RESEARCH ARTICLE

SAMRIDDHI Volume 13, Special Issue 2, 2021 Print ISSN : 2229-7111 Online ISSN : 2454-5767

Traditional and Emerging Potential Technologies for Electronics Cooling: A Review

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Abstract

The continued downsizing of electronic gadgets and appliances as well as the need for high-end performance have resulted in a significant increase in heat flux generation. The thermal management of high-performance electronics products, chips, and equipment needs innovative techniques and systems designed to enhance the heat removal rate in order to minimize their operating temperature and better functioning of the device and increase its longevity. Several cooling methods are being utilized to facilitate effective heat transfer from high-power-density chips and more efficient heat removal. However, the traditional cooling methods are progressively failing, and it has become quite difficult to cope with the high cooling demand and thermal management of emerging electronic devices so potential advanced cooling methods and a number of coolants have been introduced. Some of the coolants are based on traditional technologies, while others are based on modern breakthroughs. This study explored traditional and emerging cooling technologies as well as coolants for electronics.

Keywords: Electronics technology, Cooling Methods, Cooling Fluids, Nano-fluids, Electronics cooling.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology, (2021); DOI : 10.18090/samriddhi.v13spli02.23

Introduction

The trend to manufacture smaller electronic products or devices usually termed miniaturization and the latest advancement in semiconductors and micro-electronic technologies have resulted in a significant escalation in power density for high-speed chips, rendering many challenges including safe and reliable operation of these electronic devices in various applications [1,2]. Despite the signs of progress and developments during the last decade with respect to the management of thermal control (cooling) of electronics devices or microprocessors, there remain some profoundly serious challenges to be addressed such as disposal of surging heat flux and dissipation of erratic power [3]. Depending upon the electrical efficiency and use of materials, the temperature in microprocessors during sustained operation should not more be than 85°C. Therefore, the thermomechanical solutions should focus not only on effective heat transfer and removal from high-power-density chips but also to find ways for waste heat recovery [4,5].

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How to cite this article : Asif, M., Arefeen, M.Z., Mehare, H.B., Ahmad, I.(2021). Traditional and Emerging Potential Technologies for Electronics Cooling: A Review.

SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology, Volume 13, Special Issue (2), 245-255.

Source of support : Nil

Conflict of interest : None

The traditional cooling methods are progressively failing, and it has become quite difficult to cope with thermal management to achieve high cooling requirements for emerging electronic devices, so there is a need for high-performance chips or devices [1]. In spite of significant progress in high heat flux management research has been made over the last few decades, the removal of high-heat-flux in electronic devices used in extreme environments still faces numerous challenges. Therefore, the cooling systems in emerging electronic devices must be modified, which may need various technological requirements [2,6].

ELECTRONICS COOLING METHODS

Miniaturization of electronic devices with high performance creates heat flux resulting in increased operating temperatures. To overcome these several improved cooling methods are being utilized to manage temperature properly in these devices for better performance and longevity. Numerous methods of cooling are used in electronic applications which are classified into various categories on the basis of cooling modes and effectiveness of heat transfer which are explained in further detail below.

Traditional Cooling Methods

Traditional cooling methods are classified on the basis of the heat transfer mechanism, coolants used, and their cooling effectiveness.

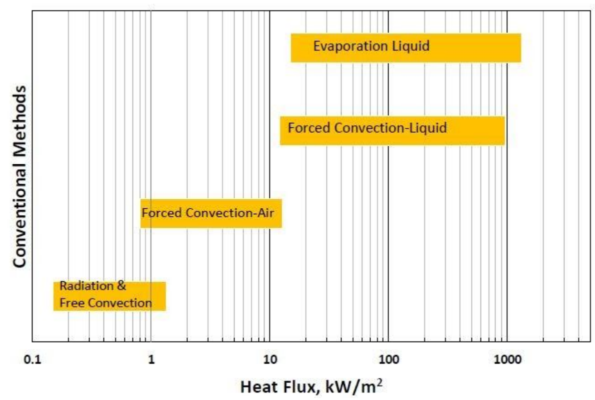

Figure 1: Traditional heat transmission technologies are compared in terms of efficiency [3]

Radiative Cooling : This method provides a cooling power in excess of 100 W m-2 under suitable atmospheric conditions and optimal device design. It is a potential passive cooling method with an ability to release energy via radiation heat exchange in which heat is directly transferred to the outer space of the device [7-10]. However, there is a limitation and it works well during nighttime. Although there are some solar reflecting materials that are reported to work during the daytime as well, cooling below the ambient temperature was not achieved [11,12]. Recently with the use of advanced nanophotonics, daytime cooling below the ambient temperatures has been achieved [13].

