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*Review*

# Nanofluids for the Next Generation Thermal Management of Electronics: A Review

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**Abstract:** Nowadays, the thermal management of electronic components, devices and systems is one of the most important challenges of this technological field. The ever-increasing miniaturization also entails the pressing need for the dissipation of higher power energy under the form of heat per unit of surface area by the cooling systems. The current work briefly describes the use on those cooling systems of the novel heat transfer fluids named nanofluids. Although not intensively applied in our daily use of electronic devices and appliances, the nanofluids have merited an in-depth research and investigative focus, with several recently published papers on the subject. The development of this cooling approach should give a sustained foothold to go on to further studies and developments on continuous miniaturization, together with more energy-efficient cooling systems and devices. Indeed, the superior thermophysical properties of the nanofluids, which are highlighted in this review, make those innovative fluids very promising for the aforementioned purpose. Moreover, the present work intends to contribute to the knowledge of the nanofluids and its most prominent results from the typical nanoparticles/base fluid mixtures used and combined in technical and functional solutions, based on fluid-surface interfacial flows.

**Keywords:** nanofluids; thermal management; electronics; fluid-surface interfacial flows



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## 1. Introduction

The technological and scientific development in the past decades has led to an increase in demand for new cooling fluids able to surpass the conventional ones, namely air and water, to improve, among other characteristics, the lifespan of electronic systems and components [1]. The working fluids that have been increasingly investigated are the nanofluids. Those fluids are the suspension of nanoparticles of metals, oxides, or multi-walled carbon nanotubes, with sizes between 1 and 100 nm, in conventional heat transfer fluids designated by base fluids (water, ethylene glycol, oil) [2,3]. The inclusion of the nanoparticles will alter the thermal properties, such as the thermal conductivity, dynamic viscosity, and the density of the stand-alone conventional fluids. The nanofluids contribute to the improvement of heat transfer processes and to miniaturize the thermal management of systems and devices [4]. The different thermal properties of such fluids, such as the thermal conductivity, can be adjusted by altering, among other parameters, the nanoparticles' concentration, making nanofluids suitable for a wide range of applications. Nevertheless, the preparation methods and use of the nanofluids still have some limitations. For instance, the sedimentation and aggregation of the nanoparticles are difficult to control and may increase the viscosity of the nanofluids, which in turn requires extra pumping power of the operating devices. In addition, the synthesis of the nanofluids is complex and it is not yet a cost-effective process, being expensive in some particular cases. On top of that, there is no consensus on the preparation protocol and exact concentration and type of particles required for the best performance. In spite of these difficulties, more competitive preparation techniques have been developed in recent years. For example, titanium dioxide nanofluids can be obtained nowadays by the Vapor Deposition Technique [5]. Due to the previously mentioned advantages, nanofluids have been applied to a wide variety of fields [6]. For instance, nanofluids were used in the cooling of electronic parts such as CPUs [7], transformers [8], motor engines [9], and nuclear reactors [10]. In machining and grinding techniques, the nanofluids were employed as lubricant and cutting fluid [11]. The thermal properties of the nanofluids were also useful to improve the heat transport mechanisms and, consequently, the thermal efficiency of systems such as heat pipes [12], thermosyphons [13], and heat exchangers and heat sinks [14]. Recently, there has been a growing interest in the use of the nanofluids in the nanomedicine field, with the use of magnetic nanoparticles on diagnostic techniques, hyperthermia treatments, and as drug carrying and release vehicles [15]. However, the scale-up production methods for commercialization are still in an embryonic stage of development. One of the most relevant properties of nanofluids is their thermal conductivity. This is influenced by the type, size, shape, and concentration of the nanoparticles and by the temperature, pH, sonication time and frequency, addition of surfactants, magnetic field, and aggregation [16]. The nanofluids, possessing superior thermal properties, can meet the cooling requirements of recent small electronic devices. Since thermal conductivity is one of the most important properties of any cooling fluid, researchers have mostly focused on this property of the nanofluids. The nanofluids also exhibit superior thermal diffusivity and viscosity than those of the base fluids [17]. The thermal conductivities of nanofluids are a function of the volume fraction of the nanoparticles. However, results from different research groups are not consistent and there are also controversies regarding the heat transfer mechanisms [18]. The study of the heat transfer characteristics of the nanofluids is critical to evaluate their suitability as coolants in electronic devices and systems. When compared to research works on thermal conductivity, studies on the heat transfer of nanofluids in heat dissipation systems are still rather scarce. Recent investigations reported that nanofluids depict improved heat transfer performance when compared to their base fluids and that the enhancement of the heat transfer coefficient further increases with an increasing loading of nanoparticles, Reynolds number, and flow rate [19]. Because of compact dimensions, lightweight and superior cooling behavior, extensive research works were performed using microchannel-based cooling systems in electronic equipment [20,21]. Given that convective heat transfer is inversely proportional to the hydraulic diameter, the better heat transfer performance can be obtained through the use of microchannels. However, the limitations of microchannel cooling performance actually come from the low heat transfer capability of conventional fluids. To overcome this fact, the use of nanofluids increases the heat dissipation rate of microchannel-based cooling systems. Some research studies have been made with nanofluids in cooling systems of commercial electronic or computing devices. The findings showed that using nanofluids resulted in improved cooling performance when compared to the conventional coolants. Indeed, in electronic devices and systems, the cooling and thermal management are of paramount importance because their performance is directly affected by the operating temperature, and their life-cycle longevity is also influenced by the thermal stress entailed by long-term working. Nowadays, the most developed and investigated cooling techniques are mainly focused on the regular use of devices with microchannels, such as heat sinks and heat exchangers, heat pipes, thermosyphons, jet and spray cooling, phase change materials, and free convection and thermoelectric devices. Those thermal management approaches, together with the use of nanofluids, will be described in detail in this work. The superior thermal properties of these innovative fluids improve the thermal management capabilities of the systems, especially concerning the enhanced thermal conductivity and heat transfer rate usually achieved by these fluids, which surpasses the performance of the traditional and commercially available cooling fluids. Despite the main shortcomings of the nanofluids, such as the high-cost preparation methods and equipment and the lack of long-term stability for certain compositions and volume fractions, the authors of this work consider their superior thermal properties to clearly surpass in importance the limitations regarding the usage of the nanofluids as thermal management fluids. The major contributions of the current work are to provide a comprehensive and actualized survey concerning the use of the nanofluids as coolants for the cooling techniques of electronic equipment, and also to give an overview of the underway projects and research lines dealing with the use of the nanofluids in the thermal management of electronics, as well as to provide extension guidelines for further research on this innovative field of application. In this sense, the laboratory of the authors of this work was very useful for the potential boiling heat transfer of the nanofluids, especially when the use of this novel class of fluids came together with the development of innovative materials and biphilic surfaces, which will certainly improve the heat transfer capabilities of systems dealing with nucleate boiling heat transfer. Moreover, the research team of the authors of the present work has performed experimental work and numeric simulations, and have already published several scientific articles on the referred subject. The present review has the following presentation structure: the first sections (Sections 2 and 3) are concerned with preparation and thermal conductivity measurement and its impacting parameters, and Section 4 analyzes the most studied methods for electronic components and devices using nanofluids.

## 2. Preparation Methods

The nanofluids were prepared via single or two-step methods. The single-step methods are suitable for small-scale production and involve the simultaneous preparation and suspension of the nanoparticles into the base fluid. The single-step methods can be divided into three main processes: vapor deposition, with special emphasis to the pulse wire evaporation method, laser ablation, and submerged arc. Figure 1 presents the most representative preparation methods of the nanofluids and Table 1 summarizes the methodology, advantages, and limitations of those methods.

