viscous dissipation

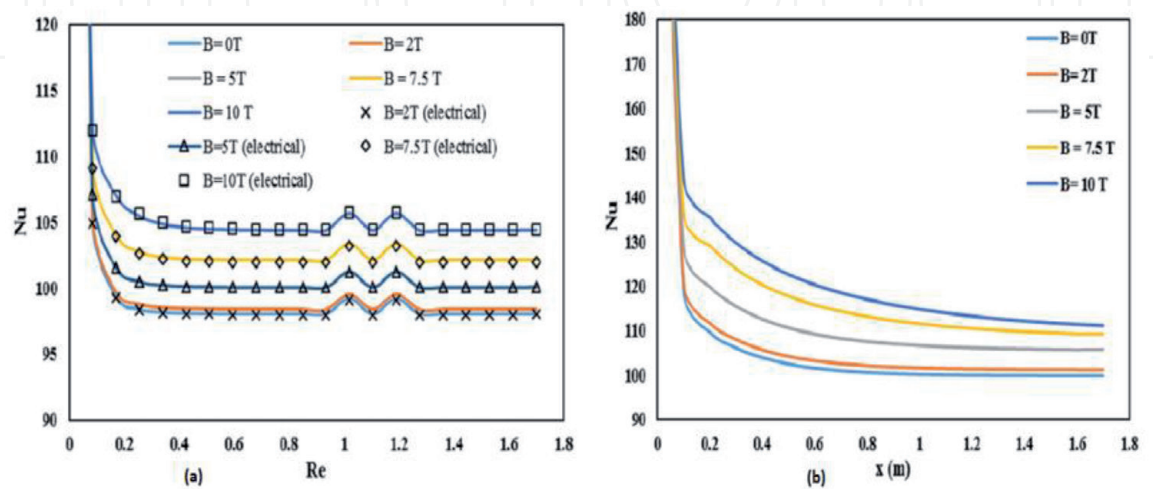


Figure 23.
The nu variation with the magnetic field (a) in the range Re, (b) along the channel [83].

and the Joule heating. This analysis shows the decrease of normal velocity with increment in the Hartmann number (Ha) without any applied lateral electric field. The increasing-decreasing trend of Velocity and temperature profiles was noticed with the rising the Hartmann number under the applied lateral electric field. The generation of entropy in the MCHS was diminished as the influence of the Lorentz force generated by the injected electric current and magnetic field applied transversely [87].

3.5 Flow boiling in MCHS

Flow boiling in the MCHS can vanish the heat fluxes in the range of 30 to 100 W/cm² with the acceptable channel surface temperatures [88]. The flow boiling implemented MCHSs were used for a variety of applications, like cooling of PEM fuel cells, thermal management of the IGBTs (insulated gate bipolar transistors), refrigeration systems, etc. [89]. Most of the researchers' attention is on estimating the impact of the mass flow rate, heat flux, vapor quality, and surface characteristics on the boiling heat transfer [90, 91]. Stable flow boiling is also one of the best way to enhance the heat transfer in the MCHS. The experimental analysis done by John Mathew et al. [92] on the copper hybrid MCHS with flow boiling revealed that the local heat transfer coefficient is consistent increases with the heat flux and becomes sensitive to the heat flux. The pressure loss was also found to increase in the 2-phase flow with heat flux under all mass flow rate conditions. **Figure 24** shows the variation of upstream heat transfer coefficient in the microchannel concerning the effective heat flux. A numerical study of Yang Luo et al. [93] on manifold MCHS with subcooled two-phase flow boiling proved that heat flux and the manifold ratio significantly influence the pressure drop and thermal resistance (R_{th}) of the micro-channel. The authors suggested that the manifold ratios should be between 1 and 2 for low-pressure drop and the better thermal performance of the manifold heatsink.