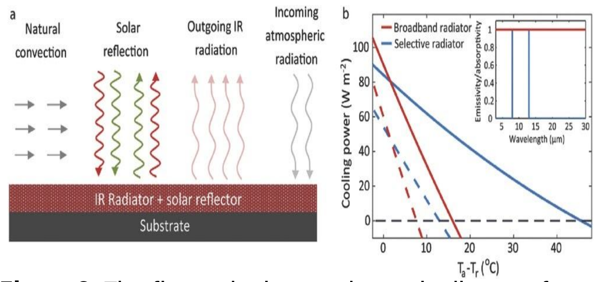

Figure 2: The figure depicts a schematic diagram for a practical radiative cooling system [14]

Air Cooling : The established air cooling approach which employs free convective air cooling is barely able to cope up with the upcoming applications which tend to produce a lot more energy and hereby need better and state of the art cooling methods. The usual fans, which have been used to a vast extent in the established air cooling method, reach a net heat relay of about 150 W/m2K, above which they tend to overwork and produce a lot more noise. Conceptually, by using the traditional fans we have the tendency to reach a limit of 900 W/m2K of heat transfer coefficient, but in the practical world this would not be feasible as the noise from the fans would be resounding, hence making it a non-practical approach in real-world applications. Newer technologies like vortex electronic coolers, piezo fans, 'nano lighting', and 'synthetic' jet cooling have been introduced over a period of time to tame the current challenges and the limits being posed by the Traditional Methods.

Liquid Cooling : It's another well-known and used cooling method and by experiments, it's thrice as effective in comparison to the free convective air cooling when used in the same devices. In some cases, it's possible to achieve a tenfold better efficiency against the same method when certain parameters are modified. This shows that without overheating the devices it is possible to transfer the convective heat fluxes of several hundred watts per square centimeter easily from the thin-film resistor and the Integrated Circuit Chip (IC Chip). But one thing to be taken into consideration is that the calculated localized temperature can be wrong because it's the localized temperature and not the mean system temperature which usually calculates the life span of the and operating properties of the device [16].

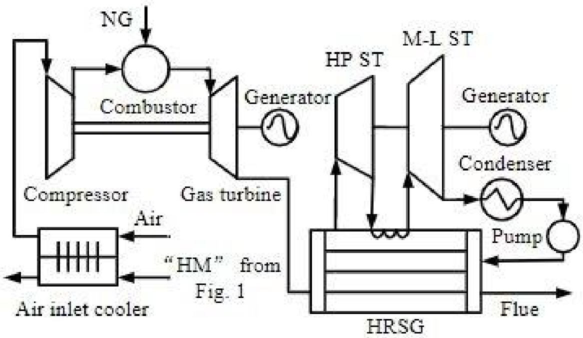

Figure 3: A simplified flow sheet diagram of the combined cycle for inlet air cooling [15]

Evaporative Cooling : In this method the principle of heat and mass transfer is taken to be the basic principle in which the heat from the device gets passed onto the water present, thus making the water evaporate and also reducing the device temperature. It's considered to be an economically viable option as it does not waste a lot of energy while being effective to a great extent. In the early days, it was considered to be practical and a profitable method for cooling devices that contained electronic parts but due to its various limitations it was discontinued [17].

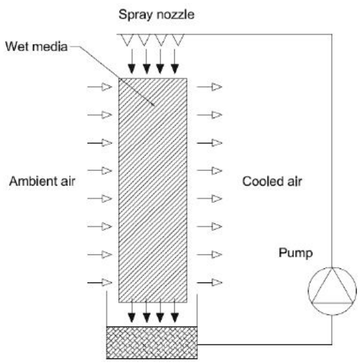

Figure 4: A schematic diagram of evaporative cooling [18]

Heat Spreading and Conduction : In this process, before the heat comes into contact with the coolants, it first passes through parts that have been brought into contact with the coolant earlier. To accomplish this, a plate with excellent thermal conductivity is kept between the chip or in some cases the heat sink. Vapor chambers which are planar heat pipes and they can spread heat in two dimensions are used to roll out the heat from the heat source. Nowadays copper is being increasingly replaced because of the importance of resistance in interface thermal surfaces and light, novel materials again which have an excellent thermal conductivity in comparison with copper. ScD (Skeleton Cemented Diamond), metal matrices, and materials that have coal, hydrocarbon petroleum products also known as carbonaceous materials are being used to replace copper. Also, another added benefit is that this enables a more efficient method of heat conduction and is in comparison to the heat conductivity of diamond. The technologies are Enerdyne's Polara and Novel Concept's Isoskin.

Piezo Fan : Piezoelectric fans use an energy harvesting device commonly known as piezoceramic patches which are glued to pliable blades which are quite thin and tend to have a low frequency and they move the fan at its suitable or desired frequency. As these blades reverberate at their desired frequency, they put together a continual airflow which reduces the heat from the electronic constituents. This technique gives us a lot more efficiency compared to the other methods and in some cases, the heat transfer is almost 100% in comparison to the well-used and known natural convention method. Also, the other advantages of this process are that the power consumption is quite low and the fans are less noisy. These qualities make it a competitive alternative to the heat management implementations for most of the small, lightweight, and compact devices which constitute electronic parts.

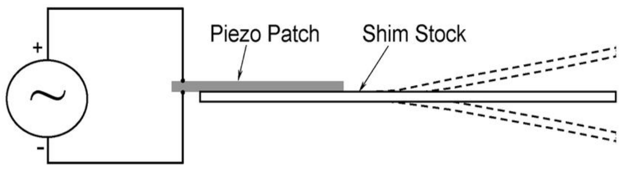

Figure 5: Schematic of a piezo fan oscillating under an applied voltage due to the contraction and expansion of a piezoceramic patch [19]

Potential Emerging Methods Cooling

Traditional cooling methods are not successful in thermal management to manage the enormous cooling power demand of the latest gadgets with electronic components. There is a need for improved mechanisms utilizing innovative methodologies, and coolants that have high heat transfer capabilities are the need of the hour in order to achieve a better heat withdrawal rate in high-performance chips or devices. Latest technological advancements in electronics cooling have provided some alternatives and modifications to traditional cooling techniques which are showing great promise for future management of thermal issues in electronics devices.

