Chapter

Nanofluid as Advanced Cooling Technology. Success Stories

Jesús Esarte, Roger R. Riehl, Simone Mancin, Jesús Mª Blanco, Maite Aresti and Juncal Estella

Abstract

Nanofluids are defined as heat transfer fluids with enhanced heat transfer properties by the addition of nanoparticles. Nanofluid's stability, nanoparticles' type and their chemical compatibility with the base fluid are essential not only to increase the nanofluid's thermophysical properties but also to ensure a long-lasting and thermal efficient use of the equipment in which it is used. Some of these aspects are discussed in this chapter. Likewise, the improvement in terms of the heat transfer capacity (thermal resistance) that the use of nanofluids has on the heat pipes-thermosyphons is shown. On the other hand, the improvement in energy efficiency that nanofluid causes in a vapor compression system is also presented.

Keywords: nanofluid, heat pipe, vapor compression, battery refrigeration

1. Introduction

In an increasingly digitized society with a growing trend in the interconnection of things (IoT and AI), the volume of information circulating through the network and to be processed is constantly growing. This information must be processed in high-speed processing and storage servers, which means that the density of heat to be dissipated has increased considerably in recent decades. This heat flux increase, together with technological advances that allow the miniaturization of electronics, forces thermal engineers to seek advanced solutions in heat dissipation. Advances in the field of electronics, and in particular power electronics, have resulted in a significant increase in heat flux density at the component level. Meeting component temperature requirements and ensuring maximum system performance requires more efficient, lower-volume cooling technologies. As a result, thermal management is becoming increasingly important and critical to the electronics industry. The need for thermal management has increased over the past decade and the prediction is that a steeper increase is yet to come in the coming years.

In parallel, other applications have demanded an increasing thermal management capability that were not even considered less than a decade ago. The advent of electric vehicles with the use of Li-Ion batteries has become a new edge for the development of reliable and high-performance thermal management systems. Due to the fact that this type of battery can be charged within minutes and present a high density of energy that can be delivered to the vehicle's systems, overheating became an issue that can potentially cause accidents, which unfortunately have already been reported in some applications. This type of issue is generally caused by heat concentration in specific areas of the battery resulting in temperature overshooting with consequent potential fire and loss of the device. Such an issue has been reported with more frequency as new vehicles that utilize electric propulsion are gaining interest from different markets, which require proper addressing using reliable thermal management systems. As a potential solution for this issue, temperature homogenization can be applied in order to minimize heat concentration, which also contributes to increasing the battery's lifetime.

On the other hand, conventional vapor compression refrigeration has, in recent years, suffered from the consequences of international environmental legislation relating to fluorinated refrigerants "HFCs". In this regard, Europe has adopted the "F-GAS" regulation, which establishes deadlines for the use of these refrigerants due to their negative impact on the climate. The climate impact of a substance is commonly expressed as the global warming potential (GWP). The lower the GWP, the more climate-friendly the substance. Most of the HFCs have a very high GWP and are hence potent greenhouse gases. Most of the HFCs are used as refrigerants in refrigeration and air conditioning. To mitigate emissions of substances with a high GWP and comply with the F-Gas Regulation, each sector needs to find solutions to quickly switch to low GWP refrigerants. The F-gas regulation is committed to so-called clean refrigerants (hydrocarbons, CO_2, HFOs) due to their zero or very low GWP. However, the use of these refrigerants often implies a reduction in the efficiency of the refrigerators as well as an extra effort to redesign them.

Under this scenario, thermal and refrigeration engineers are forced to find solutions, not only in terms of the type of refrigerant (more respectful with the environment) but also in terms of new refrigeration technologies (acoustic, thermocaloric, thermoelectric, nanofluids ...) that meet new challenges in heat dissipation and cooling. Nanofluids are envisioned as one of these solutions. Although there is little bibliography at this regard, recent works show the interest of nanofluids as key enabling technology to meet the environmental challenges vapor compression systems must face. For example, Gokulnath G [1] presents an analysis of the effect of different nano-refrigerants on a domestic refrigerator performance. Haque [2] analyzes the behavior of a domestic refrigerator when using a polyolester-based nano-lubricant.

Nanofluids are defined as heat transfer fluids with enhanced heat transfer properties by the addition of nanoparticles. When formulating a nanofluid, a fundamental aspect to consider is its stability, since its thermophysical properties pretty much depend on it. Adding dispersants in the two-phase systems is an easy and economic method to enhance the stability of nanofluids. Although surfactant addition is an effective way to enhance the dispersibility of nanoparticles, surfactants might cause several problems [3]. In this chapter an analysis of the effect of nanoparticles not only on the stability of the nanofluid but also on its thermal conductivity is carried out.

The use of nanofluids is already being seen in different applications - technologies, in this chapter some application cases are shown.

2. Nanofluids

Nanofluids [4] are a type of fluid made up of a base fluid to which naoparticles (<100 nm) are added in order to increase its thermophysical properties.. Nanoparticles manipulation and in turn nanofluid formulation requires high security measures and therefore must be handled in controlled environments, **Figure 1**.

Figure 1.
Nanoparticles handling laboratory.

Metallic nanoparticles are among the most interesting ones due to their high thermal conductivity. This nanoparticles addition makes the nanofluid thermal conductivity increase [5, 6] as well as its viscosity which is a negative effect as far as pressure drop is concerned.

