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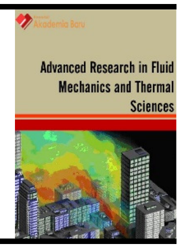

A Comprehensive Review on Numerical and Experimental Study of Nanofluid Performance in Microchannel Heatsink (MCHS)

Open

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ABSTRACT

Microchannel heatsink is an advanced technology in the cooling system that gives a superior performance to remove high heat flux generated by a modern electronic device. Many innovations of microchannel design have been dedicated to improve the thermal performance in microchannel heatsink. Besides that, application of nanofluid as a coolant in microchannel heatsink has been attracting a lot of interest among researcher due to the enhancement of thermal conductivity in a nanofluid with a small percentage of the nanoparticle. The enhancement has contributed to heat transfer augmentation in microchannel heatsink. In this paper, a comprehensive review about nanofluid as a coolant regarding its performance based on the concentration and size of nanoparticle in microchannel heatsink was presented and analysed. The discussion of this review focused on the methodology used to analyse the performance of nanofluid in a microchannel, flow condition, channel design and type of nanofluid. Finally, the suggestion of nanofluid selection, nanoparticle concentration, nanoparticle size and flow condition have been pointed out.

1. Introduction

Over the past decade, the investigation of fluid flow and heat transfer characteristic induced by natural convection on thermal performance becomes a most interesting topic in a cooling system. The effectiveness of the cooling system in such application is very important to keep the temperature of a structure or electronic device from exceeding limits imposed by needs of safety and efficiency. The applications of the cooling system in thermal engineering are known for years and have been studied critically in theoretical as well practical point of view in various engineering applications such as building energy system, electronic device, chemical vapor deposition instruments, solar energy collector, furnace engineering and many more [1].

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In recent years, rapid growth in the electronic industry has witnessed a new generation high performing dense chip packages in many modern electronic devices. The chip packages that work at high frequency has produced very high heat flux on the electronic devices. If it happens continually, the heat flux will create the hot spot on the electronic device and thus reduces the lifespan of the electronic devices due to the acceleration of the Mean Time to Failure (MTTF) as described by Black's equation [2]. The increase in power density and miniaturization of electronic packages has driven the direction of cooling system technology from air-cooling technology to advanced heat transfer technology due to the conventional method inadequate to remove very high heat flux [3]. However, the development of more compact electronic devices that will operate at high power density causes the thermal management of electronic devices becomes a very critical issue in the electronics industry due to lack of efficient technique to remove heat from the devices [4, 5].

2. Enhancement Techniques

During the past 30 years, many methods have been proposed in open literature in order to improve overall performance of microchannel heatsink with minimal thermal resistance and pressure drop that can satisfy the cooling demand. Generally, the methods can be categorized into two groups, active method and passive method. Active method will use external energy in its system while passive method no need for that. Most of researcher has widely used the passive method due to its low cost and absence of moving part compared to active method [6]. Fig. 1 shows the techniques in active and passive method that available in open literature.