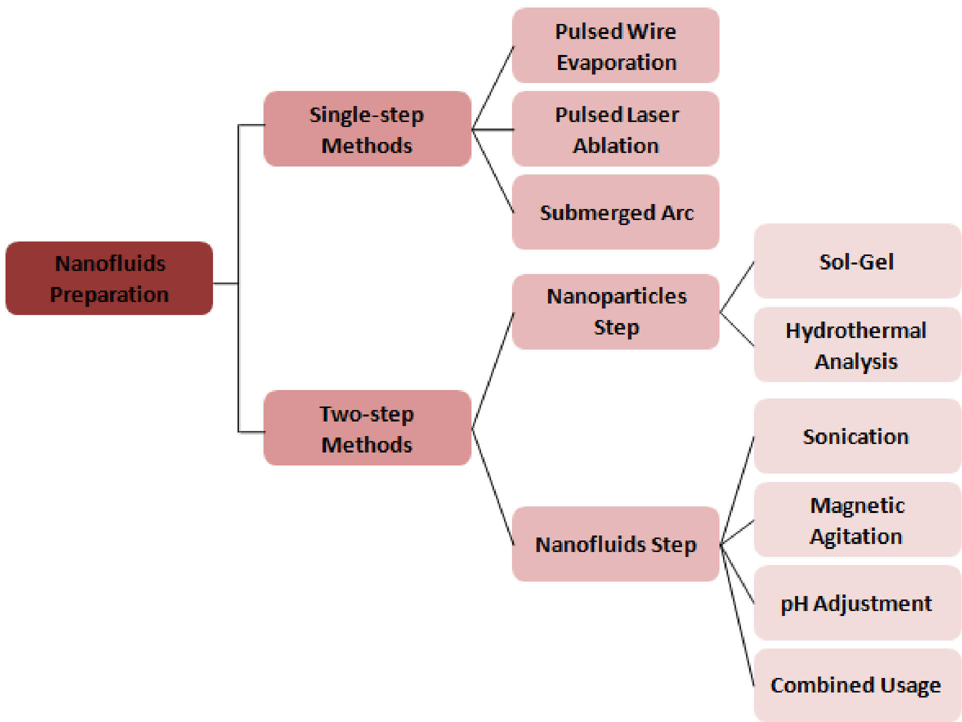


**Figure 1.** Methods for preparation of the nanofluids.

**Table 1.** Methodology, aim, advantages and limitations of the preparation methods of nanofluids.

| Single-Step | Methodology | Aim/Results | Advantages | Limitations |
|---|---|---|---|---|
| Pulsed Wire Evaporation | Applying high-voltage to a metal wire that evaporates and condensates into nanoparticles | Uniform dispersion of nanoparticles in the base fluid | Avoids contamination. Improves particle size control and minimizes agglomeration | Need of high temperatures to evaporate materials hinders the production of certain nanofluids |
| Pulsed Laser Ablation | Irradiate with laser the surface of a material submerged in the base fluid to disperse the nanoparticles | Uniform dispersion of the vaporized nanoparticles in the base fluid | Reliable and cost-effective technique. Relatively fast method | In some cases requires stirring and addition of surfactants to the base fluid |
| Submerged Arc | Apply an electric pulse to evaporate the material in the Base fluid | Uniform dispersion of the vaporized nanoparticles in The base fluid | Stable nanofluids with uniform distribution of nanoparticles | In some cases requires stirring and the addition of surfactants to the Base fluid |
| **Two-Step** | **Methodology** | **Aim/Results** | **Advantages** | **Limitations** |
| Sol-Gel | Dissolution of nanoparticles, sonication, hydrolysis and drying of the gel | Crystalline nanopowder dispersion | Nanoparticles with high surface area; Low-cost method | Agglomeration of nanoparticles requires additives or surfactants |
| Hydrothermal Synthesis | Synthesizes ingle-crystal under high temperature And pressure | Synthesize single-crystal from aqueous solutions | Low energy consumption and environmental benevolence | Cost of the autoclave and in some cases needs acid catalysts |
| Sonication | Applying frequency higher than 20 kHz to the nanofluid | Reducing cluster formation by breaking molecular interactions | Avoids agglomeration/sedimentation of nanoparticles | Adjustment of sonication time that influences the size of the nanoparticles |
| Magnetic Agitation | Spinning of a magnetic stir bar under a rotating magnetic field | Uniform dispersion of particles in the base fluid | Avoids agglomeration/sedimentation of nanoparticles | In some cases requires a surfactant; Time-consuming |
| pH Adjustment | Addition of HCl or NaOH to adjust the Ph of the suspension | Raise the zeta potential and stability | More electrically stable suspension | It requires pH measuring equipment |
| Combined Usage | Combination of sonication, magnetic agitation and pH adjustment | Uniform dispersion and stability | Avoids clusters and agglomeration | In some cases requires surfactants and solvents |

## 3. Parameters That Affect Thermal Conductivity

The thermal conductivity of the nanofluids can be affected by several factors, since many preparation parameters can vary widely. From the characteristics of the nanoparticles itself to their volumetric fraction in the fluid, all those factors contribute, directly or indirectly, to induce variations in the thermal conductivity. Figure 2 summarizes the main parameters that had an impact on the thermal conductivity of nanofluids and a brief survey of the impact of each factor is presented in the following sub-sections.

Type of the Nanoparticles: Different types of nanoparticles have been tested, such as metals, metal oxides, ceramics, and carbon nanotubes. Some reports indicated that the thermal conductivity of the nanoparticles is less relevant to increase the nanofluids' heat transfer rates, while others have suggested that nanoparticles with higher values of thermal conductivity increase the heat transfer in the nanofluids [22]. For instance, Wang et al. [23] compared the thermal conductivity of water-based nanofluids with copper and alumina nanoparticles. The greater enhancement of the thermal conductivity in the copper nanofluid was attributed to the higher thermal conductivity of the copper.

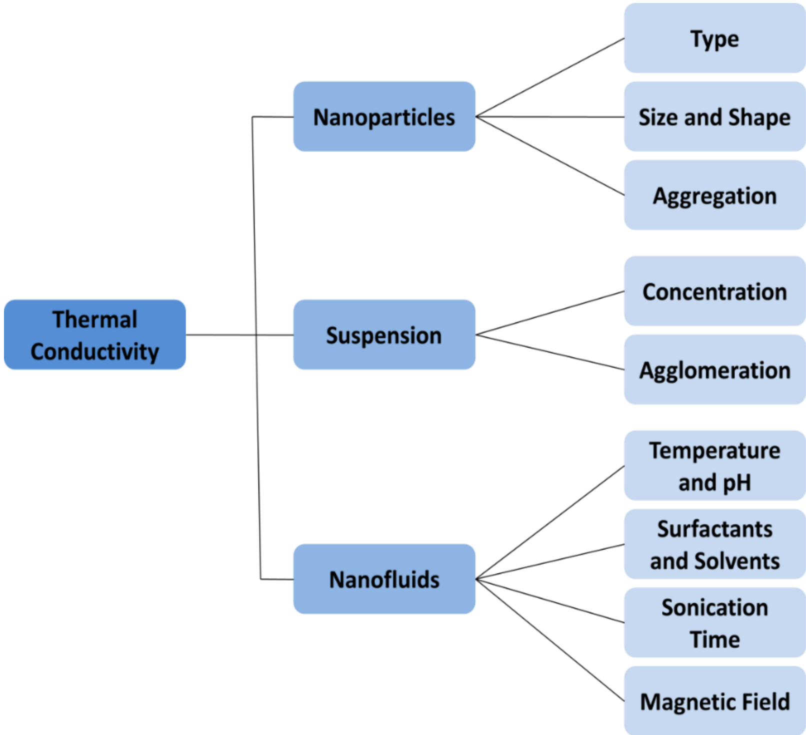


**Figure 2.** Main parameters impacting on the thermal conductivity of nanofluids.

Size and Shape of Nanoparticles: The influence of the size of nanoparticles is still not unanimous among the scientific community. Ambreen and Kim [24] believed that the reduction of the size of nanoparticles increases surface area, thickens the interfacial layer, and enhances the Brownian motion. For these reasons, the thermal conductivity of the nanofluids increases with the reduction of the particle diameter. Xu et al. [25] measured the thermal conductivity of water-based nanofluids with $Al_2O_3$ nanoparticles and a reduction with increasing sizes of the nanoparticles was observed. Spherical, cylindrical, rod, rectangular, platelet, and blade shapes of nanoparticles were studied with nanofluids. With instrumental analysis techniques like the Rayleigh scattering diagrams, it can be stated that characteristics such as the spherical/cylindrical shapes of nanoparticles, appear to be clearly symmetric/asymmetric [26]. The results indicated that the particles with larger aspect ratios contribute more to the enhancement of the thermal conductivity, since thermal penetration increases and the interfacial thermal resistance on heat transfer is reduced. Murshed et al. [27] observed a greater increase in the thermal conductivity values ofwater-based $TiO_2$ nanofluids when using rod-shape nanoparticles than when using spherical ones. In addition, the nanofluids with platelet shape particles were the lower ones among the testing group.

Aggregation of the Nanoparticles: The introduction of carbon nanotubes in the nanofluids promoted significant research efforts due to their enhanced thermal conductivity. However, the nanofluids with only a suspension of stand-alone nanotubes do not often exhibit enhanced thermal conductivity levels. This is likely due to the infrequent physical contacts of the nanotubes between each other, as they assume irregular positioning and distribution in the base fluid. Increasing the volume fraction of the nanotube on the base fluid may overcome this difficulty, but it also may lead to excessive viscosity. Moreover, some studies [28] have proved that the aggregation of oppositely charged nanoparticles (metal oxide and nanotubes) into combined clusters provided a thermal conductivity enhancement. It is also possible to add positively charged metal oxide particles on the base fluid that will aggregate on the negatively charged nanotube surface (aggregation that is enhanced with the addition of a surfactant) and hence build the aggregation cluster chain along the nanotube by electrostatic attraction.