Despite the amount of research carried out so far, which shows that the use of nanofluids increase the heat transfer coefficients, there is still much to understand in the area of nanofluids, for example, depending on which cooling technology (LHP, HP) the nanofluid is used in, other forces (capillarity) apart from the viscous and gravitational forces come into play requiring a better fluid–structure interaction understanding [7]. This interaction is given, among others, by the surface tension and the contact angle between the fluid and the porous medium. Since the contact angle is affected by the addition of nanoparticles [8–10] the capillary forces are altered and with them the LHP capillary pumping. From a theoretical point of view, the phenomena that take place at the nanoparticle level (Brownian movement, plasma, ...) that make the heat transfer coefficients improve are not clear. In the bibliography there are several theoretical models [11–19] that try to shed light on the matter but their predictions differ from the experimental values [20–22]. This theoretical field requires a greater research effort to be able to give answers to the real behavior of nanofluids.

Nanoparticles not only increase the thermal conductivity of the base fluid but also act as sources of bubble generation in boiling processes, thus increasing the boiling coefficients, important in LHPs and HPs [23, 24].

Nanoparticles stability [25, 26] in the fluid is key to have a nanofluid that ensures an enhancement of the device thermal performance over time. Different techniques are used for such purpose: surfactant addition, sonication and surface charge change.

The addition of nanoparticles to a base fluid, as mentioned above in the section, basically alters its viscosity and its thermal conductivity. These alterations depend pretty much on the nanoparticle size and concentration as shown in the following sections. This influence is reflected in the following analysis carried out for the base fluid polyol-ester when it is doped with different types of nanoparticles (CuO, AL_2O_3 and TiO_2).

2.1 Nanoparticles size - viscosity

As mentioned above, nanofluid viscosity [27] is an important property as far as thermal performance and fluid flow are concerned. As shown by the rheological analyzes carried out by different researchers [28, 29]. Among the several works regarding oil based nanofluids, Resiga et al. [30] investigated the rheological properties of highly concentrated transformer oil-based magnetic nanofluids; the results confirmed that the nanofluids were Newtonians in all concentrations except at the highest concentration of 20.8 vol%. Murshed et al. [31] experimentally studied the viscosity of silicone oil (SO) based TiO_2 and SiO_2 nanofluids confirming the nanofluids' Newtonian nature. Chen and Xie. [32] reached the same conclusion for carbon nanotubes (TCNT)-nanofluids. At low shear rates, Newtonian behavior of silicone oil (Syltherm 800) based diamond-graphene nanofluid was observed by Yang et al. [33]. The same authors [34] investigated the effects of multi-walled carbon nanotubes (MWCNT) loading, surfactant concentration and dispersion energy (ultrasonication) on the thermal conductivity and steady shear viscosity of oil (PAO6)- based-nanofluids. Polyisobutene succinimide (PIBSI) was used as surfactant. The results showed that at low shear conditions the nanofluid viscosity was governed by the PIBSI, observing a 0.1 to 0.07 Pa shear stress decrease. They also analyzed the concentration of CNT versus viscosity, it was observed that the viscosity increased for any concentration other than 3% by weight.

Heris et al. [35] studied the rheological properties of ZnO nanoparticles dispersed in mineral oil (MO) based lubricant as a function of the volume fraction in the range 0.01–0.6% and temperature from 0 to 60 °C. The results showed that the investigated nanolubricants were found to behave as yield stress fluids as mineral oil and the viscosity ratio was increased by the nanoparticle loadings. The effects of the temperature were noticeable at high temperature and concentration.

Kole and Dey [36] dispersed 40 nm diameter CuO nanoparticles at a volume fraction higher than 0.005 in gear oil and concluded that for a 10–50 °C temperature range the nanofluid shear rate was below 30 s − 1. For ultra-low concentration, it was observed a viscosity increase with increasing volume fraction.

Moreover, Saeedinia et al. [37] investigated the viscosity of CuO/oil-based nanofluids with 50 nm nanoparticle for weight fraction ranging from 0.2% to 2%. Newtonian nature was noticed in the shear rate range of 0–15 s − 1 for all the investigated temperatures and concentrations.

When analyzing the Ti2O3 nanoparticles size on the 1 wt%. polyol-ester nanofluid, **Figure 2**, it is observed that viscosity increases with the increase of NP size. This increase becomes steeper for a specific size (180 nm). This result agrees with other researchers' work [38, 39]. Although, it could be expected that viscosity would decrease with increasing NP size [40], this performance depends to a great extent on the NP concentration, which can cause a decrease or an increase in viscosity as the size of the NPs increases [41].

In any refrigeration application, the nanofluid must be pumped to flow through the pipe and this pumping work is greater the higher the viscosity. In terms of efficiency, this work must be as low as possible and consequently the nanofluid viscosity.

2.2 Thermal conductivity

The enhancement of the thermal conductivity of the base fluid is the primarily objective of the addition of nanoparticles. The literature showed that the thermal conductivity of nanofluids is higher compared to the base fluids; this is confirmed also in the case of oil-based nanofluids. Nonetheless, just a few works were devoted to investigate the thermal conductivity of this kind of nanofluids.

