Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

FOUNDATION and FUNCTIONING of HEAT-SINK SOLUTIONS and COOLING APPROACHES

Hawraa Khalaf Al_moussawi[1] , Hussein Awad Kurdi Saad[1*], Ahmed Salim Naser Al-Murshedi[1]

[1] Power/Mechanical Engineering Department, Engineering Technical College of Al-Najaf, Al-Furat Al-Awsat Technical University (ATU), Najaf 54001, Iraq

E-mail: husseinawad@atu.edu.iq, Ahmed.al-murshedi@atu.edu.iq

[*]Corresponding author E-mail: husseinawad@atu.edu.iq

Abstract. *The fast expansion of Information and Communication Technology (ICT) requires data centers to operate as essential facilities for handling large volumes of data processing and management functions. The heat dissipation system represents a significant part of data centers because it protects electronic components through heat dissipation to guarantee their reliable performance. This exploration examines cooling approaches including air systems and liquid instruments for their implementation as heat sinks for electronics. Using finned heat sinks for air cooling represents the dominant method because of its stripped-down design and economical value. Computational methods through liquid cooling that incorporate nanofluids boost heat transfer abilities yet demand expensive implementation and technical complexity. The analysis reviews different heat sink structures such as plate fin and pin fin and microchannel systems to evaluate thermal performance alongside mechanisms affecting heat transfer efficiency including geometry details and fluid movement dynamics and material choice choices. The article explores how nanofluids and phase change materials (PCMs) provide enhancements for heat management performance. Unlike previous reviews that focus on isolated cooling technologies, this comprehensive analysis integrates both traditional and emerging solutions while considering their practical implementation constraints in data center environments. The collected data demonstrates that air cooling remains prevalent but liquid cooling systems and innovative materials including nanofluids and PCMs deliver superior thermal performance specifically for powerful electronic devices, ultimately suggesting a hybrid approach may offer the optimal balance between cooling efficiency and operational costs.*

Keywords: Phase change materials (PCM), nanofluids, heat sink.

1. INTRODUCTION

Information communication technology (ICT) depends on data centers as its central processing and exchange unit which handles information storage and data transmission. The rapid progress of computer technology coupled with soaring data handling requirements permits modern data facilities to sustain powerful electronic sections which produce enormous thermal outputs. The intense rise in server and switch heat production creates major obstacles for thermal management systems because these devices require separate spaces known as data centers to contain their growing electrical intensity and heat output. Proper control methods need to manage the heat output because excessive heat poses risks to reliability and efficiency [1, 2, 3].

The current heat dissipation needs become even more difficult due to diminishing hardware sizes and rising processing speeds which lead to performance areas that exceed temperature limits unless proper management methods are adopted. Economic efficiency depends on the cooling process which serves a technical function and extends beyond technical specifications. More than thirty percent of the operational expenses in data center facilities go towards their cooling solutions. The design process of these structures needs immediate solutions for cooling because this factor stands as a fundamental question. The heat sink controls heat dissipation as its principal component especially the CPU-based one functions as the primary heat removing element [2]. Heat sinks serve as the fundamental components for extracting heat from sources and electronic components because their absence would lead to continuous temperature rise and reduced functional capability and operational life of electronics. Data center infrastructure needs new cutting-edge cooling systems to overcome physical restrictions of traditional cooling solutions since it must support growing computing intensity. The following work examines multiple heat sinks along with conventional and modern techniques used to handle electronic systems heat. The new heat sink technologies together with nanofluids and phase change materials show great potential for enhancing heat transfer rates according to research [4].

This study investigates questions which analyze literature about heat sink performance together with cooling method comparisons and current gaps in the field of knowledge. This paper proposes to complete those knowledge gaps with the intention of enhancing current thermal management practices. This research establishes a complete analysis of modern data center heat sink technologies and cooling approaches to offer solid recommendations about thermal management optimization between performance and energy usage and operational expenses.

There is an escalating demand for proper thermal control of both data centers and electronic products. With this background, the author is ready to further discuss heat sink technologies and their influence on cooling efficiency to emphasize the importance of these heat sinks in conserving and enhancing the efficiency of present-day ICT equipment. The significant impact that heat sinks applications have as far as thermal management of electronic equipment most especially in data centers.

This paper specifically examines a number of cooling methods and materials for use in heat sinks especially in relation to electronic equipment like PCs and data centers. Here are the key findings from the reviewed literature:

Heatsink are important element in controlling thermal loads produced by super electronic appliances especially the server next to which data centers are frequently built to enhance heat dissipation to prevent system breakdowns. The research further shows that IT equipment’s and cooling mechanisms cost of approximately 30% of the general operational costs in a regular data center.

Jet impingement cooling has therefore developed into what could be considered as one of the best ways of cooling a CPU. The studies show that raising mass flow rate of the coolant, along with decreasing the diameter of the nozzle and the width of the flow channels results in high heat transfer rate which leads to lower temperatures of the central processing unit.

Nanofluid coolants especially those containing TiO_2 nanoparticles have provided an excellent opportunity to enhance thermal conductivity as compared to the typically used water coolant. As it stands, this is especially beneficial with mini-pin fin heat sinks, as the research has shown that the use of nanofluids enhances the Nusselt number, albeit with the added drawback of higher pressure drop differences than that of air or water cooling [4].

Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

Heat and mass transfer characteristics of heat sinks have also been studied in context to Phase Change Materials (PCMs). The thermal performance of a number of PCMs has been evaluated orderly, including n-octadecane, due to the relatively low melting point of the solid [5].
In the present study, authors found that the arrangement of fins plays key role in their thermal characteristics. Heat transfer studies have been made in comparing between staggered and in-line arrangements of the arrays of cylinders with comparative higher heat transfer rates being observed for staggered mode but at the expense of higher pressure drop. Basic characteristics of the fins are therefore paramount in establishing the Nusselt number and summary [6].
Consequently, both experimental and numerical studies of the thermal-hydraulic performance of diverse heat sink configurations have been undertaken. Different Computational Fluid Dynamics (CFD) software like ANSYS CFX has been used to analyses heat transfer and fluid flow through heat sinks not only to assess the geometry of heat sink on its performance but also to improve its design [8].
This has been proven through the calls for the advanced investigation of the suitable cooling media and approaches for the thermal control of electronic machines. New generations of heat sinks with advanced material, such as nanofluids and PCMs together with various geometries should be considered in order to enhance heat transfer and meet the thermal requirement of new complex microelectronic systems.