Concentration of the Suspension: The increase in the particle concentration enhances the thermal conductivity due to the greater interfacial area between the base fluid and the nanoparticles and increasing agglomeration [29]. Jana et al. [30] observed a linear relation between concentration and thermal conductivity using water-based coppernanofluids. Choi et al. [31], using nanoparticles of $Al_2O_3$ and CuO, measured the thermal conductivity of nanofluids with concentrations lower than 0.05 vol. % and found that the thermal conductivity ratios increased almost linearly with volume fraction, but with different rates of increase for each group of nanoparticles tested. However, some reports noted a reduction of thermal conductivity for high concentration values. The concentration of the nanoparticles can be correlated with the thermal conductivity of the nanofluids by the Hamilton and Crosser model [32] equation:

$$K_{nf} = \frac{K_p + (n-1)K_{bf} + (n-1)\left(K_p - K_{bf}\right)\Phi_V}{K_p + (n-1)K_{bf} - \left(K_p - K_{bf}\right)\Phi_V} \times K_{bf} \tag{1}$$

where $K_{nf}$, $K_p$ and $K_{bf}$ are the thermal conductivity of the nanofluid, nanoparticles and base fluid, respectively, $\Phi$ is the volume fraction of the nanoparticles and $n$ is the shape factor connected to the particles' sphericity ($n = 3/\Phi$). This model is valid when the thermal conductivity of the particles is at least 100 times higher than the thermal conductivity of the base fluid. Similarly, Xue et al. [33] introduced a model which derives from the Maxwell model and includes the effect of the axial ratio and space distribution of the particles and can be expressed by the following equation:

$$K_{nf} = \frac{1 - \Phi_V + 2\Phi_V \frac{K_p}{K_p - K_{bf}} ln \frac{K_p + K_{bf}}{2K_{bf}}}{1 - \Phi_V + 2\Phi_V \frac{K_{bf}}{K_p - K_{bf}} ln \frac{K_p + K_{bf}}{2K_{bf}}} \tag{2}$$

Patel et al. [34] developed a model that depends once more on the volume fraction of the nanoparticles and on the radii of the nanoparticles and base fluid, and it can be expressed by the following equation:

$$K_{nf} = K_{bf}\left[1 + \frac{K_p \Phi_V r_{bf}}{K_{bf}(1 - \Phi_V) r_p}\right] \tag{3}$$

In addition, the following equation derived from the uniform distribution model, and under the assumptions of $K_{bf}/K_p << 1$ and sphericity of the nanoparticles, can also correlate the thermal conductivity of the nanofluid with the concentration of the nanoparticles:

$$\frac{K_{nf}}{K_{bf}} = 1 + \Phi_V ln\left(\frac{27K_p}{16K_{bf}}\right) K_{bf}$$

$$\frac{K_{nf}}{K_{bf}} = 1 + C_K \Phi_V \tag{4}$$

where $C_K$ is the constant determined by matching the Equation (4) with the experimental results. $C_K$ = 3 (for a dilute system with spherical particles) can be used as a medium theory criterion for a specific nanofluid. If there is an increase in the $K_{nf}$ by a factor of 3, the heat transfer coefficient of the same working fluid will double. Accordingly, it should be noted that the concentration of the nanoparticles can also be directly correlated with all the viscosity terms present in the system by the following equation under the same assumptions:

$$\frac{K_{nf}}{K_{bf}} = 1 + C_{\mu}\Phi_{V} \quad (5)$$

where $c_{\mu}$ is equal to 2.5 in the pioneering model of Einstein [35] for rigid spherical particles under low particle volume fractions. However, it is usual to determine $c_{\mu}$ by also matching the Equation (5) with the experimental results. In this sense, a first order estimation of $C_{\mu}$ = 10 can be used.

Agglomeration of the Suspension: The agglomeration of particles contributes to the enhancement of the thermal conductivity by providing extra conduction paths on the nanofluids. For fluids with smaller particles, the aggregation is more prone to occur. The way that agglomeration occurs in nanofluids with greater volume fractions depends on the shape of the particles. Hong et al. [36] observed an increase in thermal conductivity with an increase in the aggregation of the particles in a water-based alumina nanofluid. On the other hand, large agglomerates of particles can lead to sedimentation and reduction of the thermal conductivity. Jana et al. [30] noted a decrease in the thermal conductivity with an increase in sedimentation time in water-based copper and carbon nanotubes nanofluids.

Temperature and pH: Some reports indicated that the thermal conductivity is enhanced with temperature increase, while others reported a reduction of the thermal conductivity with the same effect. Duangthongsuk et al. [37] observed a decrease in the thermal conductivity with an increasing temperature in water-based $TiO_2$ nanofluids. The enhancement of the thermal conductivity with an increasing temperature is thought to be caused by the improvement of the Brownian motion and the reduction of the surface energy of the particles. On the contrary, a reduction of the thermal conductivity with increasing temperature was reported for nanofluids with non-spherical particles, which indicated that the aspect ratio of the particle is of influence. Moreover, the pH of the nanofluids affects the aggregation degree of the nanoparticles and, hence, the thermal conductivity. Wang et al. [38] reported an increasing enhancement of the thermal conductivity with increasing pH until the isoelectric point, which is then followed by a decrease. This was attributed to the increase in electrical charge on the surface of the nanoparticles, leading to greater electrostatic repulsion. An experimental work [39] has also shown that the pH influences the zeta potential, particle size distribution, rheology, viscosity andstability, which are factors that affect the thermal conductivity of the nanofluids containing $ZrO_2$ and $TiO_2$ nanoparticles.

Surfactants and Solvents: The incorporation of additives on the nanofluids can improve the stability of the fluid over time. For instance, Wang et al. [38] and Zhu et al. [40] identified the optimal concentration of the surfactant SDBS (sodium dodecylbenzenesulfonate) to increase the thermal conductivity of water-based copper and alumina nanofluids. An experimental work [41] proved the impact of the alignment and dispersion of the nanoparticles on the thermal conductivity of the nanofluids that the surfactants and solvents have. In this study, the authors measured the thermal conductivity of $Fe_2O_3$and CuO nanoparticles dispersed in water, ethylene glycol, and water with SDBS.

Sonication Time: The increase of the sonication time contributes to an increase in the thermal conductivity, since sedimentation is mitigated and the particle distribution uniformity is improved. Nevertheless, if the sonication time is too long, aggregation decreases and so too does the thermal conductivity. Hong et al. [42] reported increasing values of thermal conductivity with increasing sonication time until 50 min for ethylene glycol-based iron nanofluids, but longer sonication procedures corresponded to a decrease in thermal conductivity.

Applied Magnetic Field: The nanofluids can incorporate magnetic nanoparticles with different configurations. If the magnetic field is strong enough, the small-dimensioned particles will form networks or chains that tend to orient towards the magnetic field direction. This alignment effect moves the particles nearby and promotes a larger number of physical contacts and interaction between each other and, thus, results in the enhanced thermal conductivity and heat transfer capability of the nanofluid. This effect can be observed, for instance, in the experimental works performed with Ni and carbon nanotubes [43]. Moreover, the thermo-magnetic convection in a cubical enclosure of a silver nanofluid under a strong magnetic field was already studied [44], resulting in a heat transfer enhancement of the nanofluid and a flow structure with diagonal axis of symmetry.

## 4. Cooling of Electronics

### *4.1. Challenges and Novel Coolants*

The thermal management is still currently a technological challenge for the electronic equipment in spite of the ever-increasing microprocessor working speed. As a consequence, the dissipation of enhanced heat flux remains as one of the main limitations in the electronic field. The development of the electronic technology and non-stopping miniaturization of components and devices led to an increment in the heat power loads of high-density chips. Despite the notorious evolution that has occurred in recent years, there are still unsolved technological challenges left in the cooling kits and systems of electronic equipment. The most prominent challenges are the removal of the gradually increasing heat flux and the high-power heat dissipation. Furthermore, due to the increasing integration of components and devices, the power heat removal on the chip is getting more non-uniform, given that the heat flux of a chip is much higher than that of its surroundings. The traditional cooling techniques are insufficient to overcome the cooling requisites of the modern electronic components and devices. Consequently, the recent high-performance chips, components, and devices demand novel methods and coolants with a higher heat transfer ability in order to boost the heat dissipation rate necessary to maintain the normal operating temperature of the electronic devices. Unless the latter are cooled in an appropriate manner, their performance and durability will deteriorate faster than predicted. Moreover, the failure rate of the electronic components and devices usually augment with increasing working temperature. Furthermore, the major part of the conventional cooling methods do not achieve the required performance of the backdraws related to the heat transfer capability of conventional coolants such as air, water, water and ethylene glycol mixtures, and oil, which possess relatively low thermal conductivity and convective heat transfer coefficients. For example, to bear a heat flux of 100 $W/cm^2$ at a temperature gradient of 50 K, it requires a heat transfer coefficient of around 20,000 $W/m^2 \cdot K$, which is not possible through conventional free and forced convections [45]. Thus, there is the pressing need to find cooling fluids with superior heat transfer performance and, consequently, there are fluids like the nanofluids, which can be used as novel advanced coolants. With improved thermal properties, the nanofluids offer benefits in a wide range of applications, including the cooling of electronic components and devices [46]. Despite the progress made on electronic cooling systems, the required high heat flux removal remains very challenging. The existing cooling modes can be classified into the following categories [47]:

1. Natural convection;
2. Forced convection air cooling;
3. Forced convection liquid cooling;
4. Liquid evaporation.

Based on the heat flux dissipating rate of these methods, it is known that liquid evaporation is the best technique, followed by the forced convection of liquids and air. However, forced air convection, which is widely used in the cooling of electronic components such as CPUs, has a relatively low heat removal rate. On the other hand, liquid immersion cooling promotes high heat transfer coefficients, which reduces the temperature rise of the chip. Since the heat transfer coefficient is affected by the coolants, the following points describe the main coolants for electronic components and devices.

