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Nanofluids' stability effects on the thermal performance of heat pipes

A critical review

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Abstract
Nanofluids have been introduced as an alternative to conventional fluids to improve energy efficiency in heat transfer systems. However, their stability problems before and after operation cycles can produce inconsistent results in different heat transfer technologies that use them. This review summarizes different experimental results obtained using nanofluids in heat pipes, particularly in two-phase closed thermosyphons, and it focuses on the role of preparation and stability issues of nanofluids before and after their use in these devices. Additionally, the effects of nanofluids on heat pipes' thermal performance were compiled and compared from available experimental studies in the literature. Nanoparticles' deposition on the evaporator surface and wick or groove structures were the most common mechanism to explain the reported increase or decrease in the thermal performance of heat pipes. This review also identifies the research problems that need to be solved in order to use nanofluids that outperform conventional fluids in heat pipes.

Keywords Nanofluids · Heat pipes · Two-phase closed thermosyphon · Nanofluids' stability · Thermal performance

Introduction

Energy efficiency is a critical issue worldwide, particularly due to climate change and global warming in addition to the ever-increasing consumption. There is a constant demand for new methods and developments that can decrease the consumption of fossil fuels and can also mitigate greenhouse gas emissions. Heat transfer is one of the most important processes in the development of industrial products, and thermal systems have an important role in energy consumption [1, 2]. Energy efficiency improvements in these processes can be achieved by using high-efficiency devices with extended areas or thermal fluids with improved thermophysical properties. Any development or effort regarding the use of said fluids with enhanced properties in efficient thermal transport technologies is significant to improve the performance and efficiency of thermal energy systems.

Nanofluids are suspensions obtained by dispersing nanoparticles (typically < 100 nm) in common fluids. These were presented in 1995 by Choi and Eastman [3] as fluids with high potential to replace the conventional fluids used in heat transfer applications, due to its higher thermal conductivity. Since then, nanofluids are commonly used in heat transfer applications with the aim of increasing the energy efficiency in different devices [3–5]. Despite the reported controversy regarding their effect on thermal conductivity and the underlying mechanisms of nanofluids [6], substantial increases in heat transfer technologies with convection and boiling heat transfer of nanofluids have being widely found in the literature [7].

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Heat pipes are one of the most effective passive heat transfer technologies, and they are commonly used when efficient heat transfer with small temperature differences is the main purpose. These devices have a very high thermal conductance and are widely used in isothermal applications, temperature control, and (to a lesser extent) waste energy recovery [8]. The addition of heat pipes to heat transfer systems enables efficiently to use them, which is ideal for a number of industries and applications [9]. The main applications of heat pipes are temperature control of central processors in desktop and laptop computers [10], air-conditioning systems, thermal storage, solar heating systems [11], and waste heat recovery from furnaces [12] and boilers using the heat from exhaust gases to preheat the air used for combustion [13]. A heat pipe is composed of a sealed container with a working fluid in their interior. Generally, it comprises three sections, an evaporator, a condenser, and an adiabatic zone, additionally, in their interior can have a wick material that provides a capillary pressure to the liquid movement from the condenser to the evaporator [14]. A special but simple type of gravity-assisted wickless heat pipe is the two-phase closed thermosyphon (TPCT), which has applications in a broader temperature range than conventional heat pipes. In recent years, the number of works on these thermosyphons has risen considerably due to their numerous applications, including their popular use in heating and cooling processes and solar energy recovery [15].

Generally, thermosyphons are either vertically oriented or inclined at about 5° to the horizontal and comprise three main zones, an evaporator, an adiabatic section, and a condenser, with the evaporator below the condenser. The heat supply in the evaporator may be hot exhaust gas from an industrial process, a steam generator, or a preheater for the incoming air or process fluid [16]. Commonly used working fluids in thermosyphons are water, methanol, ethylene glycol, and their mixtures [17]. The working fluid is subjected to film evaporation and pool boiling heat transfer mechanisms in the evaporator section. After the evaporation and condensation processes, gravity-assisted condensed liquid films provide the recirculation of liquid from the condenser to the evaporator section [18]. The working principles of heat pipes as well as thermosyphons are well known [8, 14, 15, 19] and will not be elaborated further.

Nanofluids have been used also in different types of heat pipes, including mesh wick heat pipe, sintered metal wick heat pipe, oscillating heat pipe, and two-phase closed thermosyphon [20]. Literature review about specifically heat pipes and thermosyphons operated with nanofluids was firstly addressed in 2012 by Liu et al. [21]. In 2013, Buschmann et al. [22] realized an critical review and complemented and actualized this in 2015 [23]. Other reviews related to heat transfer associated with the use of nanofluids in heat pipes have been presented by Sureshkumar et al. [24] and Alawi et al. [20]. Recently, Gupta et al. [25] publish a review about the heat transfer mechanisms present in heat pipes using nanofluids. In all these literature reports, it has been concluded that nanofluids as working fluids have the potential to improve the thermal performance of heat pipes; however, all authors agree that deeper research is necessary to understand the real effect of nanoparticles in the heat pipes' thermal performance.

In this review, we focused on nanofluids' preparation and characterization and their thermal features when they are used in heat pipes.