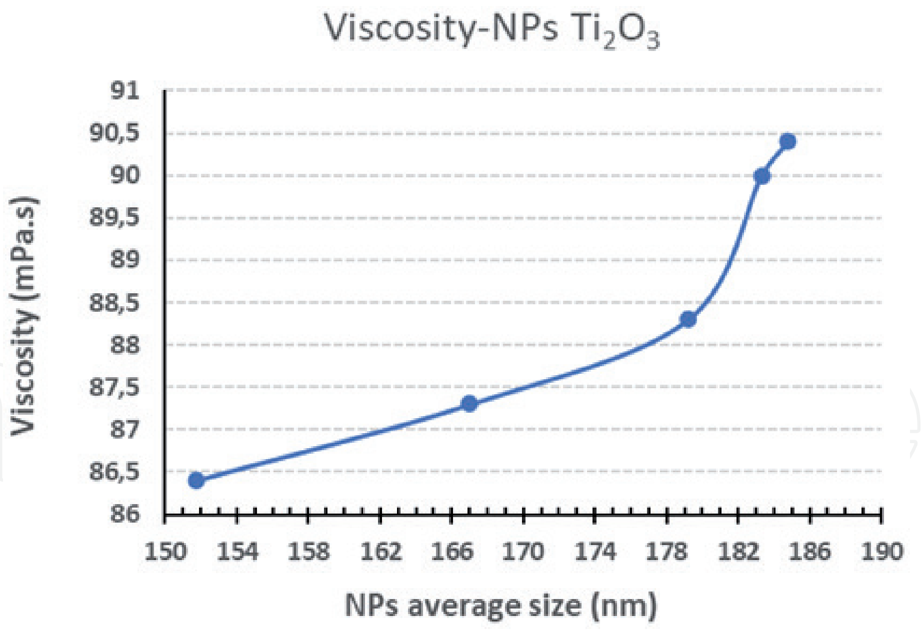

Figure 2.
Influence of NPs size on viscosity. 1 wt% nanofluid of Ti2O3 NPs in polyol-ester.

Saeedinia et al. [37] investigated the thermal conductivity of CuO/oil nanofluid. The authors, measured the thermal conductivity at different temperatures ranging between 24 and 70 °C and at two concentrations of 1 wt% and2 wt. %. The results showed a remarkable enhancement in the thermal conductivity of the studied nanofluid with temperature. With increasing the temperature, the agglomeration of nanoparticles is hindered, and thus the thermal conductivity is enhanced because of the more uniform of nanoparticles dispersion.

Wang et al. [42] studied the effects of temperature and solid concentration on the thermal conductivity of oil-based nanofluids containing graphite nanoparticles. The results highlighted that when adding 1.36%vol. of graphite a 36% enhancement in the thermal conductivity was achievable. The authors also found that the thermal conductivity enhancement was not linear with nanoparticle concentration. The temperature showed a weak effect on the thermal conductivity enhancement but when increasing temperature, the thermal conductivity also increased.

Aberoumand et al. [43] experimentally investigated the thermal conductivity of silver/heat transfer oil nanofluid at different values of concentration and temperatures. The authors found that while the thermal conductivity of the base fluid showed a decreasing trend as the temperature increased that of the nanofluid increased with the temperature. This trend has been found for all the investigated concentrations. The authors stated that this phenomenon can be explained considering the Brownian motion which are enhanced when increasing temperature. Aberoumand et al. [44] experimentally demonstrated that for a nanofluid composed of 1% wt CuO nanoparticles on engine oil, the thermal conductivity increased by 49%.

Colangelo et al. [45] The effect of adding a different amount of Oleic Acid surfactant toAl2O3/diathermic oil NF on the thermal conductivity, in different temperatures (30 to 50 °C) and three concentrations of 0.3, 0.7, and 1 vol.%, has been investigated by. Their results showed that adding surfactant does not affect the thermal conductivity of the NF. Moreover, increasing the solid concentration of the surfactant has also no effect on the thermal conductivity enhancement. They reported the maximum enhancement of 4% at the solid concentration of 1 vol. %.

Figure 3 shows the thermal conductivity variation with variation in nanoparticle concentration from 0.1 wt% to 1.1 wt% at ambient temperature. It is apparent from

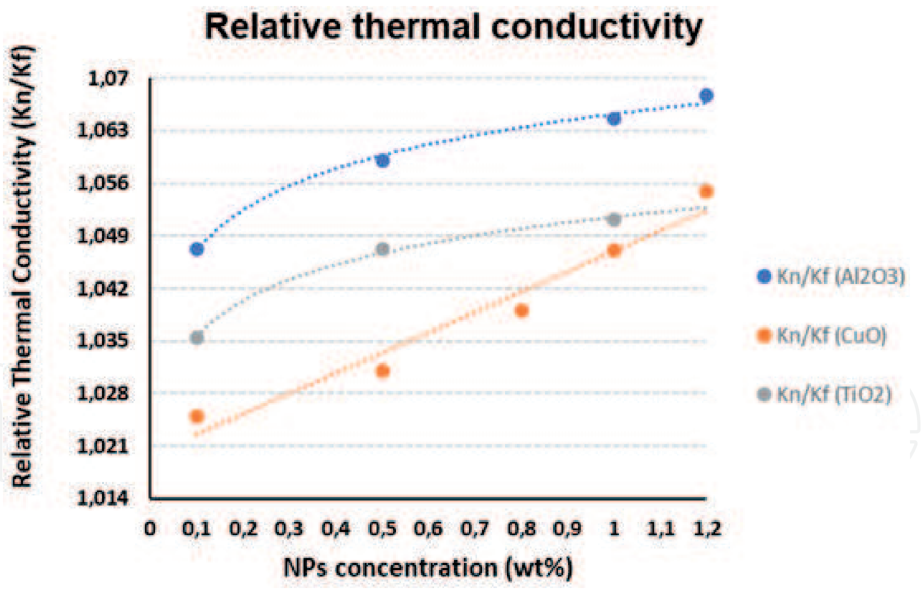

Figure 3.
Influence of NPs concentration on thermal conductivity for different NPs (CuO, Ti_2O_3 and Al2O3) and concentrations. Polyol-ester as base fluid.