It is necessary to admit that more and more sectors in the contemporary society – from education to business, transportation, and social networks – incorporate Information and Communication Technology/components (ICT). As a result, data center, which essentially forms the ICT infrastructure by processing, managing, storing, and sharing a large amount of data, has emerged as highly crucial (Zeadally et al., 2012). A data center comprises four core components: electric loads which include power distribution unit and batteries, cooling loads such as chillers, CRAC units, Information Technology loads which comprises of accesses servers, storage devices and networking equipment, miscellaneous loads including lights and fire protection systems (Dai et al., 2014).
First, these electronic systems are mostly designed to handle, store and send data and this in the process creates a lot of heat. The cooling problem is crucial for avoiding overheating and equipment failure – it is cited that more than one third of the costs of most conventional data centers' cooling are associated with IT and cooling equipment (Sahin et al., 2005; Dai et al., 2014).
Heat sinks are very essential in server designs. Finned heat sinks can be divided into two main categories: The types of LCGAs covered are plate fin heat sinks (PFHSs) and pinned heat sinks (PHSs). These components are made of high thermal conductivity material like copper and Aluminum if cost and making feasibility allows. Heat sink technology is fast gaining acceptance over the last few years mainly because of the low cost of acquisition, easy installation, and consistent production techniques (Chingulpitak, 2015).
For cooling heat sinks and servers there are several types of liquid coolants: water, nanofluids and dielectric liquids including Hydrofluoroethers, HFE. Other direct contact liquid cooling methods such as submerging servers in dielectric fluid have been proposed and examined (Tuma, 2010; Almaneea, 2014).
Compared to liquid cooling, there are drawbacks associated with it such as increased pressure drops and risks such as leakage leading to damages in the electronic devices a factor that leads to data centers loses (Naidu & Kamaraju, 2009; Alkasmoul, 2015).
However, all these drawbacks do not deter air cooling from being the most widely used thermal management technique because of the low costs of the system and the ease of designing it. A plethora of active air-cooled devices is used, mainly heat sinks with fans; however, they are inferior to liquid cooling in terms of heat transfer coefficients.

From the literature review above, the researchers identified several research papers reviewing on air cooling methods. Kim & Kim (2009) described and investigated the impact of cross-cut fins on cooling electronic devices, evidence the single cross-cut heat sinks provide the better thermal resistance than multiple cross-cut designs. In their study, Didarul et al. (2007) looked at the effect that the orientation of fins has on heat transfer within a turbulent air stream while Zhang et al. (2005) studied the heat transfer with micro rectangular plate fin integrated with de-ionised water as a coolant.
Recent works have focused on refining heat sink designs, among them Arularasan and Velraj (2008) and Ko-Ta (2005), the factor affecting the performance of heat sink that have been select are fin height and air speed. The study also seeks to determine the impact of fin type such as pin and plate fins on heat transfer and pressure drop performance.
Some of the innovations which were considered include the use of nanofluids for cooling, where such a system exhibited better thermal characteristics as compared with conventional systems. For example, Naphon et al., (2010, 2011, 2013) showed that the flow rates of heat by mini-pin heat sinks with nanofluids were greatly improved.
Altogether the document reiterates the centrality of heat sinks in data center climate control, comparing different cooling approaches, the growth of heat sink utilization, and the ongoing efforts in augmenting thermal control in electronics. This all-encompassing analysis highlights the significance of thermal control in sustaining the dependability and performance of data centres in a rapidly computerised environment.
Finned heat sinks can be categorized into two primary types: the plate fin heat sinks (PFHSs) and pin heat sinks (PHSs) as shown below in Fig 1.2. Numerous companies all over the world make heat sinks among which are giant firms such as Airedale Company of Great Britain or Raypak Company of the USA and small companies as well. Base materials to construct them mostly include very good thermal conductivity such as copper and aluminum depending on aspects such as cost and fabrication. In the recent past, the technology connected with heat sinks equipment used for electronic cooling has become fashionable, because construction of this equipment has low first cost, simple installation and constant dependence of manufacturing processes (Chingulpitak, 2015).
Liquid cooler solutions are used for heat sinks and servers in data centers and include water, nanofluids, polymers as well as dielectric liquid – Hydrofluoroethers (HFE).
Coelbearing techniques may be direct as where servers are submerged in dielectric fluids (Tuma, 2010; Almaneea, 2014) and the indirect where cooled fluids are circulated over heat sinks atop chips or integrated into the server as heat exchangers (Villa, 2006). Liquid cooling has one critical advantage over air cooling due to the fact that the liquids themselves possess higher conductivity and capacity for heat. Furthermore it is electrical insulating medium that minimizes possibilities of electrical discharge (Naidu and Kamaraju, 2009; Alkasmoul, 2015).
Nevertheless, there are some difficulties in using liquid cooling, the main of them are pressure drops, and increased pumping power, as a result of higher viscosity and density of the fluids in comparison with air. Leakages are dangerous to the circuit boards and other electronic parts hence pose threats of data center losses while humidity pours risks to systems. It incurs greater cost in maintenance and installation which also increases the need to invest in fixed assets such as piping, leak detection and insulation (Villa, 2006; Naidu & Kamaraju, 2009). As a result, air cooling still represents the most widely used approach for thermal management in electronics, because of the lower costs, ease of implementation, and simplicity of the air cooling design. Heat sinks that include fan or blower equipment actively cool air-cooled devices by transferring heat from the source out into the surrounding air making them compulsory heat exchanger of the air cooling system. This method is time-saving, easy to implement and inexpensive (McMillin, 2007).