However, the results of using nanofluids in heat pipes in the literature are not consistent and sometimes even contradictory. In the majority of cases, heat pipes' performance was enhanced [26–43], while in other cases degradation was apparent [29, 44–48]. The effect of nanofluids on the differences in the performance of heat pipes and TPCTs has commonly been attributed to a porous layer formed on the evaporator surfaces caused by the agglomeration and sedimentation of particle clusters during and after cycles. This porous layer can modify the nucleation sites and the wettability [29] promoting the growth or collapse of bubble [49]. However, the effects of this porous layer in the thermal performance are highly dependent of the nanoparticles' concentration [50].This porous layer is commonly identified using scanning electron microscopy after heat pipes' operation; an example of the evaporator surface after TPCT operation can be seen in Fig. 1.

Agglomeration and deposition of nanoparticles on the evaporator surface and differences found in thermosyphons and heat pipes' performance could be related to different parameters used during nanofluid preparation and difficulties to maintain the particles dispersed over time. Problems related to stability have limited the use of nanofluids in different heat transfer devices, and the

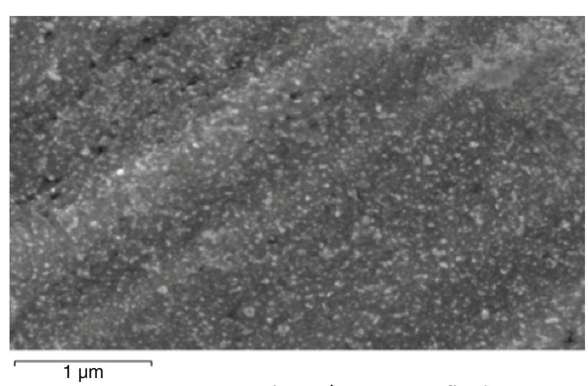

Fig. 1 Evaporator surface after TPCT operation with nanofluid

formulation of stable nanofluids remains a research challenge [51–54]. Nanofluids' preparation and their associated parameters such as sonication type and time, nanoparticle concentration, agglomerates sizes, and chemical additives were not generally studied before they were used in thermosyphons, and only very little information is provided in the experimental studies reported in the literature. Nanofluids' stability and their thermal properties measured before their use in thermosyphons can suffer modifications during and after operation cycles due to thermal loads, movement of particles, and phase changes [22]. The field of nanofluids is still under development, and further experiments and simulations need to be conducted in order to quantify and validate the effectiveness of nanofluids in different thermal devices such as heat pipes [9].

This review summarizes the reported experimental results of the use of nanofluids in heat pipes, particularly in thermosyphons, and focuses on the preparation and stability issues of nanofluids which can explain the differences found in the literature in terms of their thermal performance. This study also aims to identify the research gaps and problems that need to be solved to achieve a real application of nanofluids in thermosyphons and to verify their thermal performance reproducibility.

Nanofluids as working fluid in TPCTs

Nanofluids' preparation methods and stability issues

There are two typical methods to obtain nanofluids: one step and two step. The first option combines nanoparticles' synthesis and nanofluid production simultaneously, using physical and chemical processes; it avoids the drying, storage, transport, and dispersion stages of nanoparticles, but impurities are commonly found and the quality of the nanofluid decreases [55]. In the two-step method, nanoparticles are first obtained by different chemical or physical processes, and after that, they are dispersed in the base fluid [56]; it is commonly preferred due to its low cost and easy implementation. By this method, nanoparticles are synthetized or can be commercially obtained first, and after that, they are dispersed in the chosen base fluid using different dispersion techniques, such as ultrasonication or homogenization.

However, the main drawback of this method is the poor stability of the nanofluid caused by nanoparticle aggregation and sedimentation [57, 58]. Interaction forces between nanoparticles, mainly Van der Waals, are responsible for these phenomena [51–54, 58, 59]. Therefore, in the two-step method, the use of chemical additives (such as surfactants) or nanoparticle functionalization to minimize nanoparticle agglomeration and improve nanofluid stability is a common practice [39]. Nanofluids' preparation methods and stability issues can be reviewed more deeply in [60–66].

Nanofluid stability is one of the principal challenges in the world of nanofluid applications [51–53, 61, 67–72]. Factors like preparation method [67], nanoparticle concentration [57], nanoparticle type [54], surfactant type [57, 68, 73], surfactant concentration [73–75], pH [73, 76], ultrasonic type and time [73, 77], and ultrasonication power [78, 79] greatly affect nanofluids' stability and thus their performance in applications [72, 80]. Additionally, the stability of nanofluids can change after they are used in different applications due to different thermal loads, movements, phase changes, and other factors that can produce nanoparticle agglomeration and sedimentation that affect their behavior [22, 81].

Different methods and techniques have been employed to evaluate the nanofluids' stability, including visual inspection, zeta potential, UV–Vis absorbance variation, hydrodynamic diameter size variation and properties such as thermal or electrical conductivity, viscosity, or others over time [74, 75, 82–85]. However, the methods generally are complementary to complete a most accurate stability characterization [66, 86]. Table 1 resumes ones of the most used methods and the limitations in stability test.

Nanofluids used in heat pipes as working fluids have been commonly prepared via the two-step method. A summary of different experimental studies where the main aspects related to nanofluids' preparation, such as nanoparticle type, concentration, surfactant type and concentration and dispersion techniques before their use as working fluid in heat pipes is shown in Table 2. Most of them use commercial nanoparticles dispersed in the base fluid by different ultrasonication types, settings, and times. Also, some researchers applied surfactants or functionalized nanoparticles to avoid agglomeration.

It can be seen from Table 2, that some studies did not provide information about the stability of nanofluids after they were prepared [29, 37, 39, 94–99], and most of them reported the use of surfactants without detailing with their concentrations, type, selection, or sonication times.

