A Review on Electronics Cooling using Nanofluids

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Abstract: Continuous reduction in the size of the electronics for space limitations with higher processing speed generates high heat flux density from the electronics chips during its operational mode. However, this increased heat flux density causes a major problem for the electronics and leads to the failure of the components if not removed properly. This paper investigates the various cooling techniques especially the liquid cooling system operated with nanofluids- a special kind of fluid with the dispersion of nanometre sized particles. This paper quantifies the various kinds of nanofluids used for electronics cooling along with its thermal performance by targeting on the thermal characteristics such as heat transfer coefficient, thermal resistance, thermal conductance, interface temperature, etc. This paper also quantifies the operation of nanofluids over the various geometries of micro channel heat exchangers that serve as a heat sink for power dissipation from the electronics.

Keywords: Electronics cooling, Heat transfer coefficient, Nanofluids, Micro channel heat sink.

1 Introduction

Electronics cooling is the major concern in all the industrial and the business sectors where the organisation deals with data processing, data communication and data storage. Thermal management remains as a major part of this concern due to increase in heat dissipation from the electronic chips. Processor chips migration with increased speed from one generation to the next advanced leads to the dissipation of heat and the critical heat flux. However, the increased heat generation remains unavoidable with the increased processing speed. A survey was conducted on the electricity consumption of the data centres and it was reported that, 33% among the total electricity consumption was assigned with the thermal management [1]. Roughly, it was estimated that nearly 1.3% of the total global electricity consumption was used for the data centres ranging from 152 billion kW/year in 2005 to 238 billion kW/year in 2010 [2]. Thermal management remains as technical challenges for the electronics industries despite of progressive increase in processor computational speed. Hence, the necessary removal of increased heat flux remains as a major complication in the electronic industries. According to INEMI (International electronics manufacturing initiative) in 2004 [3], it was projected that the high heat flux and the power density in high end performance microprocessors will reach about 360W and 190W/cm\textsuperscript{2} in 2020. However, a study was conducted in 2007 [4] and the results were reported that the electronics industries were facing a major complication in maintaining the temperature of the microprocessors below 85°C leading to the adequate removal of heat flux of about 300 W/cm\textsuperscript{2}. In addition to the increased heat flux, the power dissipation becomes increasing due to the integration of several components than the surrounding areas leading to the non uniform power dissipation in the high end performing devices. In 1960s, the initiation of MSI (medium scale integration) involves the miniature of the components integrating 50-1000 componentets per chips and in 1970, this has been increased to 1000 – 100,000 components per chips introducing the concept of large scale integration (LSI) and in 1980 the technique of very large-scale integration (VLSI) involves
the integration of 100,000 – 10, 00,000 components per chip respectively [5]. Later, the chips were integrated with 100 million transistors per square centimetre in 2006[6]. A classical Moore’s law [6] was proposed for the microprocessors dealing with the size miniature, increasing transistor density, increasing processor speed and performance. In 2006, according to the international technology road map for semiconductors [7], it was examined that the transistor size decreases to 6nm with increase in the density of about 20 billion transistors /cm² in 2020 with the size of the chip ranging from 100mm².

2 Methods adopted for cooling

Hence the major solution for the increased heat flux and power dissipation is adopting a better cooling technique for the electronic circuit. However proper cooling of microprocessor leads to the maintaining of temperature increasing the performance speed. Inadequate cooling leads to the increase in the power density raising the temperature of the microprocessors affecting the performance of the chips and even leads to the failure of the operating circuits. Hence proper cooling method is to be adopted for the chips to perform at its desirable operating level. Various methods of cooling were adopted for the electronic circuits namely,

1. Air cooling,
2. Liquid cooling,
3. Refrigerant cooling.

2.1 Air cooling

Air cooling is one of the best adopted cooling methods for the electronics system with posing of both advantages and disadvantages. This method is adopted where there is a more prominent space limitation with the absence of sealed enclosures and piping’s around the processor chips [8]. This method when adopted for cooling has an advantageous of minimal maintenance of the electronics system as compared with liquid cooling. This factor together with simplicity and installation of the equipment suggests that this method of cooling is more prominent for server cooling. Despite of its simplicity, air possesses a low heat transfer coefficient as compared with the liquids and hence it has limitations in the production of high heat flux densities. Due to its heat transfer limitations, only a limited research has been made on the air cooling of electronics. Xu et al [9] analysed the effects of air cooling both experimentally and numerically compared it by developing a three-dimensional finite element method. He reported that the heat transfer rate of air was limited to 340W at base temperature of 90°C and the base area of 100cm². Katoh et al [10] experimentally compared the performance behaviour of traditional heat sink by air cooling with the pulsating heat pipe heat sink and found that the reduction in the thermal resistance was about 40% as compared with traditional heat sink. Due to its poor thermophysical properties, it was required to maintain a lower temperature and high flow rates of air as compared with liquids which increases the operating cost of the cooling system. Other studies were also performed for calculating the fan power requirements for air cooling techniques. As observed from standard fan manufactures of SUNON[11] and DELTA[12], as it delivers the flow rates of the experimental values, it was observed that the magnitude of fan power consumptions was in the order of Watts which consumes more power for providing cooling. Hence the performance of air cooling may be increased by the installation of heat exchangers by exchanging the heat from the hot air side to the liquids at the other side heat exchangers, which in turn reduces the operational cost by nearly 30-40% [13-15] but the space consideration for the installation of heat exchangers remains a problem. Thus, the air cooling does not cater the demand for the high-performance devices with high power flux dissipation due its poor thermo physical properties as compared with the liquid coolants.