Some of these cooling techniques have been studied considerably to a deep extent and are even being used in the management of thermal systems such as thermosyphons [20], heat pipes [21], electro-osmotic pumping [22], microchannels [23], impinging jets [24], thermoelectric coolers [25], and absorption refrigeration systems [26]. Based on their functioning principle these cooling techniques are classified as active and passive systems. The active cooling systems consist of a pump/compressor which provides us with higher cooling capacity and they are much more efficient while the passive ones usually depend on the buoyancy forces or capillary to circulate the working fluid in the system [27].

Heat pipes-based cooling : In this cooling technique, the heat pipes rely on the change in the phase of fluid used inside the pipes. This technique is widely used in computers, laptops, telecommunications, and satellite modules to cool the devices [28,29]. Heat pipes are quite successful in cooling electrical equipment with high heat flux due to their very high thermal conductivity together with very low thermal resistance [30,31]. Heat pipes are commercially used in cooling applications due to their high heat removal capability [29]. The assessment of small heat pipe design, fabrication, and performance analysis for cooling small electronic gadgets and systems has been shown [32].

Electronic cooling appliances usually employ mainly three types of heat pipes, classified as flat, cylindrical, and loop heat pipes. Micro-heat pipes are a type of pipe that emits a small amount of heat. Heat pipes that oscillate are also known as pulsating heat pipes. Metal envelope, wick, and cooling fluid make up a heat pipe. The envelope is divided into three parts: evaporator, adiabatic, and condenser. The most significant component is the wick, which is generally attached to the pipe's inner wall. It works as a capillary pump, pushing the fluid against gravity from the condenser part to the evaporator. This enables it to work in any particular direction. The most commonly used wick kinds are grooved, sintered, and screen mesh wicks.

Thermal Interface Materials based cooling : The use of thermal interface materials for cooling is becoming more popular. The materials available a decade ago have become obsolete as component sizes and formats have reduced, packaging materials have improved, and device integration and power density have increased.

It has been proven that the optimal thermal interface material is designed to do the following:

- Lower the power consumption of the cooling system
- No requirement for liquid cooling
- Longer operational lifetime
- The lower total cost of ownership

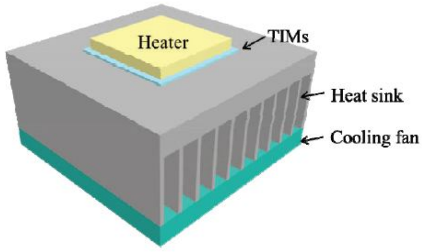

Figure 6: The home-made thermal testing station is depicted in this figure

These thermal-interface-materials (TIM) are designed to fill small gaps and cavities at the interface with a material with a greater thermal conductivity, enhancing the heat flux conductivity of the material at the interface.

Phase Changing Materials based cooling : Phase Changing Materials (PCMs)-based cooling has gained a lot of attention in the last decade as new passive technology. It is a successful cooling method since it can extract heat from gadgets and devices and store it for later use, such as heating houses or offices. PCMs have been tested for a variety of applications, including electronics cooling [22,27,33-35].

The main advantages of this process are higher value of specific heat, adaptable temperature steadiness, high latent heat of fusion, and very minute changes in volume in the course of phase shift. It was observed that a very small quantity of PCM can considerably improve the heat sink's ability to stabilize the temperature of the device, indicating that PCM-based heat sinks have a lot of potential for electronics cooling [3,36].

Thermoelectric Cooling : The Peltier effect, also known as the thermoelectric effect, causes heat flow through the two joints of different types of semiconductors in a thermoelectric cooler (TEC). Peltier heat pumps, often known as thermoelectric coolers, are cooling devices that use electrical energy to transmit heat from one side of the gadget to the other. Due to their small size and lack of moving parts, TECs have a lot of potential for improving the cooling rate of electronic modules and other devices [37]. For the cooling of hotspots in electronic packages, TEC can be used [38]. The coefficient of performance of a TEC, although has a lesser value than that of a Vapour Compression Refrigeration system [39], Zebarjadi [40] demonstrated that thermoelectric materials for electronics cooling applications must have high thermal conductivity and a significant power factor.

It has been shown that when the thermoelectric module and the heat pipe technique, when combined have the capacity to cool down 200W of heat dissolution, and the integrated cooling system's temperature was found to be lesser compared to that of the existing cooling systems when being used in cooling down Computer Chips and various other Microprocessors. [41]. TECs are widely used in a variety of applications because of their simple functioning concept. The combination of P-type and N-type of the semiconductor are totally dissimilar being the vital component in a TEC. The unbounded ends of both the separate components are applied to a certain voltage which causes a flow of DC (direct current) in both the semiconductors. This flow between the two causes a difference in the temperatures across the junction of these semiconductors. This process is the thermoelectric effect and due to this heat is absorbed from the colder region and transferred to the heat sink in that particular application, ultimately creating this temperature differential [3].