Nanofluids with different types of nanoparticles, such as metal oxides and carbonaceous materials, have been used in heat pipes and produced increases in their thermal performance [17, 36, 37, 100–102]. However, there is an information gap regarding the characteristics and use of nanofluids, as well as chemical additives and their effects on thermophysical properties and stability issues. In addition, most reports only provide incipient information about the pre-use state, i.e., before using nanofluids in heat pipes (static mode), and no data after operation cycles.

Table 1 Nanofluids' stability evaluation methods

Method	Description	Limitations
Visual inspection	In this method, sequential images of the nanofluid are taken over time, with the aim to identify phases separation and sedimentation	For low sedimentation rates and when the phases separation is not clear, it is difficult to compare the nanofluids' stability by this method [66, 87]
UV–Vis	In this method, the absorbance variation is an indicative of variation of the nanoparticles' concentration according to Beer–Lamberts law [86]	Does not work for highly concentrated fluids and nanofluids dark in color [52]. Generally required very diluted samples that no represent the real concentration used in heat transfer applications
Zeta potential	Zeta potential is a measure of nanoparticles' surface charge density. High positive or negative values represent strong repulsive forces avoiding the nanoparticles' agglomeration. Limits generally are between − 30 and 30 mV [83]	Require diluted samples and only provide information to calculate the electrostatic repulsive forces and not provide information related to the attraction forces. Then, there is the possibility that unstable nanofluids can be obtained with zeta potential values inside the stability limits [88]
Dynamic light scattering—DLS	By this method, the average size of nanoparticles or their agglomerations is monitored over time [72, 89, 90]	This technique depends of the nanoparticles' concentration and diluted samples are required [91]. Also, the samples must be clear, homogeneous and without haze [88]
Thermophysical properties variation	In this method, the properties are measured over time to identify their variation and associated this to stability [74, 87, 92]	This is an indirect method and depends on the equipment uncertainty to measure the properties and their dependence of the movement of nanoparticles during their aggregation and sedimentation [93]

Surfactant effect on heat pipes

Surfactants and other chemical additives are commonly used to improve nanoparticle dispersion without significantly changing their thermophysical properties over time. However, in the literature, several studies suggest an important relationship between the type and concentration of surfactant and their effect on stability times as well as thermophysical properties [103–106]. Any research on the effect of the surfactant on the stability of nanofluids must be focused on finding the right type and optimal amount (e.g., concentration) that enables long-term stability without changes in thermal properties before and after nanofluids which are used in thermal systems [107].

Parametthanuwat et al. [98] reported the influence of surfactant on nanofluids' performance in a thermosyphon. They used different concentrations of oleic acid to disperse Ag nanoparticles in water and found that the highest increase in thermosyphon performance was obtained with 1 w/v% of this surfactant. Nevertheless, the effect of this surfactant on nanofluid stability and heat transfer mechanisms was not reported except for mentioning that the nanofluid was stable for a long time without specifying the length.

Amiri et al. [27] compared the performances of a thermosyphon by using functionalized graphene nanoplatelets and graphene nanoplatelets (GNP) in water with the addition of SDBS as surfactant. They found that the rise in the heat transfer coefficient with functionalized graphene nanoplatelets was 33% greater than the increase with the addition of 0.1 mass% of SDBS surfactant. Additionally, they emphasized that the viscosity was increased by 136% at 80 °C due to the addition of surfactant. Nevertheless, the reasons behind the increment in viscosity caused by adding surfactant at such high temperature were not explained.

Mehrali et al. [49] evaluated the thermal performance of a grooved copper heat pipe using a nitrogen-doped graphene nanofluid, with Triton X100 as surfactant. In their results, they found increases in the thermal performance up to 74% for graphene concentration 0.06 mass% and Triton X100 (0.025 mass%) at 120 W. Additionally, the TX100 solution showed higher heat transfer coefficient compared to water as working fluid. However, the increases in the global thermal performance were superior when nitrogen-doped graphene nanofluid with Triton X100 was used instead of only surfactant solution.

Although few studies were found in the literature with respect to the effect of the surfactant on nanofluids used as working fluids in heat pipes, it is evident that the presence of the former can produce changes in the thermal behavior of the latter. Thermophysical properties such as surface tension, viscosity, and thermal conductivity can change with the surfactant addition, and this can produce changes in different heat transfer mechanism such as convection and boiling [108]. Furthermore, nanofluids are subjected to different transport and heat phenomena, which can produce variations in the surfactant, such as degradation and changes in properties. In this sense, more studies on the relationship between chemical additives, nanofluid stability, and the thermal performance of TPCTs need to be carried out in order to better understand the behavior of TPCTs in the presence of nanofluids.