2.2 Liquid cooling

Liquid cooling are more beneficial than air coolant due to its better thermophysical properties of liquid coolants as compared with air. Liquid coolants have high heat transfer coefficient as compared with the air and hence provide a better thermal management as compared with air coolant at moderate flow rate. Researches were going on the over the few decades for development of new coolants than the existing one with enhanced thermal transport characteristics and leads to the
evolution of new field of fluids called nanofluids- a nanometre sized particles seeded in the normal coolants. Choi et al [16] first discovered this class of fluids by dispersing the nano sized metal or metal oxide smaller than 100nm in size to the existing coolants viz., ethylene glycol, distilled water, etc. However, the addition of nanometre sized metal to the traditional fluids resulted in enhanced thermal characteristics of the base fluid. Later many researches were conducted on this nanoparticle dispersed coolants and several possible mechanisms were explained for the thermal conductivity enhancement and the effect of thermophysical properties on the inclusion of nanoparticles respectively.

2.2.1 Stability of nanoparticles

Inclusion of nanoparticles into the coolants should remain stable for a long time without any settlement observed. Hence, it is mandatory to prepare a stable suspension with good dispersion of nanoparticles in the coolant. Kumaresan et al [17] mixed 70 vol% de-ionized water and 30 vol% EG as the base fluid and added sodium dodecyl benzene sulphonate (SDBS) as a surfactant with the basefluid for stability and added multi-walled carbon nanotubes (MWCNT) to prepare the nanofluids. The mixture is continuously stirred in magnetic stirrer for 30 min, followed by ultra-sonication for 90 min to ensure the proper dispersion of the MWCNT in water–ethylene glycol mixture. The nanofluids prepared by the above said method seem to be more stable for more than 3 months and, no visible sedimentation was seen. Saeed Zeinali Heris [18] prepared CuO/ethylene glycol–water nanofluids by the two-step method consisting dispersion of dry nanoparticles into the base liquid mixture consists of 60% volume percentage of ethylene glycol and 40% volume percentage of water. First, after preparing the required volume of powder dispersion was carried out by using a mechanical agitator for 6 h, and then the suspension was subjected to ultra-sonication for about 2 h. No precipitation/settlement of nanoparticles was observed after 22 h of settling the suspension. Kiyuel et al [19] observed the sedimentation of copper oxide nano-particles due to the clustering of particles being dispersed. He concluded that sonication of nanofluids for nine hours is the optimum time for better stability of nanofluids.

2.2.2 Thermo physical properties of nanofluids

2.2.2.1 Thermal conductivity

Kumaresan et al. [17] was aimed to measure and analyze the thermo-physical properties of water–ethylene glycol mixture dispersed with CNT nanofluids at various temperatures and found that the thermal conductivity enhances by 19.75% for 0.45 vol% MWCNT at 40 °C. Kwak et al [20] observed the enhancement in thermal conductivity of CuO particles of 10-30 nm in length and ethylene glycol due to particle inclusion. Gallego et al. [21] observed that the thermal conductivity enhances with Al2O3 nanoparticles in ethylene glycol up to 25% in mass fraction using hot-wire method.

2.2.2.2 Density

Mahesh et al [22] experimentally investigated the density with respect to volume fraction and temperature for Al2O3 nanoparticles in DW, EG and DW (75%)/EG (25%) based nanofluids. The result indicates that the density of nano fluids decreases with temperature increment and increases with rise in volume concentration. The density decreases by 1% – 3% respectively from 30 °C to 90 °C. This result replicates the typical characteristics of fluid i.e. decrement in density with temperature increment which has been observed in other varieties of nanofluids.

2.2.2.3 Viscosity
Several researchers analyzed the changes in the viscosity effects due to the inclusion of nanoparticles in the base fluid. It was found that the viscosity enhances with increase in volume concentration and found a decrement with increase in the fluid temperature. Nguyen et al [23] observed the viscosity of alumina–water nanofluids at 4 % particle volume concentration and found that the viscosity value does not change predominantly with 36 and 47 nm alumina/water nanofluids at lower concentrations and the bigger size nanoparticles shows higher viscosity as compared with smaller ones with increase in volume concentration. The similar effect was observed by the other researches on viscosity with the addition of nanoparticles. [24-33]

2.2.2.4 Specific heat

Sheng et al [34] experimentally investigated the specific heat of the water-based nanofluid using with DSC and found that the specific heat of nanofluid shows decrement value with increasing nanoparticle volume fraction and the prediction of the thermal equilibrium model agrees with the experimental values.