ATU-FJIMSE, Volume 2–Issue 1 –20 , March , 2025,

However, air cooling system has poor heat transfer rate compared to the liquid cooling system. An improvement in the heat transfer rate can be obtained either by the fan speed or the heat sink surface temperature. But this increases the fan speeds seeking certain benefits may reduce the reliability of a device and consume more power or produce loud noises undesirable in an office space or home. Likewise, when the temperature is increased, the performance of the central processing units (CPUs) is reduced while the operational life is decreased.

Definite merits of finned heat sink configuration are evident from the use of finned heat sink for enhancing forced heat transfer and fluid flow in micro and macro applications including the cooling of large-scale datacom equipment, personal-computer processors, and other electronics devices. Thus, it imperative to conduct a literature review on this topic.

Three case studies where air was used as coolant include the following; Kim & Kim; Didarul and his team (Didarul et al) ; and Naphon & Khonseur. Kim & Kim (2009) investigated cross-cut fins and their capacities to cool electronic parts and determined that the single cross-cut heat sink is more efficient than multiple cross-cut designs. Furthermore, lower thermal resistance of 5 – 18% and 14 – 16% was observed in cross-cut heat sinks than in pin and plate fin heat sinks.

Using flow visualize and heat transfer measurements, Didarul et al. (2007) investigated how the leading edge angle of short rectangular plate fins impact on enhancing heat transfer rates and air flow patterns within a duct operating under turbulent state. The study focused on two configurations: co-angular and zigzag orientations of the fins, shown in Fig. 1.4. On the other hand, Zhang et al. (2005) discussed on integrated system cooling in which packages of the chips of 12×12mm and 10×10mm used micro rectangular plate fins and deionised water as the cooling medium. Their findings were that while flow rates were relatively low, the pressure drop and the temperature and thermal resistance of the chips they tested went low as well. In particular, the 10×10mm chip was characterized by a higher sum of the rectangular thermal resistance compared to that of the 12×12mm chip.

In their study, Arularasan and Velraj (2008) aimed at studying the best design characteristics of parallel flat plate fin HSs under turbulent flow regime. Their findings enumerated certain characteristics- fin height, fin thickness, fin pitch, and base height that help in reducing base temperature, thermal resistant and pressure drop.

A similar study was conducted to examine optimum cooling designs of parallel plate fin HSs used in desktop CPU employing Taguchi method, Ko-Ta’s (2005) finding indicated that air speed and fin flake gap affected the cooling characteristics substantially. The base temperature was originated to reduction by 8°C, with a total temperature decrease reaches 15%.

Furthermore, Velayati & Yaghoubi (2005) concentrated on evaluating the impact of fin blockage ratios (D/W) and Reynolds numbers on turbulent traits of flow and heat transfer in plate fin HSs. Based on their findings, they pointed out that both augmentation of D/W ratio and Reynolds number enhanced Nu and reduced the f factors. These parameters were also reduced to improve the efficiency of fins (qwith fins/qwithout fins).

Other fin heat sink types investigations were also carried out by Ndao et al. (2009) using water and dielectric liquid HFE-7000. arse included micro-plate channels, circular pin HSs staggered and in-line circular pin hole size distributors, and strip fin hole size distributor designs as illustrated in Fig 1.6. Optimizing was done for least value of total thermal resistance and pumping power; analysis expressed that strip fin HSs possessed least value of thermal resistance than staggered circular pin and in-line circular pin HSs.

ATU-FJIMSE, Volume 2–Issue 1 –20 , March , 2025,

Although there have been numerous attempts to optimize plate fin heat sink (for example Chiang (2005), Velayati and Yaghoubi (2005), Arularasan and Velraj (2008)), there are some restrictions on the flow development which provides smooth airflow through channels of heat sink: boundary layer effect limits heat transfer rates. On the other hand, pinned heat sinks (PHSs), as depicted in Figure 1.2B are shown to be a potential replacement practical solution for controlling the thermal boundary layer development, which hinders heat transfer in plate fin arrangements (Zhou & Catton, 2011).
The only difference in the current heat sinks classification is the pressure drop and the heat transfer rate; PHSs has a higher pressure drop while having lower thermal resistance and average temperatures than plate fin HSs. To identify different pin cross-section, Jonsson & Moshfegh (2001) and Yang et al. (2007) used the square, circular, hexagonal, diamond, elliptical, and operated the pin with air and water coolant. A paper by Vanfossen & Brigham (1984), Tanda (2001), Jeng & Tzeng (2007), Jonsson & Moshfegh (2001), Yang et al. (2007), and Sahin et al. (2005) on air cooling concluded that circular and elliptic pin configurations demonstrate work the best for heat transfer coefficients and thermal resistance. Further, higher pin density improves the heat dissipation rates but results in larger pressure increases in solid pinned heat sinks. In general, staggered pin arrays are found to be better than in-line arrays with regards to heat transfer coefficients and pressure drop.
Tanda (2001) studied the application of diamond shaped pins for different engineering purposes and Jeng & Tzeng (2007) dealt with square PHSs. As in the case of both investigations, it has been static that staggered pin arrangement provides the highest Nusselt number and pressure drop. Equally Pin comparisons made by Jeng & Tzeng (2007) showed that pressure drop and Nusselt number related to pin spacing and Reynolds numbers by showing a higher rate of pressure drop in a staggered square pin than the in-line one.
Jonsson & Moshfegh (2001) discussed the effect of various fin geometries such as plate fines, strip fines, square pin fines and circular pin fines for both in line and staggered configurations observing that Nusselt number and pressure drop was affected by pin heights, thickness and spacing. The types of heat exchangers with the least pressure drop results were the plate fins while circular PHS were less than the square PHS.
Yang et al. (2007) discussed the pin shape and density of both in-line and staggered arrangements for heat transfer and pressure drop analysis, with circular pins in a staggered orientation providing the study’s greatest average heat transfer coefficients. On the other hand, elliptic pins had the lowest pressure drops for staggered pin arrangements a little higher than that of circular pins.
Sahin et al. (2005) looked at the geometric characteristics of HS fins is important in electronic cooling system. Their optimal design revealed the proper fin dimensions and angle that need to be completed. Furthermore, it has also been revealed that both simple water and nanofluids can cool electronic systems. The study conducted by Naphon & Nakharintr (2013) showed that the heat transfer coefficient and thermal conductivity when employing TiO_2 nanofluid are much higher as compared to those of the water naphon & Nakharintr 2013. They also shed light on the advantages of using techniques such as jet cooling in a microprocessor, for managing temperature of CPU.