Table 2 Summary of available experimental studies on nanofluids used in thermosyphons

Nanoparticle/base fluid	Preparation method/sonication type/sonication time	Surfactant/NSA	Stability monitoring method	Stability time	References
Al_2O_3/water + ethylene glycol	Two-step/probe/100 min	PVP/0.1 vol%	Visual	45 days	[109]
Ag/water	Two-step/probe/120 min	PVP/1 vol%	SEM TEM	40 days	[26]
Graphene functionalized (GNP)/water	Two-step/probe/10 min	SDBS/0.5:1 GNP	NR	30 days	[27]
Al_2O_3/water $TiSiO_4$/water	Two-step/probe	NSA	Visual TEM	48 h	[36]
TiO_2/water	Diluted from commercial suspension W740X/NR/NR	NSA	NR	Stable for months	[37]
CuO/water Al_2O_3/water Laponite clay/water	Two-step/bath/2 h	NSA	NR	Several weeks	[46]
Al_2O_3/water	Two-step/bath/4 h	NSA	NR	24 h	[17]
Fe_2O_3/water	One-step	NSA	NR	NR	[94]
CuO/water	Two-step/bath/12 h	NSA	Dynamic light scattering	Several days	[110]
SiO_2 functionalized with silanes groups/water	Two-step/bath/12 h	NSA	Visual	12 months	[44]
MWCNT–Ag/water	Two-step/bath/45 min	NSA	NR	NR	[39]
MgO/water	Two-step/bath/8 h	Triton X100	NR	NR	[95]
Al_2O_3/water	Two-step/probe/60 min	Chitosan/ 0.2 mass%	UV/Vis	2 weeks	[11]
CuO/water	Two-step/bath/12 h	NSA	NR	Several days	[111]
MWCNT/water	Two-step/bath/12 h	NSA	NR	NR	[96]
TiO_2/water Au/water	TiO_2–Dilutions from W740X Au (one-step)	PVP/1 mass%	NR	NR	[97]
Ag/water	Two-step/bath/12 h	Oleic acid/ 0.5–1 vol%	NR	NR	[98]
GNP/water	NR/NR/NR	GA/0.5 mass%	NR	NR	[101]
Fly ash	Two-step/bath/NR	Triton X-100/ 0.2 mass%	Visual	NR	[112]
Ag/water	Two-step/bath/5 h	NSA	NR	48 h	[113]
SiO_2-functionalized/water	Two-step/bath/12 h	Functionalization with silanes	TEM	12 months	[114]
Fe_2O_3/water	Two-step/NR/NR	NSA	NR	NR	[115]
MWCNTs functionalized with ethylenediamine (EDA)/water	Two-step/NR/NR	NSA	NR	NR	[116]
Al_2O_3/water CuO/water	Two-step/NR/NR	NSA	NR	NR	[117]
MWCNTs oxidized with different acids/water	Two-step/NR/3 h	NSA	NR	NR	[118]
Graphene/acetone	Two-step/bath/25 min	NSA	Visual	7 days	[119]
Graphene oxide (GO)/water silver oxide (SO)/water	Two-step/probe/5 h	NSA	NR	NR	[102]
ZrO_2/water	Two-step/probe/90 min	NSA	NR	NR	[120]
Amine treated graphene quantum dots (A-GDQ)	NR	NSA	NR	NR	[121]
CuO	Two-step/bath/10 h	NSA	NR	NR	[99]
Al_2O_3/CuO	Two-step/ultrasonic cell disruptor/1 h	NSA	NR	NR	[29]

Table 2 (continued)

Nanoparticle/base fluid	Preparation method/sonication type/sonication time	Surfactant/NSA	Stability monitoring method	Stability time	References
SiC	Two-step/NR/3 h	NSA	NR	NR	[48]
Fe_2O_3	Two-step/bath/5 h	Oleic acid	Visual	NR	[122]
Nitrogen-doped graphene	Two-step/probe/60 min	Triton X-100	UV–Vis	200 days	[49]
Graphene oxide (GO)	Two-step/NR/6 h	NSA	Zeta potential	NR	[32]
Graphene nanoplatelets	Two-step/probe/NR	NSA	NR	600 h	[30]

NR not reported, *NSA* not surfactant addition

Nanofluids after operation cycles

Nanofluids in heat pipes are subjected to different thermal loads, phase changes, and movement. Therefore, their stability and thermophysical properties can change significantly after operation cycles. In the reported literature, few studies have evaluated the characteristics of nanofluids after heat pipes' operation. Some related research studies are briefly discussed below.

Grab et al. [97] investigated the changes in nanoparticle size before (stationary nanofluid, no flow, no phase change conditions) and after operation cycles in a thermosyphon using nanofluids of TiO_2 and Au. They found a considerable increase in nanoparticle size as a consequence of their agglomeration. In TiO_2 nanofluids, the size increased up to 28%, while in Au nanofluids it was as high as 125%. They also found that when the thermosyphon was not operated for a period of time, nanoparticles sedimented and formed a porous layer on the evaporator, thus affecting the thermal performance. Another study in the same laboratory [37] found that using TiO_2–water nanofluids in a thermosyphon enhanced its performance, but when the thermosyphon was left unoperated during 5 weeks it underperformed. This phenomenon was attributed to an increase in agglomerated sedimentation and to the porous layer aging formed in the evaporator.

Contrary results were also found in the literature with respect to stability after thermosyphon operation cycles. Liu et al. [111] used CuO–water nanofluids in a thermosyphon and did not find differences in performances between fresh nanofluids and nanofluids left to rest in the thermosyphon without operation for 2 weeks. Their explanation for this result was that possible sedimented nanoparticles in the evaporator mixed again in the base fluid when the thermosyphon was in operation due to the buoyant forces of the bubbles during boiling. Another study, by Chen et al. [44], used functionalized SiO_2 in a thermosyphon and evaluated its behavior a week after the first test. However, they did not observe any porous layer in the evaporator in both experiments, and thus, no difference in the thermal performance was reported. Their results were in accordance with the results found by Yang et al. [114] using functionalized silica nanoparticles and Ozsoy et al. [123] using silver–water nanofluid in a heat pipe evacuated tube solar collector.