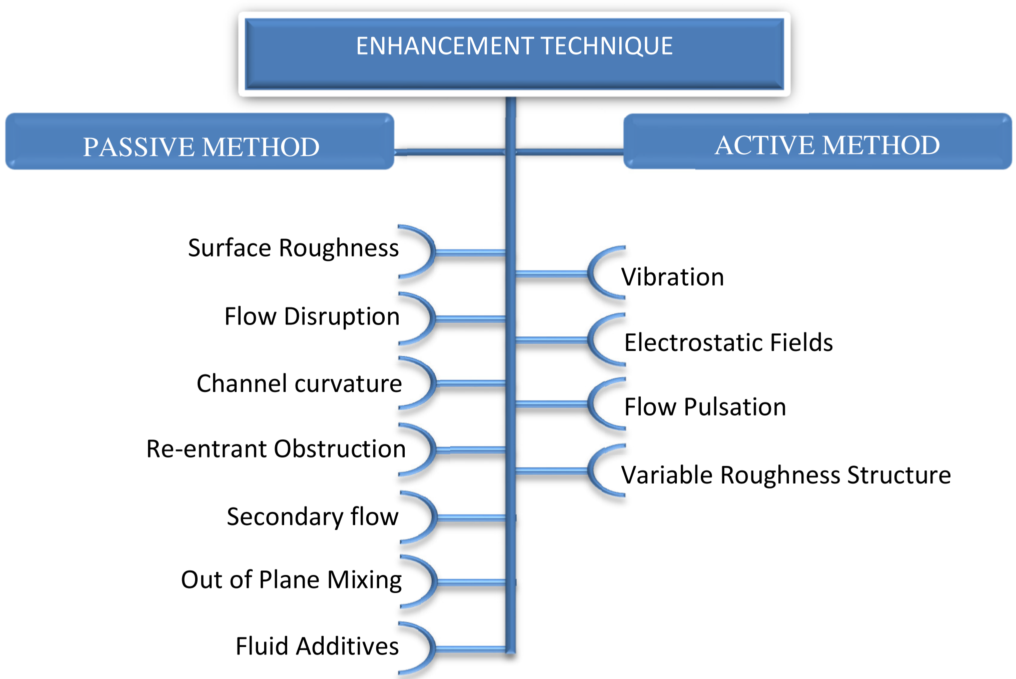

Fig. 1. Enhancement technique for microchannel heatsink

2.1 Active Method

Much of the literature since the mid-1981s emphasises the passive method rather than active method in performance augmentation of microchannel heatsink due to compactness area in advance electronic device. There is a relatively small body of literature that consider application of active method in development of microchannel design. In 2003, Jeung Sang Go [7] has evaluated experimentally the effect of flow-induced vibration of a microfin array on heat transfer augmentation. It was demonstrated that, high heat transfer rate can be obtained by increasing the vibrating displacement of the microfin. In an innovative work by T. Krishnaveni and his co-researchers [8], they proposed electric fields technique in rectangular microchannel heatsink whereby this method can induce chaotic mixing in a microchannel and thus contributes to the heat transfer augmentation. The characteristic of flow pulsation technique on microchannel performance has been investigated critically by Mir-Akbar Hessami and Andrew Berryman [9]. They have concluded that, heat transfer enhancement can be obtained by increasing the frequency and reducing the amplitude of flow pulsation.

2.2 Passive Method

Flow disruption technique is the one of the passive method that widely used in innovation of microchannel design due to its capability to increase the flow mixing and thus contributes to the heat transfer enhancement. Hong and Cheng [10] has investigated the effect of offset strip-fin on flow and heat transfer characteristic. It is found that, the fins have increased the flow mixing between the cold and hot coolant and thus enhanced the heat transfer performance. Besides that, the periodical breakup of boundary layer provided by the fins is another factor to enhance heat transfer. To fully understand about the mechanism of flow disruption technique, Chai et al. [11] has conducted one comprehensive study to analyse the effect of rectangular rib on the mainstream flow such as mainstream flow separation, recirculation or vortex, and interrupted boundary layer. In 2018, Chai et al. [12] has extended his analysis by changing the shape of rib to backward triangular, diamond, forward triangular and ellipsoidal. The analysis shows that, the presence of non-rectangular rib in microchannel decreased the total thermal resistance and entropy generation rate by 4 – 31% and 4 – 26%, respectively.

It has been well-known that Dean vortices generated by curved channel will enhance the stretching and folding of the flow element. This mechanism will increase the flow mixing and thus improve the heat transfer performance. Sui *et al*., [13] studied the how Dean vortices that generated in wavy channel may increase the flow mixing and improve heat transfer. The observation shows the chaotic advection created by the number of Dean vortices in different location along flow direction will increase the flow mixing and thus improve the heat transfer performance. In 2016, Mills and his co-researcher [14] analysed the performance of heat transfer in wavy channel for steady and unsteady flow. They have revealed that heat transfer enhancement achieved in unsteady regime is higher than that in steady regime. At low Reynolds number (steady state), the enhancement of heat transfer performance is defined by amplitude of wall waviness. However, at high Reynolds number (unsteady state), the performance of heat transfer is strongly affected by pressure drop penalty compare to the amplitude of wall waviness.

Up to now, a number of studies has demonstrated the thermal performance in microchannel heatsink can be enhanced using secondary flow technique. In 2012, Lee *et al*., [15] has designed oblique fins in copper microchannel heatsink for generating secondary flow that give a great impact on heat transfer performance that overcome pressure drop penalty issue. After two years, he and his research team [16] has continued their investigation about oblique fin parameter in silicon microchannel heatsink. They have revealed that smaller oblique angle and smaller fin pitch will contributes to the heat transfer augmentation. Secondary channel geometry in alternating orientation that connect two adjacent main channel has been investigated by Kuppusamy *et al*., [17].

They found that the combined effect of thermal boundary layer re-development and flow mixing has increased the heat transfer performance with minimal penalty of pressure drop.