The impact of the surface characteristics on the flow boiling of regasified and deionized water micro-channel was experimentally studied and found that the characteristics of the Cu microchannel surface are transient [88]. The heat transfer coefficients of the aged Cu microchannel surface were unchanged and even enhanced

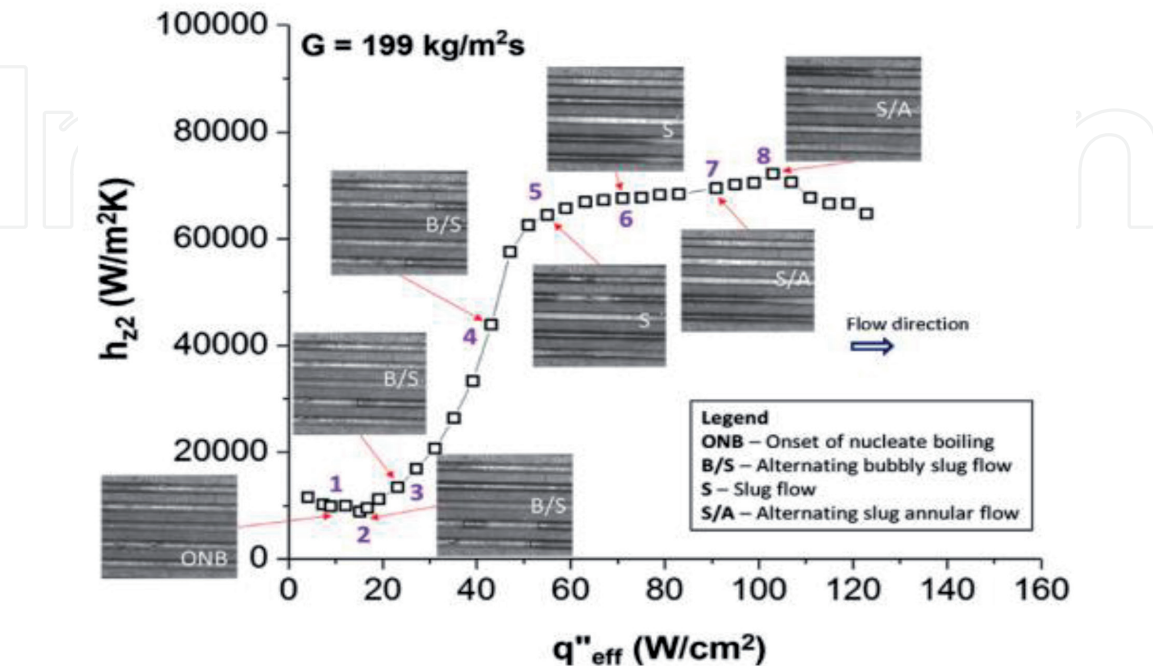


Figure 24. Variation of upstream HT coefficient in the microchannel with respect to the heat flux with the images of flow visualization [92].