**Conventional coolants:** The liquid coolants for electronics should present most of the following [48]:

1. Non-flammability and non-toxicity;
2. Cost-effectiveness;

3. High thermal conductivity, specific heat and heat transfer coefficient;
4. High boiling point and low viscosity;

The most broadly used coolant for electronic devices and systems is water, as it has higher thermal conductivity and specific heat and also lower viscosity when compared to the other conventional coolants. Nevertheless, water is not commonly utilized in closed loop cooling systems, due to its high freezing temperature and thermal expansion upon freezing. The conventional coolants can be classified into dielectric and non-dielectric fluids [48]:

**Dielectric coolants:**

1. Aromatic-based liquids: Due to lower cost and better performance, alkylated aromatics such astoluene, benzene, and xylene are the most often used coolants;
2. Aliphatic-based liquids: Aliphatic hydrocarbons of paraffinic and iso-paraffinic types (including mineral oils) and aliphatic polyolefins are used in the cooling of electronics;
3. Silicone-based liquids: The main advantage of those coolants, commonly known as silicone oils, is their properties such as viscosity and freezing point;
4. Fluorocarbon-based fluids: These fluids are inert, stable, non-flammable and non-reactive. The commercially available FC-72 and FC-77 are the most commonly used for electronic cooling.

**Non-Dielectric coolants:** The non-dielectric liquid coolants are often used in cooling kits and systems of electronic equipment due to their optimal thermal properties when compared to the ones of the dielectric coolants. The non-dielectric coolants are usually aqueous solutions with enhanced thermal conductivity and heat capacity and low viscosity. Therefore, water, ethylene glycol, and a mixture of both are widely used as coolants for electronic devices. Other often-used, non-dielectric coolants include propylene glycol, water/methanol, water/ethanol, NaCl solution and potassium formate solution [48].

**Innovative coolants:** The application of nanofluids in conventional and emerging techniques such as microchannels and heat pipes will constitute the next generation cooling systems of electronic components and devices.

### *4.2. Cooling Methods of Electronics*

Due to technological advances, electronic devices are more compact, lighter, and are made with increasing processing speed. Moreover, greater heat fluxes are generated by those devices, and the traditional cooling methods are not able to achieve the required higher heat dissipation rates. The cooling of electronic components and devices is often carried out by one of the cooling methods present in the Figure 3.

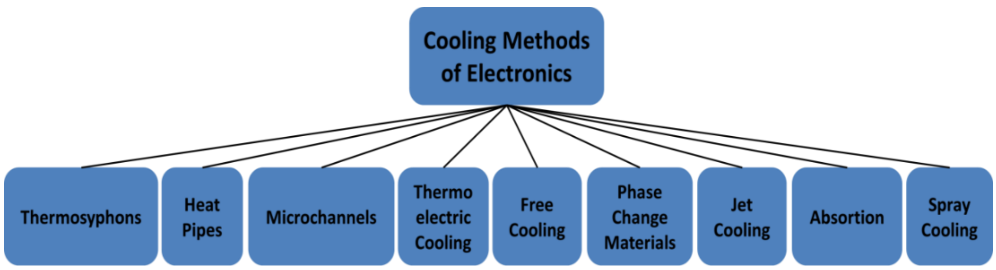


**Figure 3.** Cooling methods of electronic components and devices.

These cooling techniques can be divided into passive and active systems. The passive cooling systems utilize capillary or gravitational buoyancy forces to circulate the working fluid, while active cooling systems are driven by a pump or compressor for improved cooling capacity and performance. The next subsections explore each one of the cooling methods.

#### 4.2.1. Thermosyphons

One widely used method for the cooling of electronic devices and equipment is one that uses miniaturized closed two-phase thermosyphons with different configurations. These possess improved heat transfer characteristics, and its manufacturing is simple. Their relevant operating parameters include the length of the heating/evaporation and condensation zones, the diameter of the thermosyphon channel, and the thermal properties of the refrigerant, among others [49]. A decrease in the diameter of the channel reduces the heat transfer rate, whilst the use of nanofluids provides a notorious increase in the nucleate-boiling critical heat flux of the two-phase thermosyphon [50,51]. The best results for increasing the heat transfer in the thermosyphons were observed upon adding nanoparticles of titanium and copper oxides. It was found [52,53] that these additions significantly decreased the thermal resistance and, at the same time, improved the heat transfer performance of the two-phase thermosyphons. The volume fraction of the nanoparticles proved to be of importance, indicating that is likely to be a concentration that optimizes the heat transfer of thermosyphons.

#### 4.2.2. Heat Pipes

Several researchers focused their studies on using the heat pipe for cooling electronic devices, and all of them observed that the heat pipe due to its high effective thermal conductivity is suitable for cooling electronic devices such as desktop and notebook computers. The surface area of the process, or in notebook or laptop computers, where the greater amount of heat is generated, is commonly around ten square-millimeters. In order to achieve an efficient cooling rate, the heat has to spread over a large surface area distance from the CPU, as its surrounding physical space is limited. Therefore, heat must be drawn from the CPU and carried to a point from where it can be swiftly removed by traditional cooling methods. This feature can be accomplished with the use of a heat pipe, which can be lodged in a very limited physical space in such a manner that its evaporating section is directly linked with the heat source while the condensation section is exposed to the sink [54]. The main characteristics of the heat pipes are the absence of moving parts, minimal maintenance, no power consumption, noise free, longevity, low cost, better application flexibility due to the simple and robust construction, compact size, and sealed enclosure cooling, implicating no adverse effect to the electronic devices. Moreover, the geometric symmetry of cylindrical heat pipes facilitates the numerical simulations based on double precision axi-symmetric conditions [55]. The high heat transfer performance of a heat pipe is achieved due to the high latent heat of the vaporization of the working fluid. Due to the high thermal conductivity and low thermal resistance (0.05 to 0.4 °C/W [56]), the heat pipes' utilization is among the most viable technique of cooling high-heat-generating electronic equipment, such as a CPU. Chen et al. [57] made a review on the development and performance of the application of heat pipes on the cooling of electronic devices and systems. Yousefi et al. [58] investigated the heat transport performance of a CPU-cooling heat pipe utilizing nanofluids. Using a 0.5 wt. % $Al_2O_3$/water nanofluid, the thermal resistance decreased by 22%. This fact stipulates that this nanofluid can perform better when compared to water in cooling a CPU. Figure 4 schematically illustrates the operating principle of a generic heat pipe.

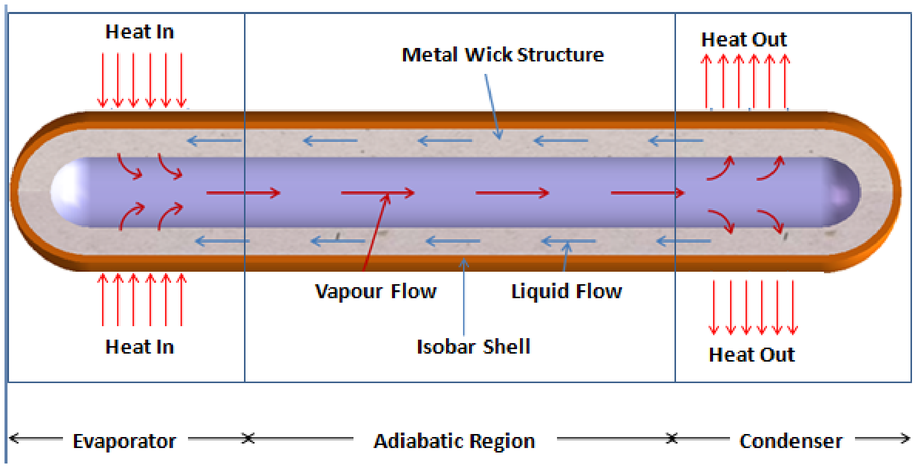


**Figure 4.** Operating principle of a generic heat pipe.

Hinge et al. [59] used nanofluids in an oscillating heat pipe and the results showed a significant enhancement of the heat transfer. To ascertain the main factors that impact the heat transfer enhancement of an oscillating heat pipe, the thermal conductivity of the motionless nanofluids was measured. At a temperature of 21 °C, the thermal conductivity of the nanofluids was determined to be 1 W/m·K, while the value for water alone was 0.6 W/m·K. The results of Kim et al. [60] showed that the utilization of a heat pipe for the cooling of a CPU augmented the amount of dissipated heat without requiring high-speed fans. Moreover, the closed-end oscillating heat pipe (CEOHP) was introduced by Rittidech and Boonyaem [61] for the cooling of a CPU. The CEOHP module was expected to transport more than 70 W of heat power. The corresponding results showed that the thermal performance improved with increasing fan speed, where fan speeds of 2000 and 4000 rpm were used. Wang et al. [62] investigated a heat pipe connected to a heat sink, with the heat input transported from the CPU to the base plate and from this to the heat pipe. The results indicated that 64% of the total dissipated heat was transferred from the CPU to the base plate and from this to the fins, whereas 36% was transported from the heat pipe to the fins. The most reduced value of the total thermal resistance for the heat pipes with heat sink was 0.27 °C/W. It should also be stated that the heat transfer coefficient in the entrance region of a pipe under laminar flow can be given by the following equation [63]:

$$h = \left(\frac{K^2 \rho V c}{xD}\right)^{1/3} \quad (6)$$

where $K$ is the thermal conductivity of the nanofluid, $\rho$ is the density of the nanofluid, $V$ is the mean velocity of the nanofluid, $c$ is the specific heat of the nanofluid, $x$ is the axial location, and $D$ is the diameter of the pipe. In addition, the traditional single-phase convective heat transfer coefficient for the fully developed turbulent flow region of a horizontal pipe can be given by the Dittus–Boelter correlation [64]:

$$h = 0.023 Re^{0.8} \frac{c^{0.3} \lambda^{0.7} \mu^{0.3}}{D} = 0.023 \frac{c^{0.3} \lambda^{0.7} \rho^{0.8} V^{0.8}}{\mu^{0.5} D^{0.2}} \quad (7)$$