2.3 Combination of Individual Passive Technique

All of the studies reviewed here has demonstrated the heat transfer performance could be enhanced by using individual technique of passive method. However, pressure drop issue become the main constrain in the design development of microchannel heatsink. Nowadays, many researchers have used multiple technique of passive method in single phase flow for enhancement of microchannel performance. The combined effect from multiple technique in microchannel design will increase heat transfer performance with minimal pressure drop. Li *et al*., [18] has proposed new novel design in order to develop high efficiency low-resistance heat exchanger. Combination structure of dimple and pin-fin in the novel design has increased the heat transfer with energy saving and low resistance features. It can be seen that the features have enhanced the thermal performance by 10.3% at Reynolds number of 200. Besides that, the area of high temperature region and temperature gradient were decreased. Furthermore, violent action of flow on heated wall provided by pin-fin has increased the uniformity heated area.

In 2013, L. Gong *et al.*, [19] has analysed the performance of microchannel structured by dimple and wavy shape. In their design, the effect of dimple number in wavy wall has been study numerically. They revealed that the presence of the dimple structure in wavy channel could enhanced the heat transfer performance and not apparently increase the flow resistance. Besides that, the overall performance of the microchannel increases with the dimple number. After six years, Gong *et al*., [20] studied the same geometry combination with different orientation of dimple structure. Their numerical result demonstrated that microchannel with dimple structure in the throat of wavy channel appeared as the best thermal performance compared with the dimple structure in the cavity of wavy channel. The dimple structure in cavities just weaken the overall performance that provided by wavy channel.

In recent years, many researchers are interested to study the effect of combination of cavities and ribs on the sidewalls and on the central of straight channel, respectively. Li and his co-researcher [21] has presented a numerical study to investigate the effect of ribs and cavities on fluid flow and heat transfer characteristic for the Reynolds number ranging from 173 to 635. The analysis revealed that combined effect of interruption, redevelopment of thermal boundary layer, the intensified mainstream disturbance and the chaotic mixing between hot and cold water has contributed to enhancement of heat transfer performance. Beng *et al*., [22] has supported this result with the same geometry design analysis. They have demonstrated that the higher heat transfer augmentation could be achieved by combining the individual technique in passive method.

There have some researchers are still using conventional design such as rectangular shape for heat transfer augmentation in microchannel heatsink. In 2012, Hung *et al*., [23] studied the performance of rectangular channel in two configurations, single-layered and double-layered. They revealed that thermal performance obtained by double-layered rectangular channel is higher than single-layered one. In order to verified the ability of rectangular shape in heat transfer augmentation, Razali *et al.*, [24] has compared the performance of microchannel with rectangular-shape and square-shape. The result shows that, microchannel with square-shape has a better thermal performance than rectangular-shape especially at low Reynolds number. However, pressure drop produced by square-shape channel is higher than rectangular channel. Selection of microchannel shape is very important to ensure the overall performance of microchannel can be enhanced without high penalty of pressure drop.

2.4 Nanofluid Application in Microchannel Heatsink

In early investigation of microchannel performance, most of researcher focus their attention to improve the design of flow passage so as the thermal resistance could be decreased and thus improve the heat transfer performance. However, there are some researcher try to enhance the heat transfer performance by changing the transport properties such as thermal conductivity of the fluid used in the microchannel heatsink. Nowadays, discovery of new potential fluid as a coolant will improve the ability of convective heat transfer in microchannel heatsink. Long years ago, early researcher has added solid particle with the size of micrometer and milimeter in the based fluid (water) to improve the thermal conductivity that could help to improve heat transfer performance. However, this method is impractical for the microchannel heatsink due to the issue of clogging effect. In 1995, Choi *et al.*, [25] has introduced the new potential coolant named as nanofluid. Nanofluid is prepared by dispersing solid particle with the size of nanometer in based fluid. The present of nanoparticle in the base fluid has increased the heat transfer coefficient of base fluid due to the thermal conductivity of solid particle is higher than fluid [26]. This characteristic contributes the heat transfer performance [27].