2.2.3 Heat transfer coefficient

Owing to the better thermophysical properties of the nanofluids, many researches revealed a better enhancement in the convective heat transfer coefficient which is the most important parameter for the nanofluids to be applied in the thermal management systems. However, the enhanced heat transfer coefficient finds a wider application of nanofluids in all the thermal management sectors with improved performance with increasing flow rate or Reynolds number [35-38]. Xuan and li [39] conducted the experiments on copper water nanofluids and reported that the Nueltt number increases by 60% at 2vol% concentration of nanoparticles. Wen and ding [40] observed the variation of heat transfer coefficient of the nanofluids with respect to the nanoparticle inclusion at the entrance region of the pipe under laminar conditions. Heris et al [41] observed an increment in heat transfer coefficient with respect to nanoparticle inclusion as well as Peclet number for both CuO and Al2O3/Water nanofluids. Vajjha et al [42] observed that the heat transfer coefficient enhances by 120% at 10vol% of aluminium oxide nanofluids and compared the convective behaviour of Al2O3, CuO and SiO2 suspended in EG/Water mixture (60/40) respectively. Apart from metal and metal oxide nanoparticles, extensive research had been performed on carbon based nanofluids which offer better performance as compared with metal and metal oxide nanoparticles. Min-Sheng et al [43] conducted the experiments on Multiwalled carbon nanotubes in synthetic engine oil and ethylene glycol and reported that the thermal transport behaviour was facilitated by the extensive three-dimensional CNT network formed due to the higher thermal conductivities and the larger specific surface area of CNT. Yulong et al [44] carried out investigations on multi-walled carbon nanotubes in aqueous suspensions flowing through a horizontal tube and found that the maximum enhancement reaches about 350% at Re = 800 for 0.5 wt.% CNT. Haisheng et al [45] experiments on spherical titania nanoparticles dispersed in water and ethylene glycol and carbon nanotubes and nano-diamond nanoparticles dispersed in water flowing through a vertically oriented straight copper tube reveals that the convective heat transfer coefficient enhancement exceeds the thermal conduction enhancement to a larger margin. The convective heat transfer deteriorates for titania ethylene glycol nanofluids and aqueous-based nano diamond nanofluids at low Reynolds numbers. Paritosh et al [46] conducted experiments on multi-walled carbon nanotubes suspended in water by 1 wt% in a straight copper tube heated by AWG wire and found that the maximum enhancements in ‘k’ and ‘h’ were observed to be 20% and 32%. Amrollahi et al [47] experiments on FMWNT/water nanofluid flowing through a Uniformly heated horizontal tube indicates that the convective heat transfer coefficient enhances by 33–40% at a concentration of 0.25 wt.% in laminar and turbulent flow conditions. Jyothirmayee et al [48] investigated MWCNT in DI water and ethylene glycol in a electrically insulated nichrome wire wounded stainless steel tube and observed that the maximum heat transfer coefficient enhancements was found to be 65% and 180% for a volume fraction of 0.03% at 56 mL/s for DI water and EG.
Binglu et al [49] carried out the studies on Water-based and ethylene glycol-based MWCNT nanofluids in a Falling film test chamber and found that the enhancement reaches by 20% for ethylene–glycol-based nanofluid. Jianli et al [50] experimentally investigated the Carbon nanotubes/distilled water in a Horizontal circular tube and found that the enhancement reaches by 70% and 190% for 0.05% and 0.24% volume concentration at the Reynolds number of about 120 respectively. Mohammad et al [51] conducted the experiments on functionalized MWCNT-water nanofluid flowing through a double tube heat exchanger and found that the heat transfer coefficient increases by 78%, Nusselt number increases by 36.5 and a 27.3% penalty in the pressure drop are observed for maximum concentration of the nanofluids. Ahmad et al [52] analyzed the behavior of MWCNTs-based turbine oil nanofluids flowing through two layer insulated copper tube with three electrical resistances. The heat transfer coefficient enhances by 48.3% for a volume fraction of 0.1%. Martínez et al [53] experiments on Water based Al₂O₃, SiO₂ and multi-walled CNTs (MWCNTs) nano fluids in a horizontal thermal insulated test-section reveals that the heat transfer coefficient increases on a constant Reynolds number basis, being the enhancement of a 65% for Al₂O₃ and 84% for SiO₂ at Re = 30000 and 5vol%. For the case of 0.1vol% MWCNTs, the enhancement was found to be of a 48% at the same Reynolds number. Tessy et al [54] carried out investigations on hydrogen exfoliated graphene (HEG) - deionized (DI) water, and ethylene glycol (EG) based nanofluids flowing through a stainless steel tube with 108 cm length and 23 mm inner diameter heated by a copper coil. Nusselt number enhancement is predominant than the thermal conductivity enhancement. Hossein et al [55] experimentally studied graphene–water nanofluids flowing through a uniformly heated circular tube and the maximum enhancements are 10.30% and 6.04% for thermal conductivity and heat transfer coefficient. Ahmad et al [56] experiment on Graphene nanosheets / Water in a Shell and tube heat exchanger reveals that HTC increases by 35.1% at 35°C for 0.1% vol frac. Ghozatloo et al [57] studied the behaviour of Ethylene Glycol/ Graphene nanofluid in a straight pipe under constant heat flux and found that the thermal conductivity and heat transfer coefficient enhances by 21.2% and 42.4% with the addition of 0.15wt % of graphene. Emad et al [58] carried out investigations on Graphene nanoplatelet/distilled water in a long stainless steel tube surrounded with heating tape and reported that HTC increases by 13-160%. Hamed et al [59] experimentally studied the graphene nanoplatelet-based water nano fluids in an annular pass heat exchanger and found that the convective heat transfer coefficient increases by 22% at Reynolds number of 17,000 in with 0.1 wt.% of GnP. Mohammad et al [60] experiments on Graphene nanoplates/distilled water in a long stainless-steel tube surrounded with heating tape reported that HTC increases by 80-200% due to increase in k and specific surface area. Based on the above literature review, convective heat transfer behaviour of any coolant will be enhanced with the inclusion of nanoparticles having higher thermal conductivity and this nanoparticle added coolants may be the better choice of cooling methods employed for the electronic circuits to remove the power heat flux.