The model expressed by the Equation (7) is very suitable for the heat transfer coefficient under laminar flow prediction, as long as the effective properties of the nanofluids are used in the calculations. No abnormal heat transfer enhancement was observed in the performed experimental works for the model accuracy evaluation [64], and through the analysis of the Equation (7), it can be noted that the heat transfer coefficient in the turbulent flow region of horizontal pipes depends greatly on the compromise balance between the thermal conductivity enhancement and the viscosity increase (requiring the avoidable setback of increasing the pumping power of the system). In this sense, a quantitative study of alumina and zirconia nanoparticles suspended in water revealed that the ratio of the heat transfer rate to pumping power was lower for these nanofluids as compared to water only [65], probably due to the dominant impact of the viscosity increment. Nevertheless, the nanofluids remain very appropriate for applications in which the consequent increase in pumping power of the system is not of great concern, such as the case of the thermal management of high-density power electronic components and devices.

#### 4.2.3. Microchannel-Based Forced Convection

The cooling technique that uses heat sinks with microchannels is among the most prominent high-performance thermal management approaches for high-heat-generating electronic components and devices. This cooling technique, besides minimizing the package size, is also appropriate for on-chip integration [21]. A single-phase cooling module comprising microchannels of silicone was developed by Colgan et al. [66] for the cooling of high-power density components such as microprocessors. It was demonstrated that such microchannel coolers are suitable for cooling chips with power densities that reach 400 W/cm$^2$. After the single-phase convection cooling technique emerged the two-phase (boiling) liquid cooling in devices with microchannels as a cooling technique with great potential for high-heat-generating electronic equipment. The impact of the flow rate of nanofluids with $SiO_2$, $Al_2O_3$, and $TiO_2$ nanoparticles suspended in various volume fractions of a mixture of water and ethylene glycol in the cooling of chips was investigated by Rafati et al. [67]. The enhanced cooling of the microchip was observed due to nanofluids. The heat transfer performance of aqueous and EG-based $Al_2O_3$ and carbon nanotubes nanofluids in a CPU cooling system was evaluated by Nazari et al. [68]. The results were compared with the cooling performances of the base fluids and the CPU temperature was found to decrease from about 20% to 22% when using $Al_2O_3$ and carbon nanotubes nanofluids, respectively. Khaleduzzaman et al. [69] investigated the stability impact of alumina water-based nanofluids through a heat sink with minichannels. The authors studied nanofluids with several volume fractions varying from 0.1% to 0.25 vol. % and reported that the volume fraction of 0.1 vol. % showed the best performance for cooling the electronic system by analyzing this nanofluid in terms of microstructure, cluster size, sedimentation, and zeta potential. Mohsen et al. [70] simulated and compared the numerical results with the experimental ones through the usage of copper oxide nanofluids in a heat sink of a CPU cooling kit. The researchers concluded that the thermal resistance of the heat sink decreased approximately 5.4% when compared with water under the same flow rate. Similarly, the conductance value of the heat sink increased by 7.7%. Sarafraz et al. [71] studied the performance of copper oxide and gallium in water in the Intel core i5 4760 processor cooling system. The experiments were carried out for the standby, normal, and overload operating conditions of the processor, and it was observed that the temperature of the CPU was found to be 67 °C, 62 °C, and 53.1 °C for water, copper oxide, and gallium nanofluids. Seyed et al. [72] analyzed the performance of alumina nanofluids in a circular heat sink for chips cooling. The authors observed an increment in the heat transfer coefficient for higher concentrations and a decrease in the thermal resistance of the nanofluids, together with a modest setback coming from the need to increase the pumping power with the incorporation of a higher volume fraction of nanoparticles. Figure 5 presents a horizontal heat sink with and without embedded heat pipes used in CPU cooling. Mehdi et al. [73] performed an experimental work on different models of conventional CPU coolers. The authors used graphene with silver nanoparticles as working fluid and concluded that this hybrid nanofluid exhibited superior thermal performance when compared with water. While considering the geometries, serpentine liquid block offers better cooling at a constant Reynolds number but possesses the disadvantage of high-pumping power requirements. Bin Sun et al. [74] studied the thermal performance of copper and aluminum oxide nanoparticles in water in the liquid-cooled CPU heat radiator.

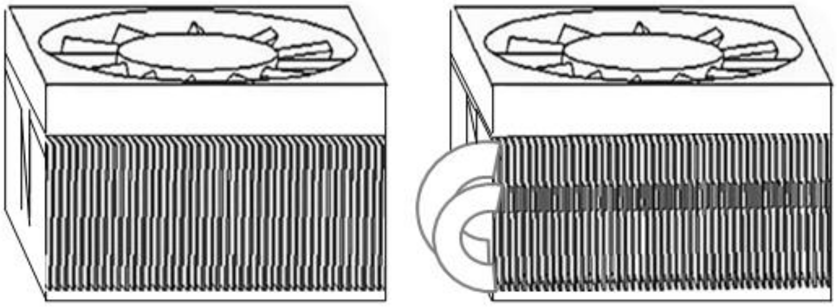

**Figure 5.** Heat sink without and with embedded heat pipes for CPU cooling.

The temperature of the CPU was found to decrease to 18 °C. The heat transfer coefficient of the copper-based nanofluids enhanced up to 2 times when compared to the one of water only and remained higher than the one of alumina nanofluids at the same, with the Reynolds number and mass fraction providing a more efficient cooling performance. Cong et al. [75] investigated the configuration of the channels in a heat sink filled with titania nanofluids. The authors observed that the CPU operating temperature decreased by 10.5% and 12.5% with an aligned and staggered arrangement and with the used nanofluids offering an improved thermal performance at 0.4 wt. %. Balaji et al. [76] developed a research work on water-dispersed graphene nanoplatelets through a microchannel heat sink. The behavior of graphene nanofluids in the thermal management of electronic chips was evaluated with the input of heat loads from 50 W to 200 W. It was noticed that the thermal conductivity increased with the concentration of graphene nanoplatelets and the heat transfer coefficient increased up to 71%. The use of these types of nanofluids decrease the base temperature of the heat sink by 10 °C, which makes these nanofluids very suitable coolants for use in the cooling of electronic chips under different working heat loads. Figure 6 shows the cooling system of a micro electronic component that comprises a heat sink and a heat pipe. In addition, it can be observed that the different structures of the microchannels have been studied. For instance, the thermal and hydraulic characteristics of nanofluids through symmetry semicircles [77] and trapezoidal [78] corrugated microchannels have been investigated. The results showed that both symmetrically-shaped corrugated channels performed better than the zigzag shaped ones. The symmetrical shape of trapezoidal was the best and presented an augmentation ratio of 1.74 of the Nusselt number at Re = 10,000.

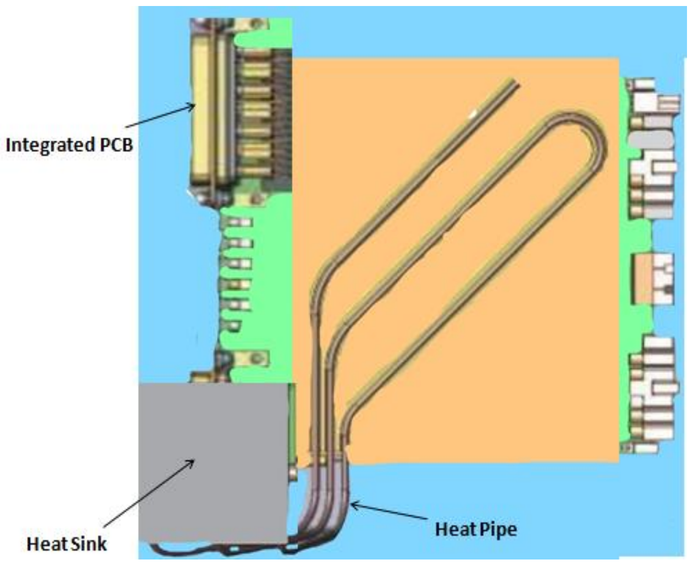


**Figure 6.** Cooling system of a microelectronic component.

Table 2 summarizes some experimental works and numeric simulations regarding different geometries of heat sinks with microchannels using nanofluids applied in the cooling of electronic components and devices.