There have some criteria that need to be considered in nanofluid preparation such as based fluid selection, nanoparticle size, nanoparticle shape, nanoparticle concentration purity of nanoparticle, dispersibility of nanoparticle, thermal conductivity, preparation method and compatibility of nanoparticle that leads to homogenies mixture of nanofluid [28]. Table 1 shows the list of nanofluid that available in open literature. It can be seen that, most of the researchers are interesting on application of Al_2O_3 nanoparticle as additives in the base fluid in microchannel heatsink. Besides that, pure water such as DI water and distilled water most widely used as the base fluid in their analysis. Alfaryjat and his co-researcher team [29] studied the effect of the base fluid that homogenized with Al_2O_3 nanoparticle on fluid flow and heat transfer characteristic in rhombus microchannel heatsink. They have revealed that Al_2O_3 nanoparticle that dispersed in pure water has the highest heat transfer coefficient compare to other base fluid such as engine oil, glycerine and ethylene glycol. Furthermore, Al_2O_3/water provide the lowest thermal resistance among other base fluid. Although all the base fluid has a similar friction factor, Al_2O_3/water shows the lowest value of pressure drop due to great enhancement of heat transfer performance. The effectiveness of Al_2O_3 nanoparticle as additives has been analysed experimentally by Thansekhar *et al.*, [30] for the low Reynolds number of 55 to 90. The result has demonstrated that Al_2O_3/water has the better heat transfer performance compare to SiO_2 due to its thermal conductivity. Thermal conductivity is one of the factor that determine the performance of nanofluid.

However, Razali *et al.*, [31] claim that the performance of Al_2O_3/water decreases for long term used due to the changed of the crystallite size that effected by growth in heating process. Due to this problem, Sivakumar *et al.*, [32] has analysed the other potential additives such as CuO nanopartcle. The analysis has compared the performance of Al_2O_3 nanoparticle with CuO naopartilce in different base fluid such as ethylene glycol and pure water. The result shows that heat transfer coefficient of CuO/EG is higher than Al_2O_3/water and CuO/water due to EG base fluid has a higher viscosity and density. This statement appears to contradict with Alfaryjat *et al.*, [29]'s research which prove that water has a better performance as a base fluid compare to EG. Volume concentration also play a mail role for heat transfer performance. It can improve or reduce the performance of nanofluid. Most of researcher use less than 1% of volume concentration for their analysis. Chabi *et al.*, [33] claims that nanofluid with too high volume concentration tends to reduce heat transfer coefficient due to rapid formation of sedimentation and nanofluid stability. The statement has been supported by Manay *et al.*, [34] in their study to determine the upper limit of volume concentration for TiO_2 nanoparticle.

The result shows that, only for the volume concentration below than 2.0%, overall thermal efficiency increases with volume concentration. Besides that, TiO_2 nanofluid just show the enhancement of heat transfer performance for the volume concentration of 0.25% - 2.0%. When the larger volume concentration was added, the heat transfer performance has decreased. Increasing in volume concentration also give a significant effect on thermal resistance due to particle deposition. Furthermore, they have stated that, the thermal resistance can be reduced by using nanoparticle that has average diameter of 25nm.

3. Conclusion

This paper presented a comprehensive review about the application of nanofluid in microchannel heatsink. There have several parameters that need to be consider for a better heat transfer performance. Thermal conductivity of the nanoparticle plays a main role that will indicate the heat transfer performance. Selection of the base fluid also give a significant effect on thermal performance. Each nanoparticle has their own limitation of nanoparticle volume concentration. Use the optimum volume concentration will increase the heat transfer performance with small pressure drop. Excessive of nanoparticle volume concentration will increase the thermal resistance and will reduce the overall thermal performance of microchannel heatsink. It is very important to understand the behaviour of nanofluid so as the performance of microchannel can be predicted. As a new coolant in a cooling system, there has many challenges that need to be identified and overcome for different application. The major concern that need to be considered are the stability of nanofluid that using two step method in nanofluid preparation and production cost to produce the nanoparticle.

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Table 1
Application of nanofluid in various shape of microchannel heatsink

Author	Nature of work	Reynolds Number	Nanofluid	Volume concentration / diameter	Based fluid	Finding
Arabpour A *et al.*, [35]	Numerical	1-100	MWCNT	0.4% 0.8%	Kerosene	• Thermal resistance decreases on increasing the volume fraction and slip velocity coefficient • Heat transfer increases with Reynolds number and volume concentration of nanoparticle • Increasing in volume fraction has increased the friction coefficient due to enhancement in viscosity and density
Tran N *et al.*, [36]	Numerical	100-900	Al_2O_3 TiO_2	0.1vol.% 0.5vol.% 1.0vol.%	DI water	• Thermal resistance was improved up to 6.7% when using TiO_2 with 1.0vol.% compare to DI water. • Thermal resistance for TiO_2 with 1.0vol.% is lower than Al_2O_3 with same concentration and DI water. • The higher thermal performance could be achieved with the nanofluid that have higher thermal conductivity and concentration
Sarafraz *et al.*, [37]	Experiment	50-1400	Silver, Ag	0.01wt.% 0.05wt.% 0.1wt.%	DI water	• Optimum concentration of silver nanofluid (0.05wt.%) has enhanced the overall thermal performance up 37% at the Reynolds number of 1400 • Silver nanofluid with 0.1wt.% has increased the heat transfer coefficient by 47% and it exhibit the highest one. • When the mass concentration of the Silver nanofluid increases, heat transfer coefficient also increases with pressure drop.