3 Nanofluids on electronics cooling

Several researches have established the experimental reports on nanofluids operated to remove the power density and heat flux of electronic components. Some of the published literatures were as follows. Based on the reviews of nanofluid operated heat sinks, Lai et al [61] concluded that the electronic cooling system operated with nanofluids serves to be the best option for increasing the performance of the microprocessor chips maintaining the temperature of the chips at the optimum level.

Nguyen et al [62] (2005) conducted numerical investigations on the performance of a high heat output microprocessor with water and ethylene glycol based aluminium oxide nanoparticles and reported that the addition of nanoparticles considerably results in the increasing of heat transfer coefficient and decrement in the maximum junction temperature. It was observed that the heat transfer coefficient increases by 53% with 7.5vol% of nanoparticles to the water for the given heat input of 150W and the maximum junction temperature decreases from 65.8°C to 58.4°C. Similarly, the same
effect was observed in case of ethylene glycol based nanofluids with decrement in the maximum junction temperature from 82.9°C to 67°C. Nguyen et al [63] (2007) investigated the performance of distilled water based aluminium oxide through the closed liquid cooling system of a microprocessor. He reported that the heat transfer coefficient was augmented by 40% with 6.5% of particle volume concentration and observed a decrement in the temperature of the heated component than the base fluid. He also reported the effect of nanoparticle size on the heat transfer behaviour by comparing 36nm and 47nm sized particles. He also concludes that the smaller size nanoparticles of 36nm augment a high heat exchange between the nanoparticle and the liquid phase due to high number of particles and high heat transfer area and hence resulted in a high heat transfer coefficient as compared with the large sized nanoparticles.

Ho et al [64] (2010) studied the thermal performance of a copper rectangular microchannel heat sink using water as a base fluid seeded with alumina nanoparticles. His experiments resulted with increase in the heat transfer coefficient by 70% as compared with the base fluid at 2vol% of seeded aluminium oxide nanoparticles while the heat sink thermal resistance decreases by 28% at the same volume concentration. The heat sink temperature exhibits a decrement of about 25% at 2vol% of nanofluids. He also reported that there is a slight increment observed in the friction factor despite of increase in the dynamic viscosity of nanofluids due to the addition of the nanoparticles. Robert et al [65] (2010) examined the effect of alumina/water nanofluids in a water block for a computational processing unit and reported that there is an enhancement in the conductance value of about 20% when using the alumina nanoparticles of about 20-30nm size. One of the major disadvantage in his experiments was the settling of alumina nanoparticles over a period of time which requires more maintenance of the commercial liquid cooling system.