**Table 2.** Experimental works and numeric simulations of various geometries of heat sinks using nanofluids. MF stands for magnetic field.

| Geometry | Nanoparticles in Water (conc.) | Nusselt Number Enhancement (%) | Thermal Resistance Reduction (%) | Heat Transfer Coefficient Enhancement (%) | Method | Ref. |
|---|---|---|---|---|---|---|
| Rectangular | $Al_2O_3$ (2.0%) | n.a. | 25.0 | 70.0 | Exp | [79] |
| Commercial | $Al_2O_3$ (1.0%) | n.a. | n.a. | 18.0 | Exp | [80] |
| Trapezoidal | CuO (4.0%) | 17.6 | n.a. | n.a. | NS | [81] |
| Triangular | $Al_2O_3$ (2.0%) | n.a. | n.a. | n.a. | NS | [82] |
| Circular | $SiO_2$ (5.0%) | n.a. | n.a. | 15.0 | Exp | [83] |
| Circular | $Fe_3O_4$ | n.a. | n.a. | n.a. | Exp | [84] |
| Complex | $Al_2O_3$ (1.0%) | 40.0 | 22.5 | 38.0 (MF) | Exp | [85] |
| Complex | $Al_2O_3$ (0.3%) | n.a. | 15.2 | n.a. | Exp | [86] |
| Wide | $Al_2O_3$ (0.2%) | 20.0 | n.a. | n.a. | Exp | [87] |
| Wide | CuO (2.0%) | 100.0 | n.a. | n.a. | NS | [88] |
| Cylindrical | Cu (0.3%) | 23.0 | n.a. | n.a. | Exp | [89] |
| Cylindrical | Cu (0.3%) | 43.0 | 21.0 | 80.0 | Exp | [90] |
| Dedicated | $Al_2O_3$ (0.2%) | 23.9 | n.a. | n.a. | Exp | [91] |
| Enclosure | CuO (1.0%) | 110.0 | n.a. | n.a. | NS | [92] |
| Pin Finned | $TiO_2$ (3.9%) | 37.8 | n.a. | n.a. | Exp | [93] |
| Pin Finned | $Al_2O_3$ (2.0%) | n.a. | 13.5 | 16.0 | Exp | [94] |
| Micro Pin Finned | $SiO_2$ (0.6%) | 14.0 | n.a. | n.a. | Exp | [95] |

The greater heat transfer enhancement was verified for copper nanofluids, probably due to the high thermal conductivity of the copper nanoparticles. The greater Nusselt number enhancement came from the oxide copper nanofluid usage. Lastly, the more pronounced thermal resistance reduction was given by the alumina nanofluid.

#### 4.2.4. Thermoelectric Cooling

One cooling technique that has demonstrated good performance in the cooling of electronics is the Peltier effect thermoelectric cooler (TEC). The TEC is compact and provides a temperature differential below the ambient conditions without the need for moving parts or vapor compression plumbing. The main component of a thermoelectric cooler is an array of two p- and n-type semiconductors. First, voltage is applied to the free ends of the two dissimilar conductive materials, resulting in current across the junction of the p- and n-semiconductors, which then generates a temperature gradient converted in a heat flux sufficient to cool computer chips [96]. Saengchandr and Afzulpurkar [97] reported an analysis on a combined thermoelectric module and heat pipe-based method for cooling microprocessors. The authors claimed that the cooling system was sufficient to remove 200 W under the form of heat. Moreover, when possessing the proper size and geometry, the TEC can provide the capability to cool multiple computer chips, as demonstrated by Simons et al. [98]. The combination of nanofluids and TEC devices can provide cooling below the ambient conditions and has sufficient heat transfer capability to dissipate heat from the TEC module in space-confined scenarios, such as the cooling of electronics. The fundamental benefit of the thermoelectric cooler device is that its required components is only a small fan or a small-scale fluid heat exchanger. The limitations concerning the overall size of the cooling system can be mitigated by the inclusion of a cooling loop, which dislocates the TEC and remaining components. The reduced footprint and the provision of the cooling requirements and improved heat transfer characteristics makes the nanofluids a mandatory, integral part of these thermal management systems. Figure 7 presents the working principle of a generic thermoelectric cooler.

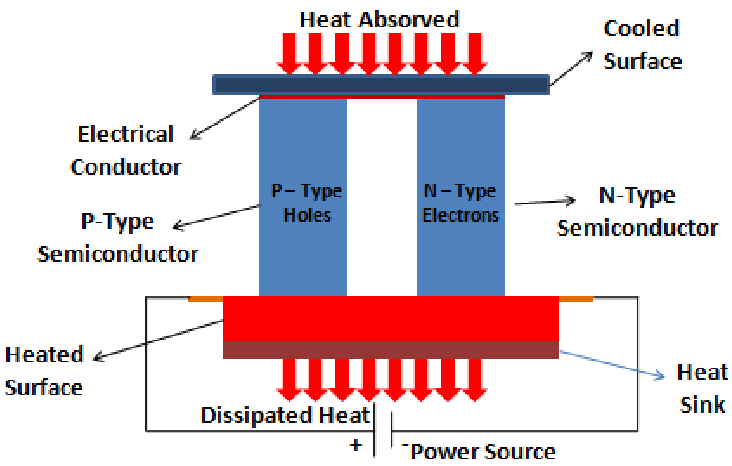


**Figure 7.** Working principle of a generic thermoelectric cooler.

#### 4.2.5. Free Cooling

The free or natural convection is often used as a cooling approach in the electronics field. This technique reduces the risk of failure and the operating energy consumption of the electronic assemblies without acoustic pollution. In applications for the cooling of electronics, a high heat transfer rate is desirable. However, the presence of a magnetic field and its Lorentz force diminishes the fluid convection flow and, hence, limits the heat transfer enhancement in the filled cooling enclosure. In order to achieve the maximum heat transfer performance, the use of nanofluids is again required for the cooling of power electronics. The study of the nanofluids as working fluids in enclosures with the presence of a magnetic field was introduced by the work of Ghasemi et al. [99]. The authors proved that an increase in the volume fraction of the nanoparticles resulted either in the enhancement or deterioration of the nanofluid's thermal performance, depending on the relative values of the Rayleigh and Hartmann numbers. Moreover, the installation of electronic assemblies in very limited spaces entails the analysis of natural convection heat transfer performance in geometrically different and small enclosures. In this sense, researchers have investigated the natural convection in magnetic field enclosures filled with nanofluids with geometries, such as a semicircular [100], C-shape [101], trapezoidal [102,103] and rectangle [104]. In recent years, several experimental works related to the natural convection of nanofluids in porous-walled enclosures have been performed. Some of them reported the natural convection heat transfer enhancement in porous enclosures with the use of nanofluids [105]. In addition, the work developed by Purusothaman et al. [106] analyzed the thermal performance using nanofluids of a 3 × 3 array of isothermally-heated quad flat non-lead (QFN) sources embedded in a printed circuit board, installed on one vertical wall of a sealed rectangular porous enclosure. The work investigated the natural convection heat transfer under the influence of a magnetic field, which experiences a Lorentz force that limits the buoyant flow field and heat transfer rate. Among other conclusions, the authors found that the effect of the enclosure side aspect ratio plays a predominant role in the heat transfer performance.

#### 4.2.6. Phase Change Materials Based Cooling

The phase change material (PCM)-based nanofluids is a promising heat transfer fluid application for electronics cooling. In addition, the nano-encapsulated phase change material is considered to be an attractive solution as thermal fluid for the cooling of electronic components and devices. This class of materials is synthesized by mini-emulsion polymerization, wherein a flexible polymer is coated on the surface of a phase change material core [107]. It can be stated that the higher superficial area to volume ratio of the encapsulated phase change material provokes a decrement in the thermal resistance between the PCM and the base fluid, enhancing, consequently, the heat transfer rate. Wu et al. [108] synthesized polystyrene nano-encapsulated paraffin PCM by mini-emulsion polymerization and the slurry was utilized in jet impingement cooling and in spray cooling. The authors verified a heat transfer rate enhancement of 50% for the jet impingement technique and of 70% for the spray cooling approach for a volumetric concentration of 28% of slurry. The experimental work, developed by Joseph et al. [109], dealt mainly with the evaluation of the heat transport properties and pressure drop effect of the polystyrene nano-encapsulated n-octadecane nanofluid under laminar flow in a channel with 8 mm of diameter. The PCM was prepared once again by mini-emulsion polymerization, with the encapsulation within polystyrene shell of the PCM core of n-octadecane being the nanofluid obtained by the dispersion of the PCM in deionized water. The PCM nanofluids showed a 37% enhancement in heat transfer rate when compared with deionized water alone. That enhancement is due to the improved heat capacity of the PCM and to its latent heat absorption during melting. Moreover, the results proved that the heat flux and flow rate of the PCM nanofluid plays a critical role in the heat transfer performance. An increase in the pressure drop and in the required pumping power for the flow with PCM nanofluid when compared to deionized water was also observed, especially at higher mass flow rates, due to the increase in the viscosity of the PCM nanofluid.