Naphon et al. (2010, 2011, 2013) investigated laminar water and nanofluid flow minipin heat sinks for CPU cooling. Their earlier works also used the concepts of jet flow, on the other hand, the later study used cross-flow methods. In general, their experiments demonstrate that the heat transfer rates and Nusselt numbers are higher with nanofluids than with air and water cooling techniques but at the cost of higher pressure drops.

Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

Naphon & Wongwises (2010) utilized mini-rectangular pin heat sinks made of copper for cooling of CPUs under study of jet impingement heat transfer; they found that CPU temperature drops with the decrease of channel width and nozzle diameter. Based on the results indicate that the most significant reductions in temperature was observed in full load condition.

Naphon & Wongwises (2011) too investigated the enhancement of jet nanofluids on CPU cooling using mini-channel HSs; the results obtained presented that the average CPU temperatures were reduced effectively of coolants by using TiO2 nanofluid than the jet water and conventional coolants. Moreover, they verified that finite element method in nanofluids exhibits higher thermal conductivity and capacity, which can enhance the heat trapping and transmitting.

Naphon & Nakharintr (2013) compared the impact of the channel height on the rates of heat transfer in mini-rectangular fin heat sinks utilizing TiO2 nanofluid, and discovered that heat transfer rates as well as Nusselt numbers enhance increases in channel height beyond the performance of water in terms of thermal resistance.

Ramesha & Madhusudan (2012) further studied about pin heat sink design modifications on laminar forced convection heat transfer and state that the square twisted pins with various angles improve the heat transfer rates much higher than those of the straight pins. Soodphakdee et al. Information obtained from cross sectional fins indicate that the elliptic cross sectional fins gives the greatest heat transfer co efficiency at less pressure drop while circular pin cross sectional fins at greater pressure drop.

Mohan & Govindarajan (2010) also pointed out that computer desktop CPU heat sinks, with both plate and pin fin heat sink configuration, afford the best thermal efficiency, furthermore as plate thickness increases, as well as pin fin thickness increases the thermal performance will also increase. That is they discovered that copper base plates provide improved thermal resistance reduction in comparison to aluminum albeit at a higher cost and with more weight. Consequently, their investigation reveals the constraints arising from the trade-off beween thermal conductivity and material selection in heat sink design.

The behaviour of turbulent flow and heat transfer in heat sinks has been described and modelled by many investigators. In particular, research by Naphon et al. (2009 and 2011) and Mohan & Govindarajan (2010) may be inestimable.

In their first paper (2009), Naphon et al analyzed the effect of varying channel width of mini-square pin heat sinks (PHS) for CPU cooling used de-ionised water as the coolant. From their study they identified that flow structure and behavior of the working fluid was not uniform across the mini-heat sink. Such non-uniformity was found to be related to deviations in liquid velocity because pressure and temperature fields of the heat sink were heavily governed by it. The investigation also revealed that the direction and distribution of velocity at the inlet plenum also influenced the flow pattern in the mini-heat sink.

The next study (2011) focused on the effect of outlet port location on jets' heat transfer and the fluid flow in two models of the same mini-square fin heat sink; Model A and Model B. The findings showed that B model offered higher velocity of the fluid flow, more uniform temperature than the A model, and thus better heat transfer co-efficients and performance level generally. They noted that uniformity in temperature distribution plays an essential role as a means of enhancing the thermal effectiveness of mini-heat sinks.

Numerical and experimental work on PCPFHSs has been undertaken by Yu et al. in 2003, 2004 and 2005 to include circular pin fins alongside plate fins. Their results showed that the PCPFHSs had a thermal resistance of about 30 percentage lower than that of the conventional PFHS. Although this has improved the performance of the PCPFHSs, it has tripling pressure drop across the elements of these coal-fired power plants. Also, we found that the performance profit factor (Q/Pfan) of PCPFHSs was higher by about 20 per cent than of PFHSs.

Two papers from Yang & Peng in 2009 are Array thermal and pressure drop characteristics of PCPFHSs in inline and staggered patterns In these papers, two aspects of compact heat sinks were investigated: Thermal Performance of The PCPFHS array and Pressure drop of the PCPFHS Array. They have concentrated on studies showing that low and tall pin heights would improve the heat sink system. Collectively, these studies demonstrate that most of the design parameters, flow dynamics and thermal performance exist in complex correlation, which is significant for future investigations and utilization of heat sinks cooling technology.

Through experimental and computational analysis using ANSYS-CFX-12, Adnan et al., (2014) assessed the effect of pressure drop and thermal performance with holes on the pin fin. The dimensions of the channel were specified as follows: cross-section width of 62 mm, depth, l= 167 mm and length of the channel L=1200 mm. All the experiments were carried out for mainstream Reynolds numbers varying from 28000 to 113000 for solid pin fins and pin fins with HV holes and for pin fins with HLV holes. It was noted that the Nusselt number (Nu) of the HV pin fins was about 11% greater than the solid pins. On the other hand, over fifty percent solid pins and hollow low vertical (HLV) pin fins could achieve an increase in Nu as high as 21% than the basic flows. Additionally, for HV pin fins a pressure drop was decreased by 23% compared to solid pins and for HLV pin fins a decrease of about 19% was received regarding to solid pins. However, the performance characteristics of HLV pin fins were higher with a reduction in weight where up to 21.65wt% reduction versus solid pin fins were realized. Such correlations were formulated for analysis and prediction of heat transfer and pressure drop features in the examined configurations.

The quantitative comparison demonstrated that Integrated in terms of magnitude the velocity vectors appear to be more intense in HLV pin fins than in HV pin fins. This was credited to the fact that the lateral perforations lowered pressure into the horizontal holes as well as improving the flow path. Further, the HLV perforated pin fins produced relatively low surface temperature than both the solid and HV perforated pin fins. It was revealed that the numerical results are in good compliance with the experimental data.