Heris et al. [118] used CNT functionalized with different acids in a TPCT. The acids were added to anchor carboxylic groups in the CNT surface. They found that with an increase in carboxylic groups in the CNT surface, thermal performances were superior. This result was associated with the stability of CNT in fluid base and the formation of homogeneous active sites throughout the base fluid in the evaporator. Nevertheless, more extensive research needs to be conducted to draw conclusions about the stability of nanofluids and their relationship with the contradictory results found in the literature regarding TPCT performance. The stability of nanofluids on rest can be changed when they are subjected to different transport and heat phenomena in heat pipes' operation. Porous layer formation is frequently reported after operation cycles and can change depending on the nanoparticle type, concentration, and morphology. The analyzed literature does not enable to draw conclusions regarding the real effect of nanofluids used as working fluid in heat pipes yet.

Therefore, there are two main questions to address: Is the stability of the nanofluid on rest before using it in TPCTs really important for TPCT performance and can such stability be maintained after discontinuous operation cycles? Can there be reproducibility in the operation of a thermosyphon with nanofluids?

Heat pipes' performance using nanofluids

Effects of nanofluids on the thermal performance of heat pipes are commonly reported in the literature as variations in thermal efficiency or thermal resistance. Additionally, these variables depend on experimental parameters such as tilt angle, filling ratio, and power [15]. An optimal combination of working fluid and experimental parameters must be found to maximize the thermal behavior of heat pipes.

Kamyar et al. [36] found an increase in the thermal performance of a thermosyphon using nanofluids composed of Al_2O_3 and $TiSiO_4$ nanoparticles dispersed in water. The thermal resistance of the thermosyphon fell down to 65% with a nanofluid of Al_2O_3 (0.05 vol%)–water and to 57% with $TiSiO_4$ (0.075 vol%)–water at 40 W. Such an increase in thermal performance was attributed to an increase in base fluid thermal conductivity and a porous layer formed on the thermosyphon evaporator surface.

Buschmann et al. [37] evaluated the effect of TiO_2–water nanofluids on the thermal performance of a thermosyphon. They reported a 24% decrease in thermal resistance when they used concentrations between 0.2 and 0.3 vol% of TiO_2. This decrease in thermal resistance was also attributed to a porous layer formed in the evaporator and not to the thermophysical properties of the nanofluids.

An increase in thermal efficiency of up to 14.7% in a thermosyphon using Al_2O_3–water (2% v/v) nanofluids with a power of 97.1 W was reported by Noie et al. [17]. However, they did not attribute this increase to a specific phenomenon, and in their analysis, they established several possibilities such as the formation of a porous layer, an increase in thermal conductivity, and Brownian motion. Nonetheless, no explicit cause for such an increase in thermal efficiency was specified.

Azizi et al. [101] observed an increase in the thermal efficiency of a TPCT using graphene nanofluids as a working fluid compared to water. The maximum thermal efficiency was 90.2% for a graphene concentration of 0.1 mass%. They attributed the thermal efficiency increase to Brownian motion, and its effects were associated with microconvection that could cause the energy exchange rate around the wall, and thus, the heat transfer between the evaporator wall and fluid increases considerably.

Grab et al. [97] were able to improve the thermal performance of a thermosyphon by lowering thermal resistance by up to 10% when using TiO_2–water nanofluids (0.2 and 1 vol%) with power variations between 150 and 300 W. While Au–water nanofluids (0.4 and 0.59 vol%) showed a fall between 10 and 20% up to 150 W, they did not show any change beyond 200 W. This reduction of thermal resistance was also considered due to the formation of a porous layer of nanoparticles in the evaporator, which was identified by scanning electron microscopy. These authors emphasized that the porous layers were different with the two types of nanoparticles and that the layer shows agglomerates bigger than the initial size of the nanoparticles.

Tong et al. [102] used graphene oxide (GO)–water and silver oxide (SO)–water nanofluids to evaluate their effects on TPCT performance. The thermal resistance of the TPCT with GO nanofluids was overall lower than when charged with deionized water, while the SO nanofluid caused a minor increase even at high concentrations of SO. They associated these reductions in thermal resistance with the increase in evaporation strength as a consequence of the fast water permeation of GO deposition.

Experimental research to determine of temperature profile and heat transfer of a thermosyphon charged with Fe_2O_3–water nanofluids was carried out by Huminic et al. [94]. Their results showed a maximum 42% increase in the heat transfer rate when using this nanofluid at 5.3 vol% concentration. This behavior was attributed to the bombardment of vapor bubbles by the dispersed nanoparticles in the base fluid, which makes them smaller and promotes heat transfer by boiling.

Shanbedi et al. [39, 100] conducted experimental studies to evaluate the performance of thermosyphons with multiwall carbon nanotubes MWCNT–water and MWCNT + Ag–water nanofluids. They found a decrease in the thermal resistance of the thermosyphon, which was attributed to the increase in the thermal conductivity of water caused by the addition of these nanoparticles. In another study using MWCNT–water nanofluids as a working fluid in a thermosyphon, a drop in evaporator thermal resistance and a rise of 150% in the heat transfer coefficient were reported by Liu et al. [96]. This improvement in thermosyphon performance was also attributed to the formation of a porous layer, which facilitated the enhancement of the boiling heat transfer mechanism.