Spray Cooling : This method is well known for its ability of large amounts of heat transfer, constant removal of heat, a compact checklist of fluid inventory, and almost no temperature overshooting. The mechanism of this technology is not very clear because of being dependent on many parameters. In spray cooling, the liquid is forced through a small orifice and scattered in the form of droplets on the heated surface. These droplets evaporate or form a thin film of the liquid on the surface, ultimately removing energy at low temperatures as a result of single-phase convection effects together with the latent heat of evaporation. By this technique, high rates of heat transfer are achieved due to less resistance in removing vapor from the heated surface. Spray cooling is quite advantageous as mentioned earlier due to uniform cooling, low droplet impact velocity, and no temperature overshoot. The requirement of pumps. Filters along with the necessity to move the surplus fluids and vapor to a condenser are the major disadvantages of this process.[42].

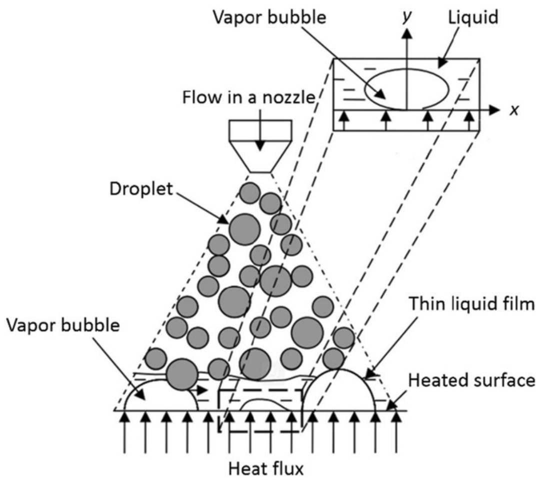

Figure 7: Schematic diagram of spray cooling process [43]

Microchannels and Minichannels : Microchannel is an effective technique of cooling for microchips that function as a heat sink or a heat exchanger. They are capable of cooling the microchips faster due to a greater heat transfer surface area than the fluid volume which allows for increased convection in comparison with the Macro-scale setups. The channel's diameter is inversely proportional to the heat transfer coefficient because when there is a decrease in the diameter, the heat transfer coefficient will increase. Although air, water, and refrigerants are commonly used in microchannels, they all have limitations in their heat transferring capabilities and the air is the preferred fluid for cooling electronic components.

The literature available puts forward four methods of chip cooling namely as microchannel single-phase flow, microchannel two-phase flow boiling, porous media flow, and jet impingement cooling[44]. Out of all these four methods, the microchannel two-phase cooling is the most promising technology because it provides lower heat resistance, less pumping power needs, and high heat withdrawal proficiencies[45]. However, single-phase microchannel cooling is relatively easy and is being used in the Aquasar computers [46, 47].

Synthetic Jet Cooling : Synthetic jet cooling utilizes periodic microjets also known as synthetic jets produced by pulsating flow. Synthetic jets are much more powerful and mix more rigorously connecting the partition films on the wall and the remaining flow than traditional jets. In this method of cooling the air surrounding the job strikes the hotter surface at the tip before the heated air is recirculated into the atmosphere which further forms a counter radial current that flows amongst the space in between the heated plates which reflects the warm air on the tip and the normal cool air below the surface.

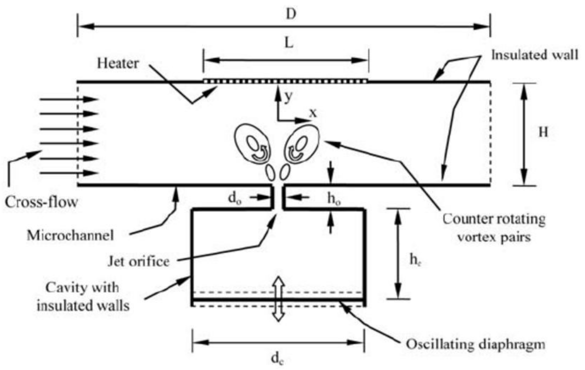

Figure 8: Schematic diagram of synthetic jet mounted on a heat sink in cross-flow configuration [48]

Nano lighting : Nano lighting increases the heat transfer coefficient by producing very high electric fields created by nanotubes through micro-scale ion-driven airflow. Other than that, there are multiple other advanced electronics cooling technologies like electrowetting and electrohydrodynamic cooling, heat pumps, liquid metal cooling, liquid jet impingement, immersion cooling, solid-state cooling, heterostructure, and superlattice cooling, and thermo-tunneling and thermionic cooling.

Heat Pumps : On the principle that heat moves from a warmer temperature to a cooler temperature, heat pumps are designed for heating and cooling electronic devices. These are some of the most energy-efficient ways to provide heating and cooling in many devices that act as renewable heat sources [49].