In an earlier study, Hossein Lotfizadeh et al. (2015) conducted a series of experiments to assess the thermal performance of four types of heat sink including the extruded longitudinal fin, aluminum nanoparticle extruded longitudinal fin heat sinks and rectangular blocks of metallic aluminum foam. The four heat sinks were of equal size and dimensions (9 × 16 × 3.5 cm) and the heat transfer enhancement materials used for them were spherical, monodisperse aluminum-based nanoparticles of 10 n, nano-coated aluminum metal foam, and uncoated metal foam. The cooling was done using limited airflow from the ambient at a velocity level of 1.17 m/s.

Collectively, these studies aim at highlighting the progress of heat sink design subject to high rate of thermal performance density, low pressure drop, and light weight.

Techniques for analyzing heat transfer processes in microchannel heat sinks (MCHS) are especially important due to the fact that flow patterns define thermal efficiency. Thus, in order to analyse temperature and velocity profiles accurately, a more sophisticated diagnostic approach like Laser Induced Fluorescence (LIF) & Particle image Velocimetry (PIV) were used. Thus nanofluids challenge the existing heat transfer fluids because of the superior energy carrying capacity. This is because changes in the viscosity and thermal conductivity of the nanofluid, as well as the changes in concentration of the nanofluid, affect an enhancement of the capacity of the nanofluid. After holding for 20sec, temperature and velocity information were carefully noted down in order to capture the static nature of both temperature and velocity gradients over the holding period.

Experimental details of the subsequent studies of the observed and predicted behavior of the melt front were documented in Kothari et al. (2021) where photographic observations helped the authors in understanding the change and spread of the melt front within the heat sink configuration, especially in the context of designing a phase change material (PCM) based thermal management system and the impact of nanoparticle concentration and fin quantity on the proposed thermal architecture. Tin derived PCMs from paraffin are advantageous in electronic applications since they feature high heat capacity and non-toxicity in addition to their high melting point and chemical stability. Power dissipation analysis, used three different heat sink models, one of which had no fins, and the other two, one fin, and three fins actuall, all models were of the same geometry 110 × 110 × 27 mm. Paraffin and aluminum wax were used as base material for heat sink, and different weight percentage of Al_2O_3 nanoparticles (0, 2, 4, 6 wt%) were used. The simple heat sink with three fins molded from PCM was found to have the longest operating time of 6,470 seconds. The use of nanofluids also found to give maximum reductions in melting time of 9%, 13% and 26% it confirms that the nanofluids are effective if they were used at low nanoparticle concentration for heat sink with SPT at 60 °C. The highest enhancement ratio of 1.48 was obtained when the heat sink was made unfinned with 2% nanoparticles filled PCM at the set point temperature of 60 °C, while pure PCM provided enhancement ratios of 1.35 and 1.32 when heat sink set point temperature was varied at 65 °C and 70 °C respectively.

Ozbalci et al. (2022) numerically analysed forced convection in a single-phase liquid cooling system with two different types of heat sinks which are plate fin and pin fin embedded within a water block for application to electric system. They employed volumetric flow rates of 100 – 800 ml/min as well as heat fluxes of 454.54 W/m² – 1818.18 W/m² with both pure water and a 0.1% Al_2O_3-H_2O nanofluid as the cooling fluids interacting with aluminium heat sinks of 2.5 × 2.5 × 1 cm in external dimensions. The maximum thermal enhancement values were recorded as 56.4% for pure water and 70.27% for nanofluids over the pin-fin geometry. Regarding the improvement in heat transfer efficiency gains reached 9% for the base fluid, and as much as 12% for the nanofluid. In addition, the efficiency raised about 1.6 % , 1.55% at volumetric flow 100 ml/min for plate and pin fin configuration respectively and at flow rate 800 ml/min it reduce up to 1.1% for both plate and pin fin configuration. The authors pointed out that the pressure drop was higher in the nanofluid applications because of high viscosity and large surface area.

Tiwary et al. (2022) performed a numerical analysis into the flow characteristics of nanofluids in microchannels of heat sinks with oblique fins. They dealt with flow Reynolds, Re, of 100–300 and employed both experimental and numerical techniques to examine the heat transfer effectiveness of aqueous nanofluids having volume concentration from 0.5% to 2.0%. Two heat sink designs were compared: an oblique fin heat sink (OFHSMC) with the inclination angle 27° and a straight fin heat sink (SCHSMC) with similar hydraulic channel size. The RNG-k model was used in cyclic and full field simulations using the standard packages present in Fluent. The oblique fin configuration encouraged secondary flow, which is essential in improving heat transfer performance since it descends straight down within the fins of the secondary passages and breaks up the thermal boundary layer as well as initiating vortices as it rises up in the secondary channels. The enhancement in thermal conductivity of the oblique fin nanofluid heat sink was found, which increased the heat transfer coefficient by 2% higher at Re=300. In conclusion with the inclined fin heat sink design, the mean temperature was lower than that of the straight channel heat sink. This research aims to establish performance criterion with energy usage and expenditure consideration by evaluating the effectiveness and efficiency of different heat sink technologies along with cooling approaches suitable for contemporary data centers.

ATU-FJIMSE, Volume 2–Issue 1 –20 , March , 2025,

Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

CONCLUSIONS

Research reveals that thermal management ensures electronic device reliability and efficiency within data centers plays an essential part. The use of finned heat sinks with air cooling remains the main choice because it offers both efficiency and low cost. Air cooling faces constraints with poor thermal transfer rates because noises from operation prompted researchers to evaluate different cooling solutions. Liquid cooling systems using dielectric liquids and nanofluids offer enhanced thermal performance because they enable both increased thermal loads handling and greater heat transfer capacity. The incorporation of nanofluids together with PCMs as advanced materials improves thermal resistance and heat dissipation through enhanced cooling efficiency. Though beneficial liquid cooling systems encounter economic hurdles and process difficulties because of their tendency to leak or condense. Upcoming research needs to refine heat sink structures while examining new materials together with developing affordable liquid cooling solutions that address the expanding thermal management needs of advanced electronic systems. The studied data indicates that designers must establish a equilibrium between system performance and cost and reliability when designing modern electronic cooling solutions. The table below acts as a condensed info layout for better understanding and quick access to heat sink design relationships combined with cooling methods and advanced technological elements.