Menlik et al. [95] evaluated the performance of a thermosyphon using MgO–water (5 vol%) nanofluids as working fluid. They reported a 26% improvement in thermal efficiency and a reduction in thermal resistance of 18% for a power of 200 W. Hung et al. [5] found a 22.7% increase in the thermal efficiency of a thermosyphon using Al_2O_3–water nanofluids (0.5 mass%). Notwithstanding, none of these researchers reported or provided a complete explanation of the real phenomenon behind such increase in the efficiency of the thermosyphon.

Soleymaniha et al. [121] in a recent work used an stable water-based quantum dots (GQD) in a thermosyphon. In their work, in order to obtain nanofluids' stability, graphene was treated with acids and an amidation reaction to include carboxyl and amine groups attached to their surface. They found an increase of 11.5% with water-based A-GQD at a concentration of 0.002 mass% was used at a power of 150 W compared with DI water.

Liu et al. [99] found increases in the condenser and evaporator heat transfer coefficients of a mesh heat pipe using CuO–water nanofluids. The maximum thermal performance enhance was found at concentration of 1 mass%, and after operation, almost no sedimentation of nanoparticles was found on the mesh surface. The increases in the thermal performance were attributed to modifications in the thermal properties of nanofluids. In the same way, Ramachandran et al. [29] used an hybrid nanofluid Al_2O_3/CuO–water in a cylindrical screen mesh heat pipe. They found decreases in the thermal resistance up to 44.25% compared with deionized water. This was attributed to the formation of a porous coating on the wick surface which enhanced the wettability and surface roughness, creating more nucleation sites.

In oscillating heat pipes, Goshayeshi et al. [122] used a Fe_2O_3/Kerosene nanofluid as working fluid in the presence of a magnetic field. They found increases in the thermal performance up to 16% compared with kerosene. In another study, Zhou et al. [34] used graphene nanofluids and they reported a reduction in the thermal resistance up to 83.6% for a graphene concentration 2.0 mass%, at filing ratio 62%, and heating power 80 W. This improvement in the thermal performance was attributed to increased thermal conductivity of the nanofluid compared with water and the enhanced surface wettability. In a similar way, in a vertical closed pulsating heat pipe, Xing et al. [124] reported a reduction in the thermal resistance by 34% compared to water using hydroxylated MWCNT nanofluid as working fluid.

As mentioned before, deteriorated heat pipes' thermal performance or without changes was found in some studies using nanofluids. For example, using carbon nanotubes (1 vol%)–water nanofluids in a thermosyphon, Xue et al. [45] reported a large increase: 3.3 times the thermal resistance of water as a working fluid. They attribute this deterioration in performance to the altered interfacial properties between deposited nanoparticles and the evaporator surface, which produce a reduction in active nucleation sites for the boiling mechanism.

In another study, Chen et al. [44] found increases in thermal resistance between 22 and 25% of their functionalized SiO_2–water nanofluids. They attributed their results to a more viscous working fluid due to added nanoparticles. Nevertheless, the way the viscosity of nanofluids contributed to the increase in thermal resistance was not explained. They also used SiO_2 nanoparticles without functionalization, and likewise, they found deterioration in thermosyphon performance. With the nanoparticles without functionalization, the authors found a layer of nanoparticles deposited in the evaporator surface and suggested that the reduced roughness of this layer was progressively responsible for the decrease in thermosyphon performance. Yang et al. [114] also used functionalized silica nanoparticles in a thermosyphon. They report that their nanofluids were stable and no sedimentation was observed due to a steric stabilization effect. They found that the evaporation heat transfer coefficient grew by 17% at the operating temperature of 40 °C, and this improvement was attributed to changes in thermophysical properties. However, no significant increases in thermosyphon heat transfer were found. Additionally, these authors used silica nanoparticles without functionalization, and a porous layer was identified in the evaporator surface, which resulted in heat transfer coefficient deterioration.

Khandekar et al. [46] found a worsening thermosyphon performance when they used nanofluids of CuO–water, Al_2O_3–water, and laponite clay–water. The maximum rise in thermal resistance was found for laponite. The results were attributed to less nanoparticle interaction with the nucleation cavities in the evaporator surface. Active sites for nucleation were blocked by nanoparticles deposited, and the density of sites for boiling was reduced.

Kyung et al. [48] found that the thermal performance of a screen mesh wick heat pipe using SiC nanofluids as working fluid was not enhanced compared to the heat pipe using water. The evaporator thermal resistance was increased due to increases in the nanoparticles–deposition layer, large viscosity, and interruption of phase change.

A summary of the experimental results with nanofluids in heat pipes found in the literature is presented in Table 3. It lists nanoparticle type, concentration, base fluid used, filling ratio, inclination angle, and the most relevant results. From this table, contradictions in reported thermal performance results can be observed regarding the most commonly used nanofluids.

Additionally, big differences among experimental parameters can be noticed. These dissimilarities can influence the results of using nanofluids in heat pipes; different experimental parameters and nanofluids must be combined to thoroughly evaluate heat pipe performance.

Finally, Fig. 2 summarizes the relationship between the thermal resistance of nanofluids and water (red dashed line) as working fluids in TPCTs and the applied power in the evaporator. It can be seen from this figure that most experimental studies reported a decrease in thermal resistance (i.e., positive results) when nanofluids replaced water as working fluid. Notwithstanding, other studies describe higher thermal resistance.