Khaleduzzaman et al [66] (2014) conducted the experiments on aluminium oxide water nanofluids flowing through a rectangular shape mini channel heat sink and reported the convective heat transfer performance of nanofluids with the heat sink. The energy efficiency was found to be 94.68% for 0.25vol% and the highest improvement in the outlet exergy of the heat sink was found to be 60.86% for 0.25vol%. It was also examined that the friction factor decreases with increase in the flow rate of the nanofluids and increase with the inclusion of nanoparticles. Nazari et al [67] (2014) experimentally compared the thermal performance of two nanoparticles viz., alumina and CNT dispersed in two different base fluid namely ethylene glycol and water respectively. The heat transfer coefficient increases by 6% for the alumina water nanofluids at 0.5vol% but the increment in the heat transfer coefficient for CNT water nanofluids was found to be 13% at only 0.25vol% of the nanoparticles. It was found that the temperature decrement of the CPU was found to be 22% in case of CNT while it was 20% for the alumina based nanofluids. Khaleduzzaman et al [68] (2015) examined the stability effects of alumina water nanofluids by passing through the rectangular minichannel heat sink. He investigated the nanofluids of different concentrations varying from 0.1% to 0.25vol% and concluded that 0.1vol% shows the better performance for cooling the electronics system as compared with other volume fractions in terms of stability by analysing the nanofluids under various factors, viz., microstructure, final particle cluster size, sedimentation, zeta potential, transmission electron microscope, photo capture method. Khaleduzzaman et al [69] (2015) investigated the thermal performance of thin channelled copper water block using titanium oxide nanoparticles seeded in distilled water with 0.1vol%. Results showed that the heat transfer coefficient was augmented by 18.91% as compared with water and the thermal resistance decreases to an extent of about 17.76% as compared with water. The base temperature was maintained minimum with the use of nanofluids and the base temperature decrement was found to be 6.4°C as compared with water. Escher et al [70] (2015) examined the microchannel heat sink performance with aqueous silica nanofluids by varying the concentration up to 31%. He reported that there is a maximum decrement in the thermal resistance of about 22% as compared with the base fluid. The experimental values were found to be converged with the theoretical prediction models and the deviation was found to be lesser than 10%.
He also varied the thermophysical properties of the nanofluids theoretically to evaluate the heat sink performance. To gain a maximum benefit of performance, the thermal conductivity enhancement should be higher than viscosity enhancement due to the addition of nanoparticles. Soheli et al [71](2015) experimentally analyzed the thermal effects of aluminium oxide suspended in water flowing through the custom-made copper minichannel heat sink and found that the heat sink temperature reduces with 0.2vol% of the nanofluids as compared with the distilled water and also calculated that the thermal entropy generation rate decreases by 11.5%. The frictional entropy generation rate increases lighter with the inclusion of nanoparticles. Mohsen et al [72](2016) analytically simulated the model and compared the results with the experimental ones by experimenting the copper oxide nanofluids passed through the heat sink for CPU cooling. He reported that the thermal resistance of the heat sink for CPU decreases about 5.4% when compared with the distilled water for the same flow rate of the nanofluids and heat load. Similarly, the conductance value of the heat sink increases by 7.7% for the investigated mass flow rate and heat load.

Sarafraz et al [73](2017) compared the convective performance of copper oxide and gallium in distilled water experimentally by passing through the Intel core i5 4760 processor liquid cooling system. The experiments were carried out for three different operating conditions of the processor, viz., standby, normal and overload conditions and it was observed that the normal temperature of CPU with air cooling will be around 69-70°C while for the temperature was found to be 67°C, 62°C, and 53.1°C for water, copper oxide and gallium nanofluids. The result shows that the gallium nanofluids exhibits a superior heat transfer performance than copper oxide nanofluids but has higher pumping power of about 51%. Seyed et al [74](2017) analysed the performance of aluminium oxide nanofluids in a circular heat sink for electronic chips cooling. He reported that there is an augmentation in the convective heat transfer coefficient at higher volume fractions of nanofluids and the thermal resistance decreases due to the participation of nanofluids with a little penalty of increasing pumping power with the addition of nanoparticles. Mehdi et al [75](2017) undergone a theoretical simulation study as well as experimental work on three different models for the conventional CPU coolers. He performed the experiments with hybrid composition of graphene decorated with silver nanoparticles on its surface as an operating fluid since no work was being performed with graphene nanofluids in electronics cooling. He simultaneously worked on evaluating the best nanofluids for electronics cooling as well as best liquid block model for cooling. Hybrid nanofluids exhibit a superior thermal performance as compared with the distilled water. While considering the geometries, serpentine liquid block offers a best cooling at a constant Reynolds number but possessing a disadvantage of high pumping power. Distributor liquid block has superiority over the other two liquid blocks due to the flow distribution maintaining a lower temperature of the electronic components. Cong et al [76](2017) studied the thermo hydraulic performance of a CPU coolers with aluminium oxide and titanium oxide-water with concentrations of aluminium oxide from 0.1wt% to 2wt% and titanium oxide from 0.1wt% to 1wt%. The result shows that the Nusselt number increases with addition of nanoparticles and after critical mass fraction, Nusselt number tends to decrease with decrease in heat transfer coefficient. He reported the optimum mass fraction for both nanofluids such that 1wt% for aluminium oxide and 0.1wt% for titanium oxide respectively. The CPU temperature reduces by 23.2% and 14.9% for both aluminium oxide and titanium oxide nanofluids respectively. Mehdi et al [77] (2017) optimized the efficiency of the specific liquid block for CPU coolers operated with aluminium oxide water nanofluids. He reported that the uniform flow distribution results in uniform temperature distribution inside the liquid block and he developed a decision making approach to optimize both minimum processor temperature and minimum pumping power. However he concluded that the higher concentration and smaller size of the nanoparticles is most important for better thermal performance irrespective of higher pumping power. Sarafraz et al [78](2017) analyzed the thermal performance of aqueous carbon nanotubes with concentrations ranging from 0.05wt% to 1.0wt% flowing through a copper made rectangular parallel microchannel heat sink. He reported that the average heat transfer coefficient enhances by 57% at lower heat flux
and there is no significant improvement observed at higher heat flux. Fouling thermal resistance depends on mass concentration and increases with respect to the operating time. Overall thermal resistance decreases linearly with the seeding of nanoparticles increasing the nanofluid concentration. Bin sun et al [79] (2017) studied the thermal performance of copper and aluminium oxide nanoparticles suspended in distilled water by passing through the liquid cooled central processing unit heat radiator. The temperature of the CPU was found to be decreased by 4-18°C. The heat transfer coefficient enhances by 1.1 - 2 times as that of distilled water in case of copper based nanofluids and the value of heat transfer coefficient remains higher than the aluminium oxide nanofluids at the same Reynolds number and mass concentration providing a better cooling performance. Cong et al [80] (2018) experimentally compared the aligned and staggered arrangement of the flow channels in a heat sink operated with titanium oxide nanofluids. He found that the CPU temperature decreases by 10.5% and 12.5% for aligned and staggered arrangement and the titanium oxide nanofluids offers a better thermal performance at 0.4wt %. He also concluded that the mass fraction and the arrangement model does not have any effects on the resistance coefficient at a higher Reynolds number. The various experiments on the nanofluids applied for electronics cooling is as listed in the table 1.