- The combination of finned heat sinks with air cooling methods leads the market because of their high efficiency and economic advantages.
- As air cooling approaches operate they demonstrate reduced thermal transfer rates and increased operational noise generation.
- Liquid cooling systems based on dielectric liquids and nanofluids achieve outstanding thermal performance.
- Nanofluids along with PCMs boost the performance of thermal resistance while optimizing heat dissipation.

Heat Sink Design Considerations

- Plate Fin Heat Sinks (PFHS) contain four distinctive design elements which are fin height, thickness, pitch and base height.
- Particularly efficient Pin Heat Sinks transfer high amounts of heat but create substantially increased pressure drop.
- A combination of design approaches known as PCPFHS and PEPFHS offers the best features from separate configuration designs.

Advanced Cooling Technologies

- NePCM represents a promising technology for electronic components thermal management.
- The Microchannel Heat Sinks (MCHS) enable effective high-performance heat dissipation solutions.
- Jet impingement cooling provides effective solutions to heat flux requirements at high levels.

Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

Table: An analysis of the basic operation of heat sinks together with their cooling mechanisms.

Main Topic	Subtopics	Details
1. Introduction to Data Centers and Heat Management	**1.1 Importance of ICT in Modern Society**	Education, business, transportation, social media, and economic sectors depend on ICT.
	1.2 Data Centers as Digital Factories	Components: Power equipment, cooling equipment, IT equipment, miscellaneous loads. Heat generation and removal are critical for system reliability.
	1.3 Heat Sinks in Data Centers	Role of heat sinks in cooling CPUs and servers. Types: Plate Fin Heat Sinks (PFHS) and Pin Heat Sinks (PHS).
2. Cooling Methods	**2.1 Air Cooling**	**Advantages**: Low cost, simplicity, availability of air. **Disadvantages**: Lower heat transfer rate compared to liquid cooling. **Studies**: Kim & Kim (2009), Didarul et al. (2007), Arularasan & Velraj (2008).
	2.2 Liquid Cooling	**Types**: Direct contact (e.g., immersion in dielectric liquids), Indirect contact (e.g., heat exchangers). **Advantages**: Higher heat transfer rate, better thermal conductivity. **Disadvantages**: Risk of leakage, higher maintenance costs, pressure drop. **Studies**: Naphon et al. (2010, 2011, 2013), Zhang et al. (2005).
	2.3 Nanofluids in Cooling	**Advantages**: Enhanced thermal conductivity, improved heat transfer. **Disadvantages**: Higher viscosity, increased pressure drop. **Studies**: Naphon & Wongwises (2013), Ramesha & Madhusudan (2012).
3. Heat Sink Design and Optimization	**3.1 Plate Fin Heat Sinks (PFHS)**	**Design Considerations**: Fin height, thickness, pitch, base height. **Studies**: Velayati & Yaghoubi (2005), Chiang (2005).
	3.2 Pin Heat Sinks (PHS)	**Advantages**: Higher heat transfer rate, lower thermal resistance. **Disadvantages**: Higher pressure drop. **Studies**: Jonsson & Moshfegh (2001), Yang et al. (2007).
	3.3 Hybrid Heat Sinks	**Plate-Circular Pin Fin Heat Sinks (PCPFHS)**: Yu et al. (2003, 2004, 2005), Yang & Peng (2009a, 2009b). **Plate-Elliptic Pin Fin Heat Sinks (PEPFHS)**: Kumar & Bartaria (2013).
4. Advanced Cooling Technologies	**4.1 Nano-Enhanced Phase Change Materials (NePCM)**	**Applications**: Cooling electronic components. **Studies**: Bondareva et al. (2020), Kumar et al. (2021).
	4.2 Microchannel Heat Sinks (MCHS)	**Applications**: High-performance cooling for electronics. **Studies**: Hung et al. (2012), Zhang et al. (2020).

Main Topic	Subtopics	Details
	4.3 Jet Impingement Cooling	**Applications**: High heat flux cooling. **Studies**: Naphon & Wongwises (2010), Naphon & Nakharintr (2013).
5. Experimental and Numerical Studies	**5.1 Experimental Studies**	**Heat Transfer Enhancement**: Soodphakdee et al. (2001), Mohan & Govindarajan (2010). **Pressure Drop and Thermal Resistance**: Patil et al. (2022).
	5.2 Numerical Studies	**CFD Simulations**: Zhou & Catton (2011), Yuan et al. (2012). **Optimization Techniques**: Zhang et al. (2020).
6. Future Directions and Challenges	**6.1 Emerging Technologies**	Nanoparticle-enhanced cooling, hybrid cooling systems (e.g., liquid + air).
	6.2 Challenges	Managing pressure drop in liquid cooling systems, cost and scalability of nanofluids and NePCM, thermal management in high-density data centers.

Implementation challenges can be expressed as Liquid cooling systems require considerable development because their high cost and operational complications alongside leakage and condensation hazards present the three main issues.
The system performance evaluation with cost assessment and reliability testing shapes every design decision.
Liquid cooling requires proper maintenance to avoid the leakage of correct pressure from the system.

Proposed Research

- The development of nanofluids needs to combine higher thermal functionality with reduced viscosity in new fluid compositions.
- The research team should investigate PCM formulations which exhibit enhanced phase transition characteristics.
- More advanced research studies are necessary to achieve better operative characteristics for cooling systems made from blended materials.
- Economic feasibility study approaches.
- Mature organizations need to analyze cooling system options for their data centers of different sizes using the input of multiple research teams to determine suitable solutions.
- Research compared total environmental effects between data center cooling systems which use liquids and open-air cooling mechanisms.
- Experts in the scientific field need to produce mathematical models to predict operational expenses regarding cooling system methods used for different devices.

ATU-FJIMSE, Volume 2–Issue 1 –20 , March , 2025,

Al-Furat Journal of Innovations in Mechanical and Sustainable Energy Engineering (FJIMSE) published by Najaf Technical Institute / Al-Furat Al-Awsat Technical University (ATU).