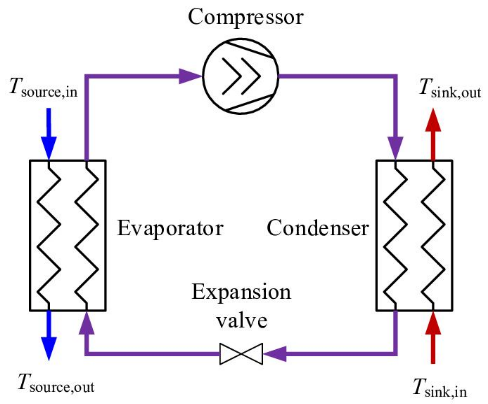

Figure 9: Sketch of The Heat Pump Cycle With Components [50]

Liquid Metal Cooling : As mentioned earlier conventional liquids have some limitations due to their low thermal conductivity and that mechanical pumps are needed to drive them. On that account, to increase the thermal conductivity, conductive nano metal particles like aluminum, copper, etc. are added to the solution and suspension creating nanofluids[51,52]. Further, the electrical contact resistance at the interface is reduced by liquid metals due to their high conductance [53].

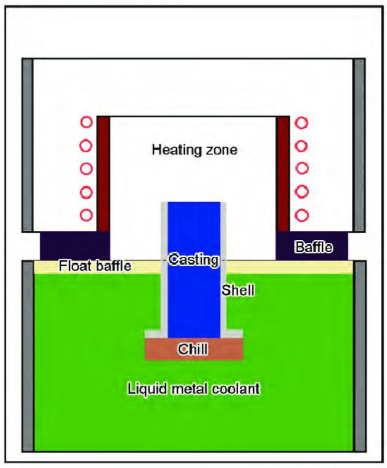

Figure 10: Simplified schematic of liquid-metal cooling (LMC) directional solidification furnace [54]

COOLING FLUIDS

Conventional Fluids

Multiple electronics cooling systems use a variety of aqueous and non-aqueous standard coolants. Water due to its excellent heat conductance, specific heat, and low viscosity is used very extensively as a coolant in electronics. But because of water's property of expanding while heating and having a high freezing temperature, it cannot be used in systems with a closed-loop. Overall the general coolant requirements vary from system to system and are based on the kind of electronic apparatus and its needs. Some of the more obvious conditions are that the liquid coolant being used should neither be flammable or toxic while being less viscous and having excellent conductance of heat and HTC [47].

The aromatic coolants which are commonly used are diethyl benzene (DEB) and toluene. In many direct cooling methods, aliphatic hydrocarbons from paraffinic and the isoparaffinic type and aliphatic polyalphaolefins are used. Silicones oils are also popular and well-known coolants. FC 72, FC 40, FC 77, and FC 87 are some of the fluorocarbon coolants commonly being used in electronic devices [1].

Because non-dielectric liquids have greater thermal properties than dielectric liquids, they are also employed for electronics cooling. They are typically aqueous solutions with elevated thermal capacity and heat conductivity. Water, EG, and a combination of both these two are frequently used as electronic coolants. Some of the well-known and used popular non-dielectric coolants are water/ ethanol, sodium chloride solutions, and liquid metals[47].

Potential New Coolants *:* The coolants mentioned earlier in this paper are not capable of handling the cooling demands of the latest electronic gadgets which generate high heat due to their fundamentally weak thermal characteristics and limited cooling efficiency.

Nanofluids are new heat transfer fluids in which nanoparticles are suspended in traditional coolants [48,50]. Nanofluids can be employed to address the cooling demands of current and compact electronic devices since they have no constraints and have excellent thermal properties. This new group of fluids have significant advantages and uses in a variety of industrial, electrical, and energy domains [48, 49, 50].

The use of nanofluids has significantly impacted the electronic industries in a better manner as the cooling efficiency of heat exchangers and other cooling methods are critical in multiple sectors. Ionanofluids, or ionic liquid-based nanofluids, are another recently developed type of fluid. In comparison to their base ionic liquids, ionanofluids have improved thermal characteristics [3, 51, 52].

ELECTRONICS COOLING USING NANOPARTICLE MATERIALS

Many nanoparticles have been used in the past to use these coolants to be used in liquid blocks. In this particular field, the oxide nanoparticles are the most commonly used particles. Various types of nanoparticles used in fluids employed for electronic cooling are summarized as follows.

Magnetic Nanoparticles

MNFs (Magnetic Nano Fluids) or Ferrofluids are magnetic nanoparticles in a non-magnetic liquid as a base. The magnetic nanoparticles being used in MNFs are often made from ferromagnetic materials like iron, nickel and their oxides, ferrites of spinel-type and they come in a variety of sizes and shapes. The main property of these nanofluids is that, in addition to improved heat transmission, they have the property of flowability which traditional liquids possess, and also have magnetic properties which are like other materials which have magnetic properties. Because of these properties, these suspensions may be used to control the flow of the liquid, heat exchange using outer magnetic fields. Due to this, there is a potential to be used in engineering and bioengineering[53]. Jahani et al[54] used an MPHP (Micro Pulsating Heat Pipe) to test the impacts of various working fluids in electronics cooling. The best charge ratio for water is 40 percent, while it reaches 60 percent for nanofluids. The MPHPs along with the nanofluids displayed a lower heat resistance compared to those with water in most states[53].

Oxide Nanoparticles

Some oxide nanoparticles, spherical ones, are being extensively used to fabricate more nanofluids to be used in liquid blocks amongst other nanoparticles. These nanoparticles are being used more commonly because of their excellent stability, low cost, and adequate thermal conductivity, among other factors. Other oxide nanoparticles have been used less than alumina and titania nanoparticles [53].