### TABLE 1 Nanofluids on electronics cooling.

| S.no | Author / year   | Nanoparticle/ Base Fluid | Volume fraction | Test Setup | Observations                               |
|------|----------------|--------------------------|-----------------|------------|-------------------------------------------|
| 1    | Nguyen et al /2005 | Al₂O₃/ Distilled water, EG | 7.5%            | High heat output microprocessor | h enhances by 53%                       |
| 2    | Nguyen et al /2007 | Al₂O₃/ Distilled water    | 6.5%            | Microprocessor        | h increases by 40%                      |
| 3    | Ho et al /2010    | Al₂O₃/ Distilled water    | 2%              | copper rectangular microchannel heat sink | h increases by 70% and the thermal resistance decreases by 28% |
| 4    | Robert et al/2010 | Al₂O₃/ Distilled water    | 1.5%            | Water block for CPU   | Thermal conductance enhances by 20%     |
| 5    | Khaleduzaman et al /2014 | Al₂O₃/ Distilled water | 0.25%           | rectangular shape mini channel heat sink | Energy efficiency was 94.68%           |
| 6    | Nazari et al/2014 | Al₂O₃, CNT/ Distilled water, EG | 0.5% for Al₂O₃, 0.25% for CNT | Heat sink | h enhances by 6% for Al₂O₃ and 13% for CNT |
| 7    | Khaleduzaman et al /2015 | Al₂O₃/ Distilled water | 0.1- 0.25%      | rectangular minichannel heat sink | 0.1vol% performs better                |
| 8    | Khaleduzaman et al /2015 | TiO₂/ Distilled water | 0.1%            | thin channelled copper water block | h enhances by 18.91%                   |
| 9    | Escher et al/2015 | SiO₂/ Water              | 31%             | microchannel heat sink | Thermal resistance decreases by 22%     |
| 10   | Sohel et al/2015  | Al₂O₃/ Distilled water    | 0.2%            | custom made copper minichannel heat sink | Thermal entropy generation rate decreases by 11.5% |
| 11   | Mohsen et al/2015 | CuO/ Distilled           | 0.86%           | Heat sink for       | Thermal resistance                     |
| Year | Authors | Fluid Type | Nanoparticles | Volume Fraction | System | Temperature Decrease | Conductance Increase |
|------|---------|------------|---------------|----------------|--------|---------------------|---------------------|
| 2016 | water   |            |               | 2.25%          | CPU cooling | decreases by 5.4% and conductance value increases by 7.7% |
| 12   | Sarafratz et al/ 2017 | CuO, Gallium/ | 0.1%-0.3% | Intel core i5 4760 processor liquid cooling system | 53.1°C by using gallium oxide nanofluids |
| 13   | Seyed et al/ 2017 | Al₂O₃/ Distilled water | - | circular heat sink | Temperature decreases by 53.1°C by using gallium oxide nanofluids |
| 14   | Mehdi et al/ 2017 | Ag decorated graphene/ water | - | CPU coolers | Hybrid nanofluid performs better than the base fluid |
| 15   | Cong et al/ 2017 | Al₂O₃, TiO₂/ Distilled water | Al₂O₃, 0.1-2%, TiO₂ – 0.1 -1% | CPU coolers | Temperature reduces by 23.2% and 14.9% for Al₂O₃ and TiO₂ respectively. |
| 16   | Mehdi et al/ 2017 | Al₂O₃/ Distilled water | 1% - 4% | liquid block for CPU coolers | Higher conc and smaller size of nanoparticles performs better than the base fluid. |
| 17   | Sarafratz et al/ 2017 | CNT/ DI water | 0.05-0.1% | copper made rectangular parallel micro channel heat sink | h increases by 57% |
| 18   | Bin sun et al/ 2017 | Cu, Al₂O₃/ DI water | 0.1%-0.5% | liquid cooled central processing unit heat radiator | h increases by 1.1-2 times for Cu nanofluids. |
| 19   | Cong et al/ 2018 | TiO₂/ Distilled water | 0.5% | Heat sink | CPU temperature decreases by 12.5% |