Figure 3 that thermal conductivity increases with increasing the NPs concentration [46]. However, in the cases of Al_2O_3 and TiO_2, the thermal conductivity increase is less the higher the concentration. The "CuO" nanofluid exhibits a linearly increasing behavior with concentration.

The effect of the type of nanoparticle is clearly observed in **Figure 3**. Al_2O_3 nanoparticles provide the largest thermal conductivity increase compared to the other two.

3. Application cases

3.1 Passive cooling devices

Nanofluids can be potentially applied as working fluids in active (mechanically driven) and passive (capillary action, slug/plug dynamics) systems. Thermal management devices employing either concepts can benefit from the advantages of using nanofluids in order to enhance their heat transport capabilities.

Liquid cooling systems use a pump to drive the liquid to the heat source (or sources) in contact with a dedicated heat exchanger (or multiple heat exchangers). Heat is then absorbed by the working fluid and transported by the lines to a condenser (one or multiple), where the heat is rejected to a medium (environmental air, liquid reservoir, etc) with low temperature. Since the liquid cooling system is a closed circuit, the working fluid operates in a cycle absorbing and rejecting heat. As a necessity from its design, liquid cooling systems require a reservoir used to self-control the working fluid being used by the system, which will be determined by the flow rate at which it is operating. **Figure 4a** presents an schematics of a liquid cooling system.

As a promising technology for complex thermal management systems, Pulsating Heat Pipe (PHPs), also known as Oscillating Heat Pipes (OHPs) can potentially use nanofluids as their working fluids, due to the fact that they do not present a wick structure that could compromise their overall thermal performance. Their simple construction based on a meandering tube bent in several parallel curves operate by means of liquid slugs and vapor plugs motion [46], transporting the heat absorbed

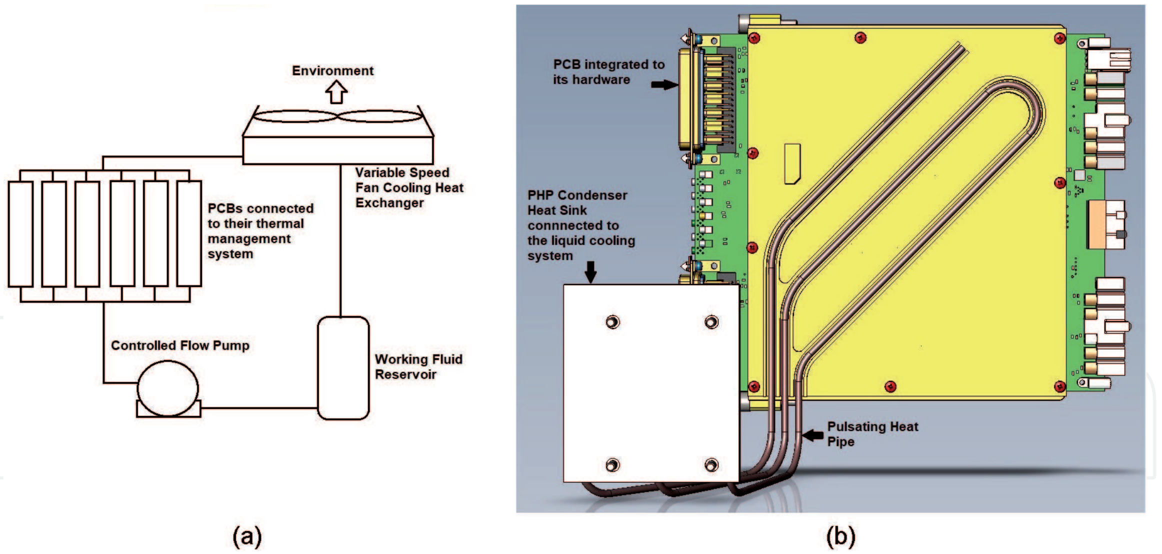

Figure 4.
(a) schematic, and (b) CAD representation of the thermal control system arrangement.

from a source and rejecting it in a sink. This kind of device can be considered a special type of heat pipe and was introduced by Akachi [47]. There are several applications in thermal control systems that PHPs can be utilized, from structures to electronics cooling, as well as thermal management of sensitive equipment such as those related to aerospace and surveillance. Given the potential use of PHPs as an effective thermal control device, investigations have been carried out towards the improvement of their overall efficiency, which leads to the search of alternative and more effective working fluids. In this case, the addition of solid nanoparticles in the working fluid has shown important improvements in its thermal conductivity that can potentially benefit PHPs [48].