It can be observed from Table 3 and Fig. 2 that no conclusions can be drawn from different experimental studies using nanofluids as a working fluid in TPCTs. Different nanoparticles, nanofluid preparations, chemical

Table 3 Summary of studies and their key results with nanofluids in heat pipes

Nanoparticle (size)	Vol%	Base fluid	Heat pipe type	Power (W)	Filling ratio/inclination angle	Key results	References
Al_2O_3 (13 nm) $TiSiO_4$ (< 50 nm)	0.01, 0.02, 0.05, 0.075	Water	TPCT	40, 70, 120, 180, and 210	Not reported/90°	Thermal resistance decreased up to 65% for Al_2O_3 (0.05 vol%) and 57% for $TiSiO_4$ (0.075 vol%).	[36]
TiO_2 (42 nm)	0.1, 0.2, 0.3, and 0.4 (dilutions from Aerodisp W740X)	Deionized water	TPCT	20, 40, and 60	Thermosyphon was filled with 24 mL of working fluid/90°	Decrease by up to 24% in thermal resistance at 20 W for concentrations between 0.2 and 0.3 vol%	[37]
Al_2O_3 (20 nm)	1, 1.5, 2, 2.5, and 3	Distillate water	TPCT	50–200	Not reported/90°	Increase by up to 14.7% in thermal efficiency (2 vol%)	[17]
TiO_2 (85 nm size of aggregates) Au (16 and 66 size of aggregates)	1.1 and 0.2 5.2×10^{-4}	Deionized water	TPCT	50–300	Not reported/90°	Thermal resistance decreased by up to 12% for TiO_2 at 50 W and 20% for Au	[97]
Fe_2O_3 (4–5 nm)	2 and 5.3	Water	TPCT	Heating from water with operating temperature between 50 °C and 95 °C	12%/30°, 45°, 60°, and 90°	42% maximum in heat transfer rate for 5.3 vol% and 90°	[94]
MWCNT (D 20 nm and 5–15 µm of length)	0.095 0.238 0.475	Deionized water	TPCT	30–90	60%/90°	Thermal efficiency grew 9.8% in the range of 30–45 W	[100]
MWCNT–Ag (D 10–20 nm and 5–15 µm length)	0.5 and 1 mass%	Deionized water	TPCT	30–120	60%/90°	Thermal efficiency reached 20.7% for 1 mass% at 29.575 W	[39]
MWCNT (D 15 nm and length range of 5–15 µm)	0.25–0.8 mass%	Deionized water	TPCT	20–200	50%/90°	The heat transfer coefficient increased by 150% for 0.8 vol% and at 7.42 kPa (operation pressure)	[96]
MgO (40 nm)	5.0	Deionized water	TPCT	200–400	1/3 of the total volume of the heat pipe/90°	A decrease of 18% at a heat load of 200 W	[95]
Al_2O_3 (20 nm)	0.5, 1.0, 3.0 mass%	Water	TPCT	20, 30, and 40	20, 40, 60, and 80%/10°, 40°, 70°, and 90°	Thermal performance reached 56.3% for 1.0 mass%, 40°, 0.45 m of length and 40 W	[11]
MWCNT (15 nm and a length of 10 µm)	1.0	Water	TPCT	230–700	20%/90°	Thermal resistance increased 3.3 times with respect to thermal resistance with water at 555 W	[45]
SiO_2 (30 nm) functionalized with silanes groups	0.5–2.5 mass%	Deionized water	TPCT	150–1400 approximately	25%/90°	Thermal resistance 22–25% higher for 1.5% functionalized nanofluid than water	[44]

Table 3 (continued)

Nanoparticle (size)	Vol%	Base fluid	Heat pipe type	Power (W)	Filling ratio/inclination angle	Key results	References
Al_2O_3 (40–47) CuO (8.6–13.5 nm) Laponite JS clay (D 25 nm and thickness 1 nm)	1 mass%	Water	TPCT	Not reported	Not reported/90°	All the nanofluids showed inferior thermosyphon performance	[46]
GNP (thickness 4–20 nm, Length 5–10 µm)	0.02, 0.05, 0.1, 0.5, and 1 mass%	Water	TPCT	30, 60, 90, 120, and 150	60%/90°	Thermal efficiency was improved with increasing concentrations and input power. It was 90.2% at 1 mass% and 120 W	[101]
Fe_2O_3	2 and 5.3 vol%	Water	TPCT	Not reported	No reported/30–45–60 and 90°	Thermal resistance decreased by 42% for 5.3 vol% and 90° inclination angle	[115]
MWCNTs functionalized with EDA	0.2–1.5 mass%	DI water	TPCT	30–150	60%/90°	EDA-MWCNT/DI water nanofluid with 1 mass% and input power of 90 W shows the maximum thermal efficiency. For powers and concentrations higher than 90 W and 1 mass%, thermal efficiency was reduced	[116]
Al_2O_3 CuO	1.5, 2, and 2.5 vol%	DI–water	TPCT	60, 80, 100 and 120 Different voltages of 5, 10, 15, and 20 kW were applied	Not reported/90°	The effect of nanoparticles on thermosyphon thermal performances is more pronounced than that of the electric field. The best thermal performance was obtained with the Al_2O_3–water nanofluid with 2.5 vol% at 120 W input heat power and 20 kV electric field intensity	[117]
MWCNT functionalized with different acids	1 mass%	Water	TPCT	30, 45, 60, 90, and 120	60%/90°	The nanofluids of oxidized CNT with HNO_3/H_2SO_4 had higher efficiencies. Many carboxylic groups in the CNT surface improved the stability, which implies less deposition of CNT	[118]

Table 3 (continued)