Al_2O_3 nanoparticles are one of the oxide materials used in electronics cooling. Hasani et al. [55] looked into the effects of varied fin interruptions on the transport properties of a chevron-shaped nanofluid-cooled electronic heat sink. At volume concentrations of 0.5 percent and 1%, water and other water-based nanofluids along with Al_2O_3 nanoparticles were tested. The results showed that utilizing interrupted fins improves heat transmission due to a decrease in the surface temperature of the fin and an increase in the outer coolant temperature. On the other hand, the increased porosity of the heat sink's fins led to consequential reductions in loss of pressure[53].

ZnO nanoparticles are another example of the oxide materials used in electronics cooling. Guo et al. [56] used static and dynamic single-phase models to evaluate the thermal and hydraulic efficiency of a micro fin heat sink with ZnO–water nanofluids. Nanofluids along with higher volume concentrations and smaller particle sizes have higher efficiency [53].

Hybrid Nanofluids

Hybrid nanofluids are made by distributing nanoparticles in a composite or mixed condition. The purpose of creating nanofluids that are hybrid was to improve the heat exchanging rates done by increasing the heat conductivity while also gaining some unique properties. Selvakumar and Suresh [57] have used a hybrid nanofluid consisting of Al_2O_3-Cu nanoparticles in a thin-channel copper liquid clock. After examining the results it was found out that when the hybrid nanofluid is used instead of the base liquid, the convection heat transfer coefficient increases considerably. Furthermore, when the hybrid nanofluid was used instead of water, the increase in pumping power was less than the increase in convection thermal transfer coefficient [53].

Conclusion

Despite significant advancements in recent decades, the heat management of modern and powerful electronics products and equipment continues to face significant technological challenges. To efficiently get rid of the heat dissipated for optimal execution and good longevity, high-performance electronics items require new mechanisms, methodologies, and coolants with excellent and better thermal transfer conductivity. Nanofluids have much higher thermal properties than their basic conventional fluids, such as thermal conductivity, convective, and boiling heat transfer so can be promising coolants as it has been shown that nanofluids are superior to their traditional counterparts as coolants. Furthermore, research on the usage of nanofluids has indicated that the new emerging fluids are superior to conventional coolants for electronic equipment. Thereby, applying nanofluids to a wider range of electronics cooling systems to evaluate their relevance, importance and performance are needed. On the basis of our review, it is concluded that the emerging cooling approaches, such as microchannel systems, in combination with these innovative fluids, can significantly improve heat withdrawal performance and address the cooling demands of high-heat-producing electronic equipment. However, further research is required before their commercial use in the electronics industry.

References

[1] Murshed and S.M. Sohel, "Introductory chapter: electronics cooling—An overview." *Electronics Cooling*, 2016.

[2] B. Indulakshmi and G. Madhu, "Heat transfer modeling and simulations for electronic cooling systems embedded with phase changing materials." *Heat Transfer—Asian Research* vol. 47.1, pp. 185-202, 2018.

[3] Murshed, S.M. Sohel and CA Nieto De Castro, "A critical review of traditional and emerging techniques and fluids for electronics cooling." *Renewable and Sustainable Energy Reviews* 78, pp. 821-833, 2017.

[4] Patel, Chandrakant D. "A vision of energy-aware computing from chips to data centers." *The international symposium on micro-mechanical engineering*. 2003.

[5] Kamlesh Mehta, Nirvesh Mehta and Vivek Patel, "Experimental investigation of the thermal performance of closed loop flat plate oscillating heat pipe", *Experimental Heat Transf.* 34:1, pp. 85-103, 2021.

[6] Ebadian, M. A., and C. X. Lin, "A review of high-heat-flux heat removal technologies." *J. of heat transf.* 133.11, 2011

[7] Lewis, S. Nathan, "Research opportunities to advance solar energy utilization", *J. Science* 351.6271, 2016.

[8] Kraemer, Daniel, Qing Jie, Kenneth McEnaney, Feng Cao, Weishu Liu, Lee A. Weinstein, James Loomis, Zhifeng Ren, and Gang Chen, "Concentrating solar thermoelectric generators with a peak efficiency of 7.4%", *Nature Energy* 1, no. 11, pp. 1-8, 2016.

[9] Zhang, Ruiyan, Eric S. Kim, Sandra Romero-Diez, Yaxian Wang, Gang Huang, Andy Li, Yong Yang, and Patrick C. Lee. "Cyclic olefin copolymer foam: A promising thermal insulation material." *Chemical Engg J.,* 409:128251,2021.

[10] Kajihara, Takeshi, Kazuya Makino, Yong Hoon Lee, Hiromasa Kaibe, and Hirokuni Hachiuma. "Study of thermoelectric generation unit for radiant waste heat", *in Proc. 2.2 Materials Today*, pp. 804-813, 2015

[11] Fu, Yang, Jiang Yang, Y. S. Su, Wei Du, and Y. G. Ma, "Daytime passive radiative cooler using porous alumina", *J. Solar Energy Materials and Solar Cells* 191, pp. 50-54, 2019.

[12] Yao, Kaiqiang, Hongchen Ma, Min Huang, Haipeng Zhao, Jiupeng Zhao, Yao Li, Shuliang Dou, and Yaohui Zhan. "Near-perfect selective photonic crystal emitter with nanoscale layers for daytime radiative cooling." *J. ACS Applied Nano Materials* 2, 5512-5519, 2019.