Another thermal control device that can benefit from the improvements given by nanofluids is called Loop Heat Pipe (LHP). Given its architecture, LHPs are high efficient thermal control devices that can transport heat over long distances. It is built with a capillary evaporator responsible for generating capillary pressure that drives the working fluid throughout the loop. It is directly connected to a heat source where it absorbs the heat transferring it to the working fluid causing its evaporation. Due to the presence of a fine pore structure (wick), it generated capillary pressure that pushed the vapor towards the condenser, where it condenses back to liquid phase. By the capillary pressure action, liquid is sent back to the evaporator to complete the cycle. A compensation chamber (or reservoir) present at the capillary evaporator's inlet, which is hydraulically connected to the evaporator's core, will supply or drain the working fluid depending on the heat loads that are applied [49]. Depending of the level of accuracy needed to control the heat source, the LHP can present a pressure control regulator that sets the device's operation temperature with great precision [50, 51]. The potential in applying nanofluids in LHPs has been presented, showing a considerable enhancement in their performance. However, since the pressure drop increases with the use of nanofluids, the overall performance can be compromised due to limitations in the capillary pressure generation by the evaporator [52, 53].

Due to the potential in using nanofluids in thermal control devices, PHPs have been designed and integrated in a hybrid thermal management system installed in a surveillance system. This hybrid thermal management system was composed of a liquid cooling loop that connected several heat sources by heat exchangers, where PCBs were directly attached, in order to keep their electronic components within the required levels of temperature. A magnetic pump with variable flow rate was responsible for driving the working fluid throughout the loop, in order to guarantee that the heat generated would be properly absorbed and rejected. However, some PCBs were located far from the heat exchangers, which required the use of PHPs to connect the PCBs to them in order to transport the heat generated by the electronics to be properly rejected in a heat sink, while keeping their temperature according to the project's requirements. Due to the complexity of the system, along with the presence of hundreds of PCBs, several PHPs were designed, built and integrated to their dedicated heat sink, which were connected to the liquid cooling system. All the heat generated by the PCBs was transported to a condenser, responsible for dissipating it to the environmental air. According to the project's requirements, the hybrid system had to operate between +5 and + 50 °C of ambient temperature for a maximum humidity level of 95%. The schematics of such arrangement is presented by **Figure 4a** and **b** presents the hybrid setup where the pulsating heat pipe and the heat sink are connected [54].

The nanofluid selected for this application was composed of de-ionized water as the base fluid and CuO nanoparticles, since this combination presents a stable chemical compatibility. The solid nanoparticles presented an average diameter of 29 nm with 98% of purity. The nanoparticles concentration varied from 3.5 wt% to 20 wt%, which were used to compare their effects on the system's thermal performance while operating in real conditions.

As mentioned before, several PHPs were designed, built and integrated in this surveillance system, which showed to be a very complex thermal management problem to be solved. The PHPs had different configurations regarding their total effective length, number of turns, etc. all due to the fact that they were operating under different heat loads. The different designs for the PHPs are shown in **Figure 5** with the representation of their integration with their respective PCB [54]. The PHPs were charged with a nanofluid formed with de-ionized water (base fluid) and CuO (nanoparticles), with the same characteristics as the ones applied to the liquid cooling system. The nanoparticles concentration ranged from 2.0 wt% to 3.5 wt%. Due to the PHPs requirements towards the temperature homogenization of all their related PCBs, the heat dissipation capabilities of the entire thermal management system could be optimized.

Due to the thermal management characteristics at which a given device must operate, such as those found in heavy duty processing demands of computer clusters, as well as some electronics found in avionics, etc., a specific design is required. For high heat densities, PHPs are not indicated as thermal control devices due to their limitation in transporting the heat, which can generate concentrated heat loads and an eventual device's failure. In this case, LHPs are the most indicated to be applied as they can efficiently remove the heat from concentrated areas, being known to operate in applications where the heat flux in the heat source can be as

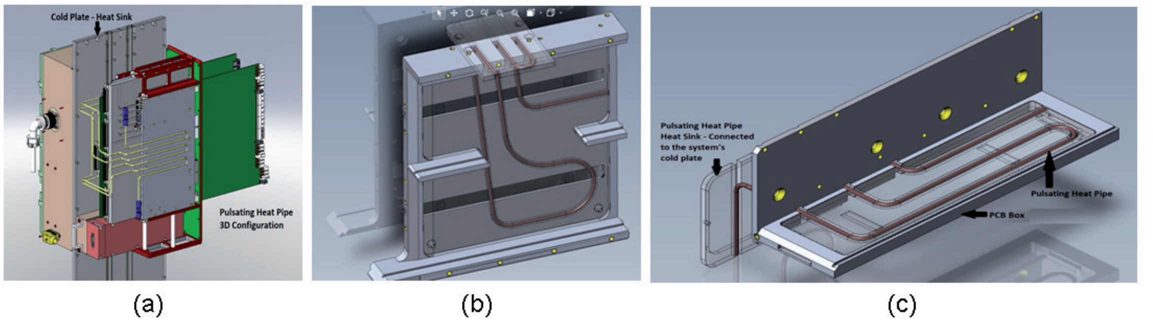

Figure 5.
PHPs with nanofluids applied to the thermal control of PCBs. (a) low, (b) medium, (c) high thermal load configuration.

much as 100 W/cm^2, or even above that. There are different architecture configurations for LHPs destined to the thermal control of high heat density electronics, being able to operate with a regular working fluid or with a nanofluid, such as shown by **Figure 6** [52–54].