Abdollahi *et al.*, [38]	Numerical	200-700	Al_2O_3	1.0vol.% 2.5vol.% 5.0vol.%	DI water	• No significant effect on pressure drop by using nanofluid in interrupted MCHS • At least 2.0vol.% is required to obtained an enhancement in heat transfer performance • Al_2-O_3/water with 5.0vol.% can enhance Nusselt number more than 30% and give a great impact on heat transfer performance.
Vinoth *et al.*, [39]	Experiment	300-850	Al_2O_3	0.25vol.%	Distilled water	• Adding nanoparticle into water could increases the heat transfer rate up to 4.6% • Heat transfer rate improvement for trapezoidal cross section of oblique finned MCHS is highest than square and semi-circle cross section for both water and nanofluid by 3.13% and 5.88% respectively. • Heat transfer rate improvement for trapezoidal cross section of oblique finned MCHS is highest than square and semi-circle cross section for both water and nanofluid by 3.13% and 5.88% respectively.
Duangthongsuk *et al.*, [40]	Experiment	NA	SiO_2	0.3vol.% 0.6vol.% 0.8vol.%	DI water	• Thermal performance provided by nanofluid is better than water by 3-15%. • Application of nanofluid in cross-cutting flow channel just have small increases in pressure drop • Nusselt number increases with volume concentration and Reynolds number

Arani *et al.*, [41]	Numerical	500-2000	SWCNT	4vol.% 8vol.%	Distilled water	• Thermal resistance, ratio of maximum temperature to minimum temperature on the bottom surface and ratio of thermal resistance decreases on increasing the volume fraction and Reynolds number • Heat transfer rate increases with volume fraction
Sarafraz *et al.*, [42]	Experiment	100-1400	MWCNT	Nominal size: 5-10nm length: 2µmeter	DI water	• MWCNT has the higher heat transfer coefficient than based fluid. Approximately 29% enhancement. • Heat transfer increases significantly with volume concentration and fluid flow rate • Fouling thermal resistance decreases with the mass concentration. • MWCNT shows the lower temperature profile along the MCHS than based fluid in microchannel. The higher mass concentration , the lower temperature profile is obtained
Snoussi *et al.*, [43]	Numerical	100-1000	Al_2O_3 Cu	1.0vol.% 2.0vol.%	DI water	• When using nanofluid, heat transfer coefficient can be enhanced by applying the higher heat flux. • At the higher heat flux, wall temperature deceases on increasing the volume fraction • Heat transfer increased by 14% - 20% when using nanofluid compared to the base fluid

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S. B. Abubakar *et al.*, [44]	Numerical	140 700 1400	Fe_3O_4	0.4vol.% 0.6vol.% 0.8vol.%	Distilled water	• The presence of Fe_3O_4 nanoparticle in pure water has a better heat transfer performance than pure water due to the higher dynamic viscosity and lower heat capacity. • The temperature of channel wall decreases on increasing the volume fraction of Fe_3O_4. • When using Fe_3O_4/water, the surface temperature decreases up to 0.04%, 0.07% and 0.08% for the 0.4vol.%, 0.6vol.% and 0.8vol.%, respectively
Alfaryjat A., *et al.*, [29]	Numerical	700	Al_2O_3	4.0vol.% 25 nm	DI water Engine oil Glycerin Ethylene glycol	• Al_2O_2/water shows the lower value of thermal resistance than other tested nanofluid in the rhombus shape cross section. • Al_2O_2/water has a higher heat transfer coefficient than other tested nanofluid. • Al_2O_3/water shows the lower value of pressure drop than other tested nanofluid in rhombus shape cross section
Sivakumar A., *et al.*, [32]	Experiment Numerical	100-1300	CuO Al_2O_3	NA	Ethylene glycol Distilled water	• Heat transfer coefficient for CuO/EG and Al_2O_3/water is higher than their base fluid. • Heat transfer coefficient for CuO/EG is higher than Al_2O_3/water and CuO/water • Brownian motion of nanoparticle in serpentine shape channel has contributed to the enhancement of heat transfer rate.