[13] Liu, Junwei, Ji Zhang, Jianjuan Yuan, Debao Zhang, Jincheng Xing, and Zhihua Zhou. "Model development and performance evaluation of thermoelectric and radiative cooling module to achieve all-day power generation." *J. Solar Energy Materials and Solar Cells* 220, 2021.

[14] Hossain, Md Muntasir, and Gu. Min, "Radiative cooling: principles, progress, and potentials", *J. Advanced Science* 3.7, 2016.

[15] Zhang, Guoqiang, Wenlong Xu, Yongping Yang, and Dongke Zhang, "Utilization of LNG cryogenic energy in a proposed method for inlet air cooling to improve the performance of a combined cycle", Conf. *Energy Procedia* 61, 2014.

[16] Baker, E., "Liquid cooling of microelectronic devices by free and forced convection." *J. Microelectronics Reliability*, vol. 11, pp. 213-222, 1972.

[17] Maltezos, George, Aditya Rajagopal, and Axel Scherer, "Evaporative cooling in microfluidic channels." J. *Applied physics letters, vol.* 89, 2006.

[18] Alam, Hilman Syaeful, John Sasso, and Imam Djunaedi, "Study on performance improvement and economical aspect of gas turbine power plant using an evaporative cooling system", *J. of Mechatronics, Electrical Power, and Vehicular Tech, vol.* 6, pp.97-104, 2015.

[19] Wait, Sydney M., Sudipta Basak, Suresh V. Garimella, and Arvind Raman, "Piezoelectric fans using higher flexural modes for electronics cooling applications." *J. IEEE transactions on components and packaging technologies* 30, pp. 119-128, 2017.

[20] Pal, Aniruddha, Yogendra K. Joshi, Monem H. Beitelmal, Chandrakant D. Patel, and Todd M. Wenger. "Design and performance evaluation of a compact thermosyphon." *J. IEEE Transactions on Components and Packaging Technologies* 25, pp. 601-607, 2002.

[21] Maydanik, Yury F., Sergey V. Vershinin, Mikhail A. Korukov, and Jay M. Ochterbeck. "Miniature loop heat pipes-a promising means for cooling electronics." *J. IEEE Transactions on Components and Packaging Technologies* 28, pp. 290-296, 2005.

[22] Jiang, L., Mikkelsen, J., Koo, J.M., Huber, D., Yao, S., Zhang, L., Zhou, P., Maveety, J.G., Prasher, R., Santiago, J.G. and Kenny, T.W., "Closed-loop electroosmotic microchannel cooling system for VLSI circuits", *J. IEEE Transactions on Components and Packaging Technologies*, vol. *25*, no. 3, pp. 347-355, 2002.

[23] Kandlikar, Satish, Srinivas Garimella, Dongqing Li, Stephane Colin, and Michael R. King, "*Heat transfer and fluid flow in minichannels and microchannels",* Elsevier, 2005.

[24] Bintoro, Jemmy S., Aliakbar Akbarzadeh, and Masataka Mochizuki, "A closed-loop electronics cooling by implementing single phase impinging jet and mini channels heat exchanger", J. *Applied thermal engg. vol.* 25(17-18), pp. 2740-2753, 2005.

[25] Simons, Robert E. "Application of thermoelectric coolers for module cooling enhancement", J. *Electronics Cooling* 6, pp. 18-25, 2000.

[26] Kim, Yoon Jo, Yogendra K. Joshi, and Andrei G. Fedorov., "An absorption-based miniature heat pump system for electronics cooling", *Int. J. of refrigeration*, vol. 31, no. 1, pp. 23-33, 2008.

[27] Kandasamy, Ravi, Xiang-Qi Wang, and Arun S. Mujumdar, "Transient cooling of electronics using phase change material (PCM)-based heat sinks", *Applied thermal engg, vol.* 28, no. 8-9, pp. 1047-1057, 2008.

[28] Mochizuki, M., Nguyen, T., Mashiko, K., Saito, Y., Nguyen, T., & Wuttijumnong, V. (2011). A review of heat pipe application including new opportunities. *Frontiers in Heat Pipes (FHP)*, *2*(1), 1-15.

[29] Faghri, Amir, "Review and advances in heat pipe science and technology", *J. of heat transfer*, vol. 134, no. 12, 2012.

[30] El-Nasr, A. Abo, and S. M. El-Haggar, "Effective thermal conductivity of heat pipes", *Heat and Mass transfer*, vol. 32, no. 1, pp. 97-101, 1996.

[31] Garner, Scott D., "Heat pipes for electronics cooling applications" J. *Electronics Cooling* 2, pp. 18-23, 1996.

[32] Chen, Xianping, Huaiyu Ye, Xuejun Fan, Tianling Ren, and Guoqi Zhang. "A review of small heat pipes for electronics." Applied Thermal Engineering 96 (2016): 1-17.

[33] Kandasamy, Ravi, Xiang-Qi Wang, and Arun S. Mujumdar, "Application of phase change materials in thermal management of electronics", J. Applied Thermal Engg., vol. 27, no. 17-18, pp. 2822-2832, 2007.