Nanofluids have been reported to increase by up to 20% the heat transport capability in LHPs, even though they were facing higher pressure drops as nanofluids present a higher viscosity when compared to the base fluid's only. In this case, a better assessment regarding the LHP's thermal characteristics must be well balanced in order to not compromise its performance and cause a system's failure.

A subject that is commonly neglected by some researchers and manufacturers is related to the degree of chemical compatibility between the base fluid, the solid nanoparticles and the material used to build a PHP and a LHP, since they operate with their working fluid at saturation conditions. This is a key factor to ensure instant operation of those devices as soon as heat is administrated to their evaporator, being promptly absorbed by latent heat. If chemical incompatibility is found between the working fluid, solid nanoparticles and other materials used to build the device, the working fluid will begin its degradation resulting in the generation of non-condensable gases (NCGs). The velocity at which the degradation will occur will depend on the materials and working fluid involved, as well as with the operational temperature. Incompatible materials and fluids, such as water and aluminum, ammonia and copper, etc., will present a degradation much faster than known compatible materials and fluids, such as water and copper, ammonia and aluminum.

The NCGs generated during the base fluid's degradation will be accumulated at the coldest part of the PHP/LHP (condenser), being accumulated there during the device's operation. Since more NCG will be accumulated, the device will lose its condensation capability, compromising the heat rejection by the system that will end up causing an increase in the evaporator's temperature and, finally, the device's failure due to a dryout caused by the lack of liquid returning to the evaporator.

A process that has been often neglected by many professionals working with PHPs/LHPs and heat pipes, as well as with nanofluids, is called *aging*. This process forces the system to generate as much NCG as possible under controlled conditions that will eventually guarantee that the device will operate for a long time without the effect of NCGs [55].

As part of the manufacturing processes of any device like PHPs, LHPs and heat pipes, the aging process will be executed after the vacuum/charging procedure applied to those devices. The vacuum/charging procedure is of great importance and must be carefully controlled in order to ensure that the device will properly operate under the designed requirements. In this case, the device must reach a vacuum level that is adequate for its operation, which is also applied as a final cleaning process and moisture removal to any device. Prior to transferring the working fluid to the device, it needs to go through a process called *outgassing* that

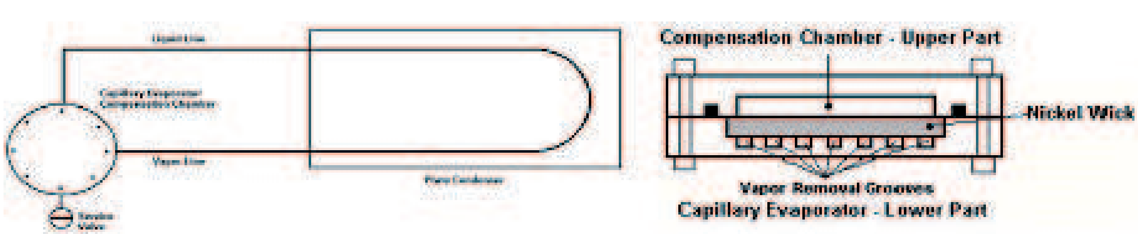

Figure 6.
Loop heat pipes applied to computer clusters thermal control.

will bring the working fluid to its saturation condition at the local temperature. Along with this, the *outgassing* will eliminate any dissolved gases present in the working fluid that will certainly contribute to the NCG generation and compromise the device's performance. This is not a complex process to be executed and can be done as presented by **Figure 7**. The technician needs to pay attention to the valves sequence to ensure that the device will be properly evacuated at the required vacuum level, as well as the adequate outgassing of working fluid prior to transfer it to the device. In order to perform the vacuum in the device, valves V1 and V3 must be open, keeping V2 closed. Upon reaching the required vacuum level and no leaks have been detected, the working fluid is outgassed by opening V1 and V2 keeping V3 closed. Once the outgassing has been completed, the technician can transfer the working fluid to the device by closing V1 while opening V2 and V3, ensuring that the required inventory of working fluid is properly transferred to the device [55].

When using low pressure working fluids, such as water, methanol, and acetone, it is possible to watch the entire outgassing process when using a clear glass bottle. During this process, all dissolved gases that will be removed from the working fluid will present a "boiling" pattern, indicating that the vacuum pump is bringing the internal volume to the working fluid's saturation condition. **Figure 8** presents the outgassing process being executed for deionized water. In the case of a nanofluid, due to the addition of solid nanoparticles, the resulting working fluid can result in a dark substance that can present some difficulties to see the outgassing occurring. A trained technician can overcome this issue and perform the outgassing as needed, as shown by **Figure 9** for the case of CuO-deionized water nanofluid (concentration of 2 wt%).

The outgassing process will be over once the bubbles stop appearing in the working fluid. This is the time when the working fluid can be transferred to the device. Nanofluids present a faster outgassing process due to the presence of solid nanoparticles. The working fluid volume that needs to be transferred to the device will determine the time required for the outgassing process, as well as the vacuum pump's speed.