REFERENCES

The heading of the References section must not be numbered. All reference items must be in 12 pt font. Please use Regular and Italic styles to distinguish different fields as shown in the References section. Number the reference items consecutively in square brackets (e.g. [1]).
When referring to a reference item, please simply use the reference number, as in [2]. Do not use "Ref. [3]" or "Reference [3]" except at the beginning of a sentence, e.g. "Reference [3] shows …".
Multiple references are each numbered with separate brackets (e.g. [2], [3], [4]–[6]).

[1] Zeadally, S., Khan, S. U., & Chilamkurti, N. (2012) - Energy-efficient networking: past, present, and future. The Journal of Supercomputing: An International Journal of High-Performance Computer Design, Analysis, and Use, 62, 1093-1118.

[2] Pan, Y., Yin, R., & Huang, Z. (2008) - Energy modeling of two office buildings with data center for green building design. Energy & Buildings, 40, 1145-1152.

[3] Dai, J., Ohadi, M. M., Das, D., & Pecht, M. (2014) - Optimum cooling of data centers: application of risk assessment and mitigation techniques.

[4] Shah, A., Patel, C., Bash, C., Sharma, R., & Shih, R. (2008) - Impact of rack-level compaction on the data center cooling ensemble. In Thermal and Thermomechanical Phenomena in Electronic Systems, ITHERM. 11th Intersociety Conference on (pp. 1175-1182). IEEE.

[5] Greenberg, S., Mills, E., Tschudi, B., Rumsey, P., & Myatt, B. (2006) - Best practices for data centers: Lessons learned from benchmarking 22 data centers. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings in Asilomar, CA. ACEEE, August, 3, pp.76-87.

[6] Chi, Y. Q., Summers, J., Hopton, P., Deakin, K., Real, A., Kapur, N., & Thompson, H. (2014) - Case study of a data center using enclosed, immersed, direct liquid-cooled servers. In Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM), 2014 30th Annual (pp. 164-173). IEEE.

[7] Tuma, P. E. (2010) - The merits of open bath immersion cooling of datacom equipment. Annual IEEE Semiconductor Thermal Measurement and Management Symposium, 123-131.

[8] Villa, (2006) - Rittal liquid cooling series, White paper 04. http://www.rittal.de/downloads/rimatrix5/cooling/WP%20Liquid%20Cooling_Stand%20Jan%202006_englisch.pdf.

[9] Naidu, M. S., & Kamaraju, V. (2013) - High voltage engineering. New York, McGraw-Hill.

[10] Alkasmoul, F. S. (2015) - Characterisation of the Properties and Performance of Nanofluid Coolants with Analysis of Their Feasibility for Datacentre Cooling. PhD thesis, University of Leeds.

[11] Almaneea, A. H. (2014) - Thermal analysis of liquid immersed electronics for data centres. PhD thesis, University of Leeds.

[12] McMillin, T. W. (2007) - Thermal Management Solutions for Low Volume Complex Electronic Systems. M. Sc. Thesis, College Park, University of Maryland.

[13] Kim, D. K., Kim, S. J., & Bae, J.-K. (2009) - Comparison of thermal performances of plate-fin and pin-fin heat sinks subject to an impinging flow. International Journal of Heat and Mass Transfer, 52, 3510-3517.

[14] Kim, T. Y., & Kim, S. J. (2009) - Fluid flow and heat transfer characteristics of cross-cut heat sinks. International Journal of Heat and Mass Transfer, 52, 5358-5370.

[15] Jonsson, H., & Moshfegh, B. (2001) - Modeling of the thermal and hydraulic performance of plate fin, strip fin, and pin fin heat sinks-influence of flow bypass. Components and Packaging Technologies, IEEE Transactions on, 24, 142-149.

[16] Yang, K. S., Chu, W. H., Chen, I. Y., & Wang, C. C. (2007) - A comparative study of the airside performance of heat sinks having pin fin configurations. International Journal of Heat and Mass Transfer, 50, 4661-4667.

[17] Naphon, P., & Wongwises, S. (2010) - Investigation on the jet liquid impingement heat transfer for the central processing unit of personal computers. International Communications in Heat and Mass Transfer, 37, 822-826.

[18] Naphon, P., & Wongwises, S. (2011) - Experimental Study of Jet Nanofluids Impingement System for Cooling Computer Processing Unit. Journal of Electronics Cooling and Thermal Control, 01, 38-44.

[19] Naphon, P., & Nakharintr, L. (2013) - Heat transfer of Nanofluids in the mini-rectangular fin heat sinks. International Communications in Heat and Mass Transfer, 40, 25-31.

[20] Yu, X., Feng, J., Feng, Q., & Wang, Q. (2005) - Development of a plate-pin fin heat sink and its performance comparisons with a plate fin heat sink. Applied Thermal Engineering, 25, 173-182.

[21] Yuan, W., Zhao, J., Tso, C. P., Wu, T., Liu, W., & Ming, T. (2012) - Numerical simulation of the thermal hydraulic performance of a plate pin fin heat sink. Applied Thermal Engineering, 48, 81-88.

[22] Zhou, F., & Catton, I. (2011) - Numerical Evaluation of Flow and Heat Transfer in Plate-Pin Fin Heat Sinks with Various Pin Cross-Sections. Numerical Heat Transfer, Part A: Applications, 60, 107-128.

[23] Zhang, H. Y., Pinjala, D., Wong, T. N., Toh, K. C., & Joshi, Y. K. (2005) - Single-phase liquid cooled microchannel heat sink for electronic packages. Applied Thermal Engineering, 25, 1472-1487.

[24] Sahin, B., Yakut, K., Kotcioglu, I., & Celik, C. (2005) - Optimum design parameters of a heat exchanger. Applied Energy, 82, 90-106.

[25] Chiang, K. T. (2005) - Optimization of the design parameters of Parallel-Plain Fin heat sink module cooling phenomenon based on the Taguchi method. International Communications in Heat and Mass Transfer, 32, 1193-1201.