[34] Krishnan, Shankar, Suresh V. Garimella, and Sukhvinder S. Kang., "A novel hybrid heat sink using phase change materials for transient thermal management of electronics", *IEEE Transactions on Components and Packaging Technologies,* vol. 28, no.2, pp. 281-289, 2005.

[35] Wang, Siyun, and Michael Baldea. "Storage-enhanced thermal management for mobile devices." *2013 American Control Conference*, pp. 5344-5349. IEEE, 2013.

[36] Jaworski, Maciej, and Roman Domañski, "A novel design of heat sink with PCM for electronics cooling." *10th Int. Conf. on Thermal Energy Storage, Stockton*, vol. 31, 2006.

[37] Simons, R. E., and R. C. Chu., "Application of thermoelectric cooling to electronic equipment: a review and analysis." *Sixteenth Annual IEEE Semiconductor Thermal Measurement and Management Symposium (Cat. No. 00CH37068)*. IEEE, 2000.

[38] Seifert, W., V. Pluschke, and N. F. Hinsche., "Thermoelectric cooler concepts and the limit for maximum cooling" *J. of Physics: Condensed Matter*, vol. 26, no. 25, 2014.

[39] Baby, R., and C. Balaji., "Thermal management of electronics using phase change material based pin fin heat sinks", *J. of Physics: Conf. Series*, vol. 395, no. 1, IOP Publishing, 2012.

[40] Zebarjadi M., "Electronic cooling using thermoelectric devices" J. *Applied Physics Letters*, vol.106, no. 20, 2015.

[41] Sangchandr B., and V. Afzulpurkar., "A novel approach for cooling electronics using a combined heat pipe and thermoelectric module", *J. Eng. Appl. Sci*, vol. 2, no.4, pp. 603-610, 2009.

[42] Kim and Jungho., "Spray cooling heat transfer: The state of the art", *Int. J. of Heat and Fluid Flow*, vol. 28 no. 4, pp. 753-767, 2007.

[43] Liu, H., Cai, C., Yan, Y.A., Jia, M. and Yin, B., "Numerical simulation and experimental investigation on spray cooling in the non-boiling region", *Heat and Mass Transfer,* vol. 54, no. 12, pp. 3747-3760, 2018.

[44] B. Agostini, M. Fabbri, J. E. Park, L. Wojtan, J. R. Thome and B. Michel, "State of the art of high heat flux cooling technologies", *Heat Transfer Engineering*, vol. 28, no. 4, pp. 258-281, 2007.

[45] Marcinichen, Jackson Braz, John Richard Thome, and Bruno Michel, "Cooling of microprocessors with micro-evaporation: A novel two-phase cooling cycle", *Int J. of refrigeration*, vol. 33, no. 7, pp. 1264-1276, 2010.

[46] P. Ganapati "Water-cooled supercomputer doubles as dorm space heater", *IBM, Zürich, Switzerland, accessed Jan* 29 (2009): 2018.

[47] W. Escher, T. Brunschwiler, B. Michel and D. Poulikakos, "Experimental investigation of an ultrathin manifold microchannel heat sink for liquid-cooled chips", J. of Heat Transfer, vol. 132, no. 8, 2010.

[48] Chandratilleke, T. Tilak, Deepak Jagannatha and Ramesh Narayanaswamy, "Synthetic jet-based hybrid heat sink for electronic cooling", *Heat Transfer-Mathematical Modelling, Numerical Methods and Information Technology*. InTech, pp. 435-454, 2011.

[49] Omer, Abdeen Mustafa, "Ground-source heat pumps systems and applications." *Renewable and sustainable energy reviews,* vol. 12, no. 2, pp. 344-371, 2008.

[50] Volkova, Anna, Henrik Pieper, Hardi Koduvere, Kertu Lepiksaar, and Andres Siirde, "Heat pump potential in the Baltic states", 2021.

[51] Choi, S. US, and Jeffrey A. Eastman, "*Enhancing thermal conductivity of fluids with nanoparticles*", No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab., IL (United States), 1995.

[52] Buongiorno and Jacopo, "Convective transport in nanofluids", pp. 240-250, 2006.

[53] Ma, Kunquan, and Jing Liu, "Liquid metal cooling in thermal management of computer chips", *Frontiers of Energy and Power Engineering in China*, vol. 1, no. 4, pp. 384-402, 2007.

[54] Xuewei Yan, Ning Tang, X. Liu, G. Shui, Qingyan Xu and Baicheng Liu, "Modeling and simulation of directional solidification by LMC process for nickel-base superalloy casting" Acta Metallurgica Sinica -Chinese Edition-. 51, pp. 1288-1296, 2015.

[55] S.C. Mohapatra and D. Loikits, "Advances in liquid coolant technologies for electronics cooling" *Semiconductor Thermal Measurement and Management IEEE Twenty-First Annual IEEE Symposium,* pp. 354-360, 2005.

[56] Choi, Stephen US, Z. George Zhang, and Pawel Keblinski, "Nanofluids", *Encyclopedia of nanoscience and nanotechnology*, vol. 6, no. 773, American Scientific Publishers, pp. 757-773, 2004.

[57] Wong, V. Kaufui, and Omar De Leon, "Applications of nanofluids: current and future", *Advances in mechanical engg.* 2, 2010.