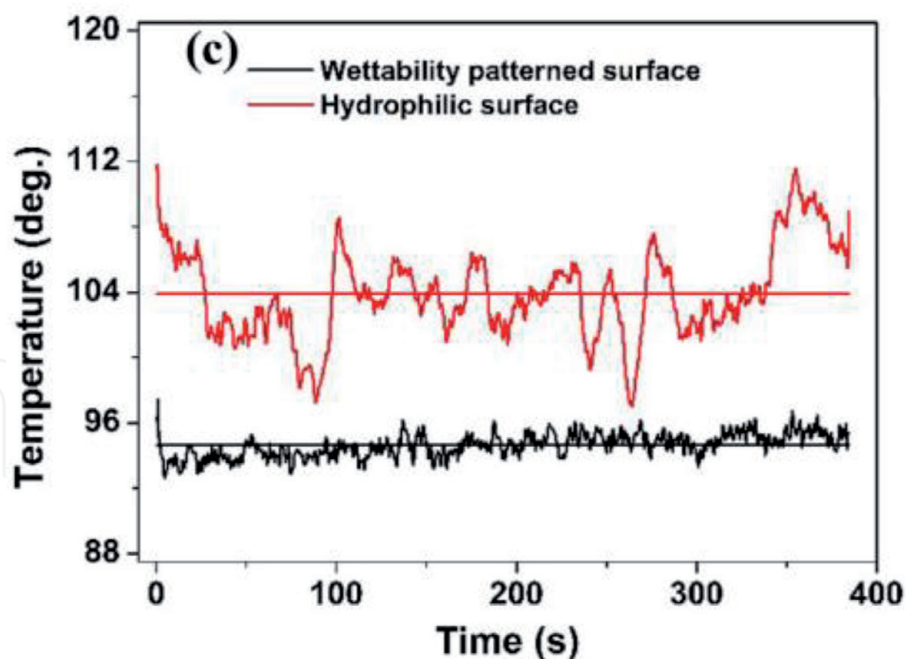


Figure 25.
 Transient variation of heaters' temperature (lines represents the average temperature) [94].

after proper cleaning. Hongzhao Wang et al. [94] examined the wettability patterned microchannel and homogeneous hydrophilic microchannel and found a 22% higher heat transfer coefficient for wettability patterned microchannel. The heat transfer coefficient was noticed to be improved for the wettability patterned channel with the mass flux. The transient variation of Heaters' temperature variation is shown in **Figure 25**.

The experimental and simulation analysis on microchannel with 2-phase continuous boiling revealed that heat transfer was improved at the fixed heat flux with increment in mass flux but it may tend to unstable boiling [95]. For the unstable boiling in a microchannel, the oscillation amplitude was observed to be influenced by the structural parameters of the microchannel and the thermal conductivity. In the experimental investigation on 2-phase flow regimes in a microchannel, the formation of the wave on the liquid film was observed in film flow regimes [96] and the wavelength of the waves on the liquid film is depending on flow rate of the gas and liquid.

Along with the MCHS performance improvement methods discussed above, a few other inventive methods were noticed in the literature. C.J. Ho et al. [97] examined the microencapsulated PCM (MEPCM) based MCHS under the sudden pulsed heat flux and disclosed that the layer of MEPCM layer not effective in controlling the temperature rise in the MCHS. At the high amplitude of heat flux pulse, the MEPCM layer has the improved cooling performance. Soumya Bandyopadhyay, Suman Chakraborty [98] investigated the thermophoretic force effect and the interfacial tension by studying Newtonian fluid dynamics in a microchannel with the consideration of temperature dependency of viscosity. Linda Arsenjuk et al. [99] investigated the slug flow in parallelized microchannel and obtained static fluid distribution with high-pressure loss. Zan Wu et al. [100] analyzed the slug flow in a square microchannel and correlated the velocity of the slug in terms of the Capillary number using bulk velocity and continuous phase viscosity.

4. Conclusions

The advancements in the thermal performance enhancement methods for microchannel heat sinks are discussed so far. Each method is selected based on

heatsink application, the heat flux needs to be dissipated, space availability, etc. The primary conclusions drawn from this chapter are,

- The accuracy of the solution depends on the numerical method implemented to solve the fluid flow problem. The lattice Boltzmann method was considered an efficient numerical method to solve the fluid flow problems coupled with heat transfer in complex geometry.
- The geometry modification of the heat sink by adding the fins, changing the channel shape, flow pattern, etc., is the basic heat transfer enhancing technique but with increasing the complexity of the geometry the fabrication becomes difficult and expensive.
- The large pressure drop is also one of the disadvantages with the complex geometry of the heat sink.
- The microchannel heat sink developed with the phase changing process is well suited for the heat dissipation application where large fluctuations in the heat flux are involved.
- The flow boiling and jet impingement in the microchannel heat sink is considered the best methods to dissipate the large heat fluxes generated in the electronic components with the penalty of a large pressure drop.

5. Existing lacuna and future scope

The major observations from the present chapter are

- Efficient Phase changing materials (PCM) based MCHS has to be developed and its influence on the heat transfer has to be analyzed thoroughly.
- High-pressure loss is the main limitation for the microfluidic systems, heat sinks with the low-pressure drop has to be developed
- There is more scope for electro-hydrodynamic and magneto-hydrodynamic studies in the field of microfluidics.
- The research on the influence of surface effects on the behavior fluid flow must be extended to analyze the thermal performance.
- Low-cost manufacturing methods for microfluidic devices are required as the existing fabrication is very expensive.

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