#### 4.2.7. Jet Cooling

The study of the heat transfer of an impinging nanofluid jet can be found in recent studies [110], where planar and slot jets were investigated in confined and free conditions. It should be emphasized that data related to the heat transfer behavior of nanofluids under a confined and submerged impinging jet is rather scarce. In the work developed by Nguyen et al. [111], the behavior of a confined and submerged impinging jet in a liquid cooling system using a nanofluid of alumina nanoparticles with 36 nm diameter dispersed in water was analyzed. There were considerations of different nozzle-to-heated-surface distances and nanoparticle concentrations. It was found that the highest surface heat transfer coefficients were obtained with a nozzle-to-surface distance of 5 mm and a nanoparticle concentration of 2.8%. The authors also found that nanofluids with a higher nanoparticle concentration were unsuitable for a relevant heat transfer augment in a confined and submerged impinging jet. Jaberi et al. [112] studied the heat transfer performance over a circular aluminum disc of a 15 nm $Al_2O_3$ based nanofluid using the free jet impingement technique, and reported that the heat transfer coefficient increased, with an increase in the weight fraction of the nanoparticles until 0.0597 wt. %. Thereafter, the heat transfer coefficient decreased to 0.0757 wt. % upon loading more nanoparticles. Naphon and Wongwises [113] experimentally investigated the heat transfer characteristics of the jet impingement of a mini-rectangular fin heat sink for the cooling of a CPU, using a $TiO_2$ nanofluid. The authors made a comparison between the jet nanofluids impingement cooling system, jet liquid cooling system, and the conventional cooling system. Out of these three cooling systems, the Nusselt number for the jet nanofluids impingement cooling was higher than the other cooling techniques, due to the alteration in the fluid transport properties and flow characteristics of the working fluid because of the suspension of the nanoparticles. In contrast, the thermal resistance of the jet nanofluid thermal management technique was lower when compared to the one of other cooling techniques because of the thermal dispersion of jet technique. In addition, the operating temperature of the CPU was 3% as compared with the jet technique without nanofluid impingement cooling. Several investigations revealed that, when the fluid commences to flow outward, the liquid film starts to thicken, producing thin thermal boundary layers derived from jet deceleration and pressure. Consequently, very high heat transfer coefficients are obtained in the stagnation zone, although with a fast decrease on the radial flow region. The non-uniformity of jet cooling has prompted the use of array jets for cooling applications, where the nozzle array arrangement is of vital importance [114].

#### 4.2.8. Absorption Refrigeration Systems

One efficient cooling technique for electronic chips is the vapor compression refrigeration systems (VCRS). The VCRS have great potential for the heat dissipation through high-power cooling systems. Although liquid cooling systems have the shortcomings of bulky equipment and leakage, these systems present improved heat dissipation performance. The addition of nanofluids to these cooling systems can reduce the dimensions of the liquid cooling systems and improve its thermal performance. The study performed by Jeng et al. [115] had the aim of developing a hybrid cooling system that combined the benefits of liquid cooling and VCRS. This system used a nanofluid of alumina nanoparticles dispersed in water as the working fluid of a liquid cooling system and a hydrocarbon refrigerant of the VCR Sofa CPU. Several measurements were made of the surface temperature of the heating module that mimicked the working of the CPU and the pumping power consumption under various experimental conditions. The results demonstrated that the hybrid cooling system achieves a maximum cooling capacity of up to 540 W, and, thus, is a very suitable system to cool chips and other components to improve equipment performance and extend service lifetime. Recently, the ammonia absorption refrigeration system (AARS) has attracted much attention due to its environmental friendliness. However, and especially for certain applications, this cooling system still needs coefficient of performance (COP) improvement and miniaturization. These shortcomings can be overcome by enhancing the thermal conductivity and reducing the surface tension of the fluid with the addition of nanoparticles and, hence, obtaining a nanofluid. The main difference between an AARS and the aforementioned VCRS is that the circulation of the solution in an AARS replaces the need for a compressor in VCRS. In the former, the generator, absorber, and solution of the heat exchanger operates together as an overall thermal compressor which can efficiently be improved with the use of nanofluids. Several researchers [116,117] have found that the addition of nanofluids improved the heat and mass transfer of the absorption and generation processes. Particularly, the application of nanofluids in the practical AARS field was investigated by Jiang et al. [118]. The authors verified the influence of adding different amounts of titania nanoparticles on the COP of an AARS. To select the most adequate nanofluid, different types of nanoparticles with several dispersants were mixed in ammonia-water base fluid, and the results showed that titania nanoparticles present a uniform dispersion in the ammonia water and, at the same time, enhance the thermal conductivity and can significantly improve the heat transfer performance of the final working fluid [119]. The studied dynamic characteristics of the ammonia-water-based titania nanofluid, such as suspending ability, dynamic viscosity, and surface tension showed that the dynamic circulating process can greatly improve the suspending ability of the referred nanofluid. Therefore, the $TiO_2$ ammonia-water nanofluid proved to be suitable as working fluid for an AARS.

#### 4.2.9. Spray Cooling

The spray cooling technique is an efficient approach to remove high heat flux from heated surfaces, such as the ones from microelectronics. Researchers believe that the spray cooling performance and critical heat flux depend on various parameters such as the type of the nozzle, distance from the nozzle to the heated surface, condition of the surface, thermophysical characteristics of the coolant, and droplet dynamics [120]. On the other hand, it is fundamental to study some of the geometric parameters, especially both the spatial and temporal symmetry of the jet spray in order to better understand the involved phenomena and also to reduce the required computational times in numeric simulations [121]. The physical process of spray cooling, due to the impact of the impinging droplets onto a heated surface, may entail the phenomena of splashing, spreading, or rebounding [122]. The latter phenomenon can result in decreased liquid cooling capacity and efficiency. The complexity of spray/droplet wall interactions is still addressed nowadays [123], as researchers are still looking for alternative ways to further enhance spray cooling effectiveness. The advances in nanofabrication processes have led to innovations in spray techniques and the use of nanofluids as refrigerants in spray cooling for electronic components and devices is an emerging field of research [124]. However, some inconsistent results were found regarding the heat transfer performance by nanofluids in the spray cooling method [125]. It can be stated that, whether the heat transfer coefficient increases or, alternatively, decreases with the addition of a load of nanoparticles, depends on the base fluid used, target surface temperature distribution, spray duration time, and the surface-nanofluid impact velocity. Moreover, the critical heat flux is enhanced for the pool boiling scenarios due to the deposition of the nanoparticles onto the heated surface that changes the surface properties, such as capillarity and wetting. Therefore, measurements of the surface contact angle showed that this quantity decreases using nanofluids in nucleate boiling conditions. Several studies [126,127] have been carried out to evaluate the thermal properties of the nanofluid in film-boiling conditions using non-linear approaches. The used mathematical models relied on the Lie theory that is based on the symmetry and self-similar forms of the equations, defining the variables for the flow rate, enthalpy, and nanoparticle concentration and transport. Moreover, it appears that there is a limited knowledge base of the experimental data related to the spray cooling of heated surfaces for situations when the nanofluid coolant has a very small volume fraction of nanoparticles (0.0075%), especially in the case of metal particles and multi-walled carbon nanotubes. The work performed by Hsieh et al. [128] studied the steady and transient spray impingement heat transfer rate with Ag or multi-walled carbon nanotubes as nanoparticles dispersed in deionized water. The results showed that only at low heat flux ($\leq$25 W/cm$^2$) and high heat flux ($\geq$115 W/cm$^2$) a heat transfer augment for the Ag nanofluid occurred with 0.0075% of volume fraction. The results also demonstrated that the heat transfer coefficient increases by adding Ag nanoparticles or multi-walled carbon nanotubes. The critical heat flux was found to be 48.5 W/cm$^2$ and 274.3 W/cm$^2$ for 0.0075% of volume fraction of carbon nanotubes and Ag nanoparticles, respectively. Figure 8 illustrates the heat transfer mechanisms closely related with the spray cooling technique.