4 Nanofluids on microchannel heat sink

Owing to the nanofluid performance in electronics cooling, some researchers examined the nanofluid performance passing through microchannel heat sinks that removes the power densities from the electronics. Weilin et al [81](2002) analysed the behaviour of a rectangular microchannel copper heat sink both experimentally and numerically using distilled water. He reported that all the experimental values measured were found good in agreement with the numerical solutions and also concluded that the existing navier stokes and energy equations accurate predicts the heat transfer behaviour of micro channels from the obtained numerical solutions. Reiyu et al [82](2005) experimentally analysed the silicon heat sink of different geometries with copper dispersed nanofluids and compared the solutions with the theoretical models. He found that the experimental result agrees with the numerical solutions and concluded that the performance of the heat sink enhances by using nanofluids. He reported that the thermal conductivity of the nanofluids and the thermal dispersion effect were major possible reason for the enhnacement. It was noted that the pressure drop was not increased since the considered volume fraction was very low and the size of the nanoparticle was small. Seok et al [83](2006) compared the experimental results of two nanofluids of different sizes viz., diamond of 2nm and copper 6nm dispersed in water by using those fluids to evaluate the
performance of a microchannel heat sink. He reported that the cooling performance of the diamond (1 vol%, 2nm) nanofluids on the heat sink enhances upto 10% as compared with water and this nanofluid performs better as compared with the copper based nanofluids.

Tsung et al [84] (2007) theoretically compared the performance of two nanofluids namely copper and carbon nanotubes in distilled water flowing through a microchannel heat sink. The nanofluids enhance the heat sink performance when the porosity of the heat sink and aspect ratio remains low. He numerically arrived at the optimum values of aspect ratio and porosity that leads to a minimum thermal resistance and the nanofluid enhances the performance of heat sink even when the porosity and the aspect ratio values remains lower than the optimum values. Reiyu et al [85] (2007) experimentally analyzed the performance of the silicon micro channel heat sink using copper oxide water nanofluids. He compared the experimental results with theoretical predictions. He reported that the nanofluid performs better in energy absorption as compared with water. It was noticed that the nanofluid absorbs no energy at higher flow rated. The experimentally measured temperature was found in good agreement with theoretical predictions at low flow rate. At high flow rates, the particle agglomeration and deposition results in the deviation of experimental and theoretical values. No penalty was found for the rise in pressure drop across the channel even though the viscosity increases due to the inclusion of nanoparticles.

Mohammed et al [86] (2012) analysed the performance of a rectangular micro channel heat sink with alumina nanofluids both theoretically and experimentally. Heat sink was made with silicon wafer with glass layers for experimental works and eulerian method by finite volume approach was used for numerical study. He found that the values of homogenous model deviates more than the two phase method with the experimental values and the deviation was to be 12.61% and 7.42% for homogenous and two-phase study respectively. He reported that the nanofluid enhances the cooling performance of the microchannel heat sink by 130% as compared with the base fluid. Peyghambarzadeh et al [87] (2014) conducted his experiments on Cu-Be alloy heat sink with rectangular micro channels at a constant heat flux using copper oxide and aluminium oxide nanoparticles dispersed in distilled water. He experimentally determined that the nanofluid enhances the heat transfer performance of the heat sink and the heat transfer coefficient enhances by 27% for 0.2vol% CuO nanofluids and 49% for 1vol% of Al2O3 nanofluids respectively. He concluded that the copper oxide nanofluids shows superior thermal performance as compared with the aluminium oxide nanofluids since it can be used in lower volume concentrations only for the better performance. Yasser et al [88] (2014) conducted his experiments on titanium oxide nanofluids of 10nm size flowing through a vertical annulus tube under non-uniform heat flux designed for the flow through the nuclear fuel rods in non-radiating environment. It was found that the nanofluid of low volume concentration (less than 0.005) has no effect on the thermal transportation performance. The value of heat transfer coefficient gets doubled at 1.5vol% of nano particles as compared with the base fluids. Benjamin et al [89] (2014) analyzed the performance of micro channel heat sink with copper oxide water nanofluids of three different concentrations viz., 0.24vol%, 1.03vol% and 4.5vol%. Pressure drop increases abundantly by about 70% when 4.5vol% was used while it was lower about 30% for 0.14vol%. Lower concentration of 0.24vol% shows a better heat transfer performance and best energetic performance as compared with the other higher concentrations of nanofluids.