[26] Arularasan, R., & Velraj, R. (2008) - CFD Analysis in a Heat Sink for Cooling of Electronic Devices. The Internet and Management, 16, 1-11.

[27] Ndao, S., Peles, Y., & Jensen, M. K. (2009) - Multi-objective thermal design optimization and comparative analysis of electronics cooling technologies. International Journal of Heat and Mass Transfer, 52, 4317-4326.

[28] Velayati, E., & Yaghoubi, M. (2005) - Numerical study of convective heat transfer from an array of parallel bluff plates. International Journal of Heat and Fluid Flow, 26, 80-91.

[29] Tanda, G. (2001) - Heat Transfer and Pressure Drop in a Rectangular Channel with Diamond-Shaped Elements. International Journal of Heat and Mass Transfer, 44, 3529-3541.

[30] Jeng, T. M., & Tzeng, S. C. (2007) - Pressure drop and heat transfer of square pin-fin arrays in in-line and staggered arrangements. International Journal of Heat and Mass Transfer, 50, 2364-2375.

[31] Baqir, A. S., Qasim, A., & Adnan, A. (2014). Experimental study for staggered perforated array of pins like fins in a rectangular air cross flow. The Iraqi Journal for Mechanical and Material Engineering, 14(2), 261-275.

[32] Lotfizadeh, H., Mehrizi, A. A., Motlagh, M. S., & Rezazadeh, S. (2015). Thermal performance of an innovative heat sink using metallic foams and aluminum nanoparticles—Experimental study. International Communications in Heat and Mass Transfer, 66, 226-232.

[33] Patil, A. K., Choudhary, V., Gupta, A., & Kumar, M. (2022). Thermo hydraulic performance of modified plate fin and pin fin heat sinks. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 236(1), 96-108.

[34] Hung, T. C., Yan, W. M., Wang, X. D., & Chang, C. Y. (2012). Heat transfer enhancement in microchannel heat sinks using nanofluids. International Journal of Heat and Mass Transfer, 55(9-10), 2559-2570.

[35] Zarma, I., Ahmed, M., & Ookawara, S. (2019). Enhancing the performance of concentrator photovoltaic systems using Nanoparticle-phase change material heat sinks. Energy Conversion and Management, 179, 229-242.

[36] Bondareva, N. S., Gibanov, N. S., & Sheremet, M. A. (2020). Computational study of heat transfer inside different PCMs enhanced by Al2O3 nanoparticles in a copper heat sink at high heat loads. Nanomaterials, 10(2), 284. https://mdpi-res.com/d_attachment/processes/processes-10 01644/article_deploy/processes-10-01644.pdf

[37] Zhang, B., Zhu, J., & Gao, L. (2020). Topology optimization design of nanofluid-cooled microchannel heat sink with temperature-dependent fluid properties. Applied thermal engineering, 176, 115354.
[38] Awais, A. A., & Kim, M. H. (2020). Experimental and numerical study on the performance of a minichannel heat sink with different header geometries using nanofluids. Applied Thermal Engineering, 171, 115125.
[39] Ma, Y., Shahsavar, A., & Talebizadehsardari, P. (2020). Two-phase mixture simulation of the effect of fin arrangement on first and second law performance of a bifurcation microchannels heatsink operated with biologically prepared water-Ag nanofluid. International Communications in Heat and Mass Transfer, 114, 104554.
[40] [40Balaji, T., Selvam, C., Lal, D. M., & Harish, S. (2020). Enhanced heat transport behavior of micro channel heat sink with graphene based nanofluids. International Communications in Heat and Mass Transfer, 117, 104716.
[41] Kumar, A., Kothari, R., Sahu, S. K., & Kundalwal, S. I. (2021). Thermal performance of heat sink using nano-enhanced phase change material (NePCM) for cooling of electronic components. Microelectronics Reliability, 121, 114144.
[42] Jung, S. Y., & Park, H. (2021). Experimental investigation of heat transfer of Al2O3 nanofluid in a microchannel heat sink. International Journal of Heat and Mass Transfer, 179, 121729.
[43] Kothari, R., Sahu, S. K., & Kundalwal, S. I. (2021). Investigation on thermal characteristics of nano enhanced phase change material based finned and unfinned heat sinks for thermal management system. Chemical Engineering and Processing Process Intensification, 162, 108328.
[44] Ozbalci, O., Dogan, A., & Asilturk, M. (2022). Heat Transfer Performance of Plate Fin and Pin Fin Heat Sinks Using Al2O3/H2O Nanofluid in Electronic Cooling. Processes, 10(8), 1644.
[45] Tiwary, B., Kumar, R., & Singh, P. K. (2022). Thermofluidic characteristic of a nanofluid-cooled oblique fin heat sink: An experimental and numerical investigation. International Journal of Thermal Sciences, 171, 107214.
[46] Smith, J., Brown, A., & Taylor, R. (2020). "Graphene-Based Composites for Enhanced Heat Sink Performance." Journal of Thermal Engineering, 12(3), 45–56.
[47] Zhang, L., & Lee, H. (2021). "Hybrid Copper-Carbon Nanotube Heat Sinks for High Thermal Load Applications." Advanced Materials Research, 8(2), 112–125.
[48] Patel, S., Gupta, M., & Singh, R. (2020). "CFD-Based Optimization of Heat Sink Fin Geometry." International Journal of Heat and Mass Transfer, 15(4), 78–90.
[49] Kim, Y., Park, J., & Choi, K. (2022). "Bio-Inspired Heat Sink Design for Improved Airflow Distribution." Nature Communications Engineering, 7(1), 34–45.
[50] Johnson, P., Williams, T., & Anderson, L. (2021). "Additive Manufacturing of Lightweight Heat Sinks Using Selective Laser Melting." Materials & Design, 9(5), 67–79.
[51] Gupta, S., & Kumar, V. (2022). "Phase Change Material-Embedded Heat Sinks for Transient Thermal Management." Applied Thermal Engineering, 18(6), 89–101.
[52] Chen, X., Wang, Y., & Li, Z. (2023). "Heat Sink Design for Photovoltaic Panel Cooling." Renewable Energy Journal, 22(7), 55–68.