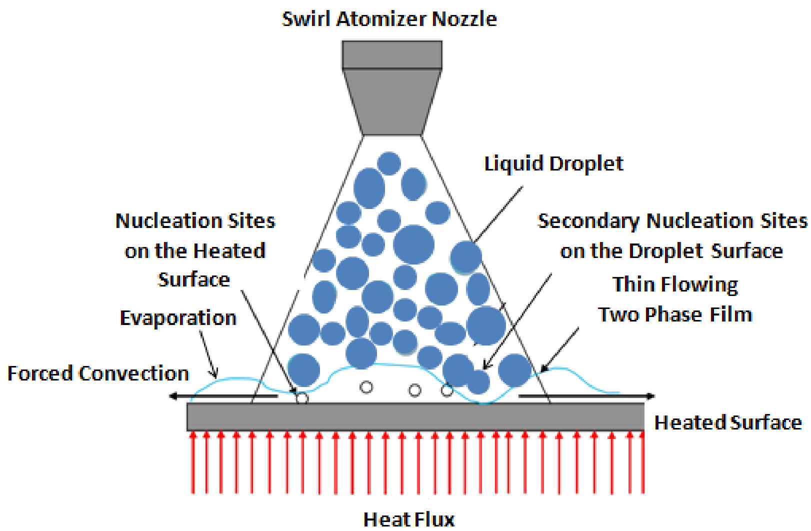


**Figure 8.** Heat transfer mechanisms of spray cooling.

## 5. Conclusions

Due to their superior thermal properties, nanofluids have become protagonists in increasing the heat transfer from the thermal systems, as their use is suitable to thermal management fluidic systems. Although the studies published by the scientific community are not always consistent, the majority of the results converge to the same conclusions:

- The thermal conductivity and heat transfer ability of nanofluids is greater than that of the base fluids;
- Long-term stability is mandatory for miniaturized fluidic systems;

- The production costs for systems using nanofluids are still high;
- The nanofluids enhance the critical heat flux, which can be attributed to the enhanced surface wettability, verified in the deposition of the nanoparticles. The findings concerning the influence of the nanofluids on nucleate boiling are, nevertheless, not consistent with each other, which is due to the involvement of a large number of not yet completely understood factors, such as the type of working fluid, surface roughness, heat flux, nanoparticle type, size, and concentration, and preparation procedures, which can strongly affect the thermal properties of the nanofluids;
- Comparing Equations (4) and (5) that correlate the thermal conductivity and viscosity of the nanofluids with the volume fraction of nanoparticles and, particularly, the empirical constants, i.e., $C_\mu = 10$ and $C_K = 3$, it can be stated that the enhancement in viscosity is higher than the increment in thermal conductivity. However, there is still a real benefit derived from the use of nanofluids, given that the addition of surfactants to the system does indeed mitigate the dynamic viscosity effect. Moreover, a thermal conductivity increase can correspond to a double heat transfer coefficient, which in many applications, such as in the cooling of electronic equipment, there is the need for removing high-density heat loads in the shortest time possible, and the heat transfer characteristics are critical to accomplish that purpose. This fact usually comes first in terms of importance despite the setback of an overall greater pumping power in the cooling devices working with fluids with increased viscosity. Furthermore, this work mentioned experimental studies carried out with only slightly extra pumping power of the cooling devices operating with nanofluids;
- Despite the progress during the past decades, the electronic industry is still facing technical limitations related to the thermal management of their electronic products. This fact is closely related to the traditional cooling techniques and coolants that are gradually falling short in fulfilling the evermore compelling cooling requirements of the high heat-generating electronic equipment. Consequently, high performance electronic components and devices (chips, CPU, etc.) require novel methods and coolants, having improved heat transfer properties for their better performance and longevity.
- Many research works reported that heat pipes and devices with microchannels filled with forced convection cooling flows are very propitious techniques for the cooling of electronic components and devices. Moreover, findings from the investigations on the application of nanofluids demonstrated that they showed an improved performance when compared to traditional coolants. However, it is still of paramount relevance to use the nanofluids in a wider range of cooling methods and systems in order to address their thermal behavior as coolants of electronic equipment. The nascent cooling approaches with the simultaneous utilization of these innovative coolants can improve their heat dissipation performance and can fulfill the cooling demands of the high heat generating electronic components and devices.

The shortcomings related with nanofluids can be summarized as follows:

- Long-term stable nanofluids are difficult to prepare because they require continuous maintenance. The influence of the preparation should be further studied, namely the sonication time, volume fraction, and type of the nanofluids, in order to avoid the sedimentation and agglomeration, and achieve optimal performance;
- Although adding dispersants to promote the dispersion of nanoparticles in the base fluid can maintain a long-term improved suspension performance, this addition may cause the decrease in the overall thermal conductivity of nanofluids, due to the lower thermal conductivity associated to the dispersants;
- Lack of multi-scale common protocols for the preparation of the nanofluids. Moreover, a considerable gap still remains between laboratory experimental studies and engineering applications. In this regard, the industrial application of nanofluids will be realized only when their long-term stability is guaranteed;

- Methods to scale-up production for commercialization are still in development. Despite the relative maturity of nanofluid-related studies, issues such as long-term stability, clogging, erosion, corrosion, maintenance and cleaning procedures have remained as obstacles to mass commercialization;
- No comprehensive theory has been introduced to justify the critical heat flux amelioration for a wide spectrum of nanoparticle sizes and chemical compositions. A lack of such a framework has limited the nanofluids commercialization in various fields, including nuclear reactor, fossil fuel boiler, and spray cooling.

As practical examples of underway projects and new lines of research of the nanofluids, the following points can be enounced:

- The use of nanofluids having particle nanosheets with a larger surface area that may enable the achievement of the same levels of thermal conductivity with lower volume fractions;
- The use of nanofluids as a response for the growing demand of green manufacturing based on environmentally benevolent processes;
- The development of methods to determine the specific enthalpy of the nanofluids;
- The development of nanofluids with self-assembling nanotubes;
- The determination of theoretical and empirical mathematical expressions to predict the thermal conductivities of hybrid nanoparticles (e.g., metal oxide and carbon);
- The resuming of experimental works conducting an accurate evaluation of the Brownian motion and thermophoresis' (thermodiffusion or Soret effect) impact on the thermal properties of the nanofluids;
- The determination of the potential adverse impact of the nanoparticles on industrial equipment (it was concluded so far that these ones are harmful to stainless steel but may provoke corrosion in equipment made of copper or aluminum);
- An underway research project concerning the use of nanofluids in the cooling modules of power electronics in electric and hybrid vehicles;
- An underway research project regarding the cooling of a data center with the use of silicon carbide and alumina nanofluids in demonstrator units such as a server blade cabinet.

By way of guidelines for future studies and developments, the following should be emphasized:

- The stability of the nanofluids should be improved by optimizing the concentration of the nanoparticles and the base fluid characteristics. The stability of nanofluids should be predicted by experimental studies of the surface tension of the nanofluid overtime, when operating in microfluidic devices;
- The average size of the nanoparticles should become smaller. In this sense, cost-effective techniques of preparation of reduced-dimensioned nanoparticles should be developed. Moreover, the impact of the size effect of the nanoparticles in the base fluid needs further investigation in order to prevent clustering and sedimentation;
- The development of a database of the thermo-physical properties, together with details about nanoparticle shape, size and suspension stability over time, with and without the addition of surfactants and dispersants, and in which database the most prominent nanofluids should be prioritized, is recommended;
- The novel types of nanofluids such as the shell-core, microfluidic, and hybrid are also to be exploited, owing to their phase-change characteristics and optimal thermal properties, which result in improved heat transfer performance, as well as in greater stability;
- Additives for decreasing the nanofluids viscosity while maintaining the same level of thermal conductivity are of paramount importance to achieve a better performance of the nanofluids;
- The systems using nanofluids as working fluids should become more cost-effective, without the need for extra pumping power and expensive maintenance. One path

to be followed is the optimization of the design of, for instance, heat sinks, with the adjustment of the microchannels configuration parameters such as the total number of channels and/or the inlet/outlet positioning.

In a research line more closely related with the one of the research team in which the authors of this work are included, the further points are to be followed:

- The development of physical models that can be used to better understand the thermal performance of suspended nanoparticles in a base fluid, especially regarding the thermal management of electronic equipment in the final application;
- The development of boiling heat-transfer experimental works and numerical simulations involving the use of nanofluids as preferential coolants. In this sense, these are necessary research projects concerning the composing materials of biphilic surfaces in pool boiling scenarios, as well as the optimal geometric arrangements, numbers, dimensions, and pitches of the superhydrophobic spots of these kind of surfaces;
- The contribution to the development of small-scale pilot lines for the preparation of nanofluids and also to the project of future large-scale pilot lines, where the knowledge of the industrial equipment characteristics and turbulent flow regime conditions are essential.

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## Nomenclature

| | |
|---|---|
| m | Flow Rate [kg/s] |
| $\rho$ | Fluid Density [kg·m$^{-3}$] |
| h | Heat Transfer Coefficient [Wm$^{-2}$K$^{-1}$] |
| TS | Interface Temperature [K] |
| Cv | Latent Heat of Vaporization [J·kg$^{-1}$] |
| Cp | Specific Heat [J·Kg$^{-1}$K$^{-1}$] |
| C | Thermal Conductance [W·m$^{-2}$·K$^{-1}$] |
| K | Thermal Conductivity [Wm$^{-1}$K$^{-1}$] |
| R | Thermal Resistance [K·W$^{-1}$] |
| μ | Dynamic Viscosity of Suspensions [Pa·s] |
| vol. % | Volume Concentration of Nanoparticles |
| wt. % | Weight Concentration of Nanoparticles |

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