Balaji et al [90] (2020) performed the experiments on functionalized graphene nanoplatelets dispersed in deionised water flowing through the rectangular microchannel heat sink. The text was carried out in the laminar region through the microchannel. The behaviour of graphene nanofluids in the cooling of electronics chips was experimentally simulated with the heat load varying from 50W to 200W. The thermophysical variation of graphene nanofluids with temperature variation and nanoparticle addition was also studied in detail. The thermal conductivity enhances with the seeding of graphene nanoplatelets and thereby the heat transfer coefficient and Nusselt number enhances upto 71% and 60% respectively. The nanofluid reduces the heat sink base temperature by 10°C which
promotes this graphene nanofluid as a promising coolant in the cooling of electronic chips under various operating load conditions. The various experimental works on nanofluids passing through the microchannel heat sink is as listed in the table 2.

**TABLE 2** Nanofluids on microchannel heat sink.

| S.no | Author / year | Nanoparticle/ Base Fluid | Volume fraction | Test Setup | Observations |
|------|---------------|--------------------------|-----------------|------------|--------------|
| 1    | Weilin et al/ 2002 | Distilled water          | -               | a rectangular microchannel copper heat sink | Experimental and theoretical predictions found in good agreement |
| 2    | Reiyu et al/ 2005 | Cu/ DI water              | 0.3%, 1%, 2%    | Silicon heat sink | h enhances due to thermal dispersion effect |
| 3    | Seok et al/ 2006 | Diamond-2 nm copper- 6nm/ DI water | 1% | microchannel heat sink | Cooling performance enhances by 10% |
| 4    | Tsung et al/ 2007 | Cu, CNT/ distilled water | 2%, 4%         | microchannel heat sink | Optimum values of porosity and aspect ratio enhances thermal performance |
| 5    | Reiyu et al/ 2007 | CuO/ distilled water | 0.2% - 0.4%    | silicon micro channel heat sink | Particle agglomeration and deposition deviates the experimental values from theoretical predictions. |
| 6    | Mohammed et al/ 2012 | Al₂O₃/ Distilled water | 0.1%, 0.2%     | rectangular micro channel heat sink | Experimental and theoretical predictions deviate within 7.42% |
| 7    | Peyghambarzadeh et al/ 2014 | Al₂O₃, CuO/ Distilled water | 0.2% for CuO, 1% for Al₂O₃ | Cu-Be alloy rectangular micro channel heat sink | h enhances by 27% for 0.2vol% CuO nanofluids and 49% for 1vol% of Al₂O₃ nanofluids |
| 8    | Yasser et al/ 2014 | TiO₂/ Distilled water | 1.5%           | vertical annulus tube under non uniform heat flux | h value gets doubled as compared with basefluid. |
| 9    | Benjamin et al/ 2014 | CuO/ distilled water | 0.24vol%, 1.03vol% and 4.5vol% | micro channel heat sink | h enhances at lower conc of nanoparticle at 0.24% |
| 10   | Balaji et al/ 2020 | GnP/Distilled water | 0.01%, 0.05%, 0.1%, 0.15%, 0.2% | Copper microchannel heat sink | h enhances by 70% at higher heat load of 200W |
5 Conclusion

From the above review, it was observed that the aqueous CNT nanofluids were found to be the promising coolant among the other nanofluids due to the plausible better heat transfer characteristics. The maximum temperature difference for 0.1vol% aqueous CNT nanofluids was found to be 24°C at higher power density of 275W [78]. For the same, the enhancement in ‘h’ was found to be 57% as compared with the basefluid. However there still exists a demand for cooling with increase in processing speed and it was expected that the power density will reach about 360W in 2020. Hence, it is mandatory to choose a coolant with better performance characteristics than the existing fluid for cooling of electronics chips providing the enhanced temperature difference optimizing several parameters such as reduction in size, increasing operational time, increasing speed, cost of the coolant etc. Studies revealed that the micro channels operated with nanofluids serves as a better promising technology for the cooling of electronics in the upcoming generations increasing the performance of electronics. Extensive studies are to be made for choosing the best nanofluids on the electronics cooling for commercial scale applications in all the industrial sectors.

NOMENCLATURE

vol% - volume percentage

\[ C_{p,nf} = \text{nanofluid specific heat capacity (kJ/kgK)} \]

\[ k = \text{thermal conductivity of the nanofluids (W/mK)} \]

\[ \text{Nu} = \text{Nusselt number} \]

\[ \text{Re} = \text{Reynolds number} \]

\[ \phi = \text{volume fraction} \]

ABBREVIATIONS

GnP = Graphene Nano Platelets

MWCNT = Multi Walled Carbon Nano Tubes

CHTC = Convective Heat Transfer Coefficient

DI water = De-ionised water

EG = Ethylene Glycol

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