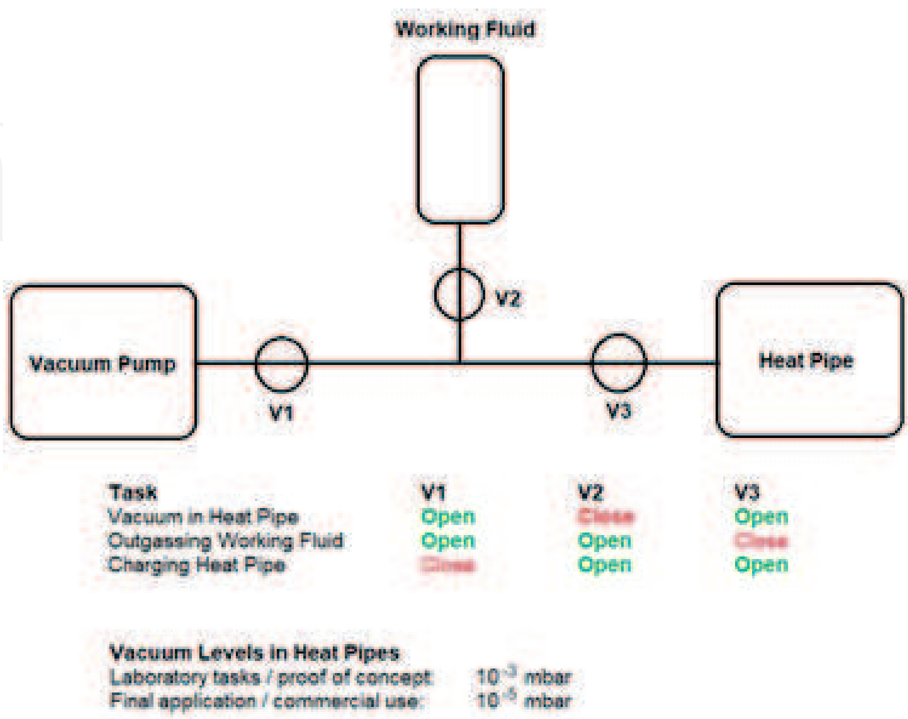

Figure 7.
Charging process of a heat pipe operating at saturation conditions.

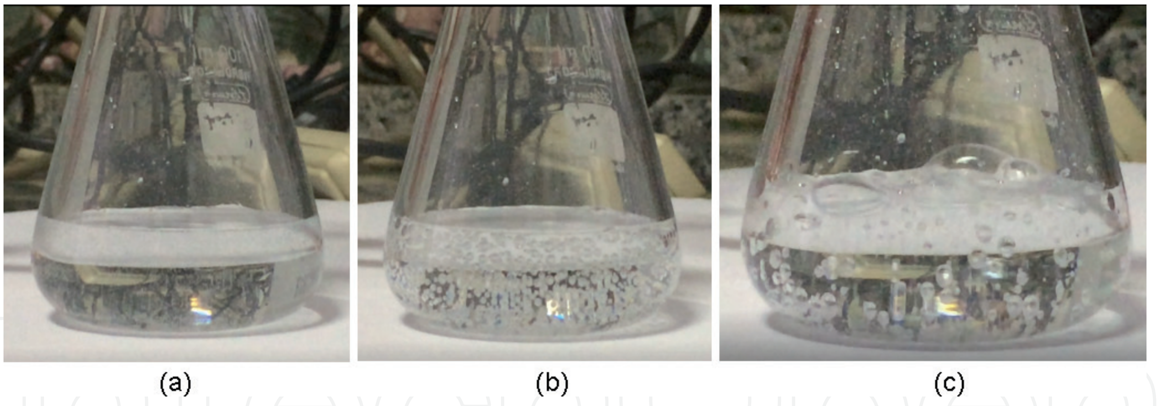

Figure 8.
Outgassing process for the de-ionized water: (a) beginning of the process; (b) dissolved gases being released; (c) intense release of dissolved gases.

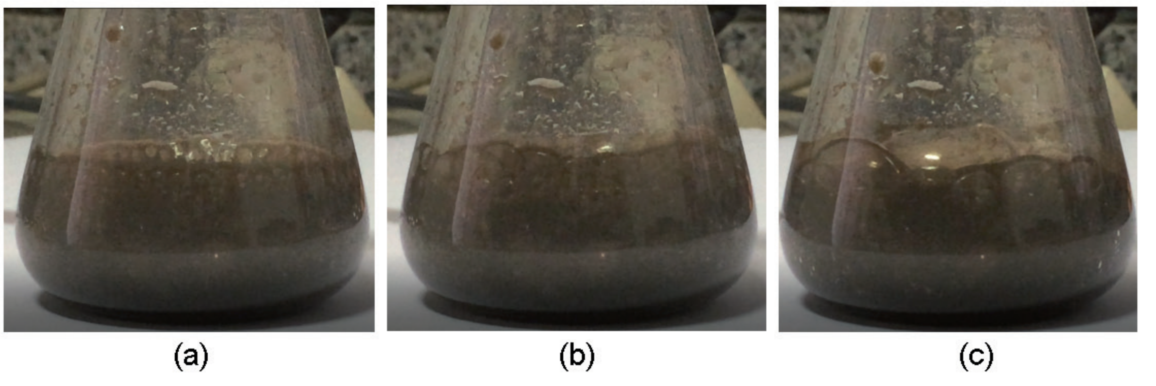

Figure 9.
Outgassing process for the CuO- water nanofluid: (a) beginning of the process; (b) dissolved gases being released; (c) intense release of dissolved gases.

3.2 Active cooling -vapor compression

Another potential application for nanofluids is vapor compression refrigeration "VCS". In these systems, the working fluid is circulated actively through a compressor. The compressor generates the pressure difference necessary for the refrigerant to circulate. During its journey, the refrigerant undergoes a cyclical phase change, condensation-evaporation, which gives it a greater heat transport capacity compared to liquid cooling.

The coefficient of performance "COP" of the VCS systems can be improved in two ways: firstly, by increasing heat abstraction rate in evaporator, and secondly, by reducing the work done in a compressor The use of nanoparticles to increase the COP of vapor compression systems is something that has already been confirmed, as evidenced by the research works on the matter [54, 55]. Some works are more focused on the increase of heat transfer rates [56–58] while others are on the compressor lubrication improvement [59, 60].

The present work aims to provide more scientific information about nano-lubricants and how they influence the COP of a vapor compression system. The refrigeration system used for determining the COP values was built in-house, **Figure 10** and whose characteristics are listed in **Table 1**.

The Polyol ester lubricant is doped at 1.5% by weight with two types of nanoparticles (Cu and CuO). Both the clean lubricant and the two formulated nano-lubricants are tested on the bench in order to record the corresponding COP. The results are shown in **Table 2**.

The level of lubricant in the refrigerant circuit also has its effect on the COP of the refrigerator, as shown in **Figure 11**.

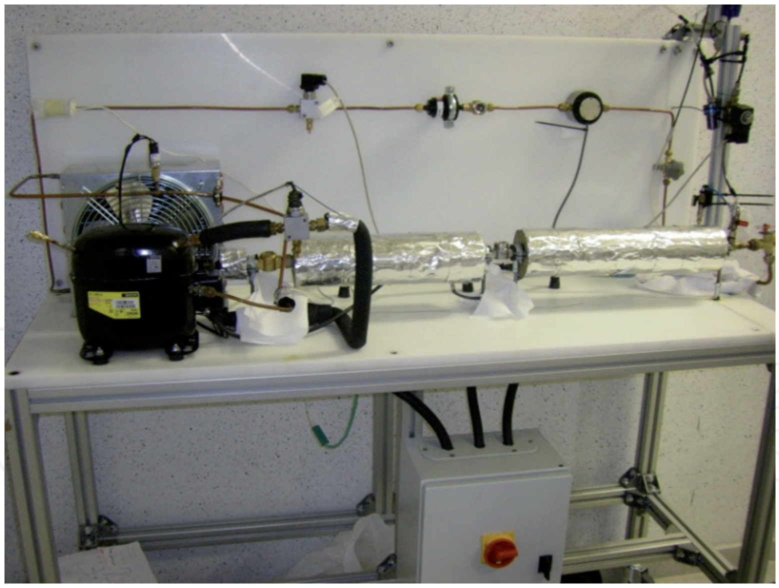

Figure 10.
VC system to test nano-lubricant effects on COP.

Cooling capacity	400W
Compressor	Secop SC12MLX
Refrigerant	R449A
Charges mass	400gr

Table 1.
Components' technical characteristics.

Lubricant	COP	COP increase
Polyol ester	1.25	---
Polyol ester +1.5% Cu	1.41	12%
Polyol ester+3%Cu	1.31	5%

Table 2.
COP improvement.

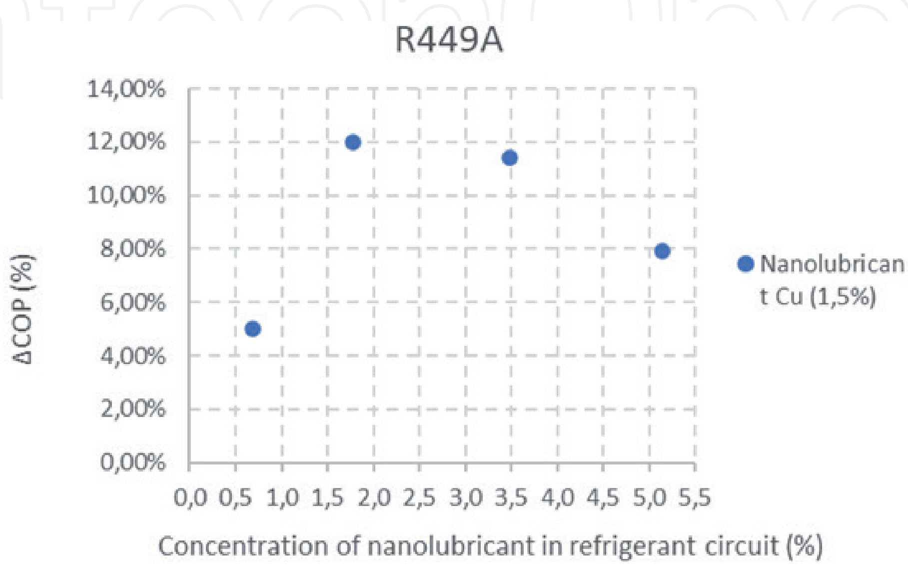

Figure 11.
Effect of the 1.5%Cu nano-lubricant on the VCS's COP.

4. Conclusion

- In view of what is stated in this chapter, it can be concluded that: nanofluids is a promising science to improve the heat transfer capacity of different technologies
- It is applicable to different sectors with minimal investment cost
- Nanofluid stability continues to be a challenge and therefore an open door to research
- A greater understanding of the causes that make the thermophysical properties of nanofluid improve is still necessary, more theoretical research is required
- The large amount of experimental research work carried out to date positions nanofluids as a key enabling technology for the advancement of thermal and cooling management in the immediate future.

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