Nanoparticle (size)	Vol%	Base fluid	Heat pipe type	Power (W)	Filling ratio/inclination angle	Key results	References
Graphene	0.05, 0.07, and 0.09 vol%	Acetone	TPCT	10–50	80%/90°	Comparing a TPCT operating with acetone, the temperature difference between evaporator and condenser was reduced by 64.23, 31.8, and 19% with 0.09, 0.07, and 0.05 vol%, respectively. Additionally, the thermal resistance was reduced by 70.3% at 0.09 vol%	[119]
Graphene oxide Silver oxide	0.01, 0.025, 0.05, 0.075, and 0.1 mass%	DI water	TPCT	2–16	16.7%/90°	Thermal resistance dropped with GO and SO nanofluids compared to water	[102]
ZrO_2	3 and 4 mass%	Water	TPCT	10–100	50%/90°	The thermal performance was enhanced up to 22.8% using ZrO_2 nanofluids	[120]
Amine treated graphene quantum dots A-GDQ) (D 5–20 nm)	0.001 and 0.002 mass%	Water	TPCT	30.1, 59.7, 90.5, 119.9, and 149.8	Not reported/90°	Thermal efficiency and the overall heat transfer coefficient were increased by 11.5% and 38.34% for the 0.002 mass%, respectively	[121]
CuO (50 nm)	0.5–2.0 mass%	DI water	Mesh heat pipe	5–60 kW/m^2	60%/0°	Maximum heat transfer was found at a CuO concentration of 1 mass%. For heat flux below 44 kW/m^2, thermal resistance decreases by 60% at the pressure of 7.45 kPa	[99]
Al_2O_3/CuO	0.1 vol%	DI water	Mesh heat pipe	50–250	100%/0°	At 250 W, a reduction of 44.25% was reached for hybrid nanofluid (25% Al_2O_3–75% CuO)	[29]
SiC	0.01 and 0.1 vol%	Water	Mesh heat pipe	120–1120	100%/0°	Higher thermal resistance at the evaporator section with 0.1 vol% concentration because the SiC layer formed on the wick structure acted as additional thermal resistance	[48]
Fe_2O_3 20 nm	2 vol%	Kerosene	Oscillating heat pipe	15–85	50%	Thermal performance was improved by add nanoparticles to kerosene, moreover, when a field magnetic was present the thermal performance was increased up to 16% compared to kerosene as working fluid	[122]

Table 3 (continued)

Nanoparticle (size)	Vol%	Base fluid	Heat pipe type	Power (W)	Filling ratio/inclination angle	Key results	References
Nitrogen-doped graphene	0.01, 0.02, 0.04, 0.06 mass%	DI water	Grooved heat pipe	10–120	Not reported/0°–90°	Thermal resistance was reduced by 60% with nitrogen-doped graphene (0.06 mass%) compared to DI water in the presence of Triton X100	[49]
Graphene oxide	0.01 and 0.03 vol%	Water	Mesh heat pipe	100–300	Not reported/90°	Evaporator thermal resistance was decreased by 25% compared to water for 0.01 vol%	[32]
Graphene nanoplatelets	0.025, 0.05, 0.075, and 0.1 mass%	Distilled	Sintered wick heat pipe	20–80	Not reported/0–90°	Thermal resistance was reduced up to 48.4% compared with distilled water	[30]

additives, and experimental parameters make the comparison difficult. Interestingly, in most cases any increase or even decrease in the performance of the thermosyphon using nanofluids was generally attributed to a porous layer formed in the evaporator surface and its effect on the boiling mechanism. In that sense, the thermophysical properties of nanofluids were set aside as a secondary factor.

The study of such porous layer can be very complex because its formation and structure are affected by nanoparticle type, size, morphology, concentration, agglomerate sizes, and chemical additives used during their preparation. Moreover, several experimental parameters produce variations in the transport and thermal phenomena that could have different effects on nanofluid behavior during TPCT operation. In this regard, more theoretical and experimental studies are necessary to better understand the different phenomena involved in the thermal behavior of heat pipes using nanofluids as working fluid before they are introduced at the industrial level.

Heat transfer mechanisms in heat pipes affected by nanofluids

In TPCTs, the heat transfer mechanism has been established to be directly related to the heat flux in the evaporator. In specific, at low flux, the main heat transfer mechanism reported is natural convection, while at a high flux nucleate boiling is the associated mechanism [15, 46]. However, from the literature, the most common analyzed mechanism to explain the effect of nanofluids is nucleate boiling [26, 46, 94, 96, 97, 119]. The boiling heat transfer characteristic of the TPCTs is related with the thermophysical properties, stability of the nanofluids, and the surface characteristics of the heater [21]. Accordingly, the increase in the nanofluid thermal conductivity and the nanoparticle deposition on the heated surface is considered to be responsible for the modifications of the thermal performance in the TPCT [102].

Nanoparticles' deposition on the evaporator surfaces forms an artificial layer. This was reported as the main responsible for the thermal performance variations in heat pipes [30–35, 48, 102, 125]. Reduction in the bubble size during bubble formation at the solid–liquid interface and reduction in the nucleate sites by blocking of nucleation cavities has been used to explain the increase or reduction of the thermal performance, respectively.

Do et al. [41] and Liu et al. [99] observed in their work a thin porous coating layer formed by nanoparticles on the wick structures. Both authors concluded that this is the primary mechanism to enhance the heat pipes' thermal performance, because this layer can not only extend the

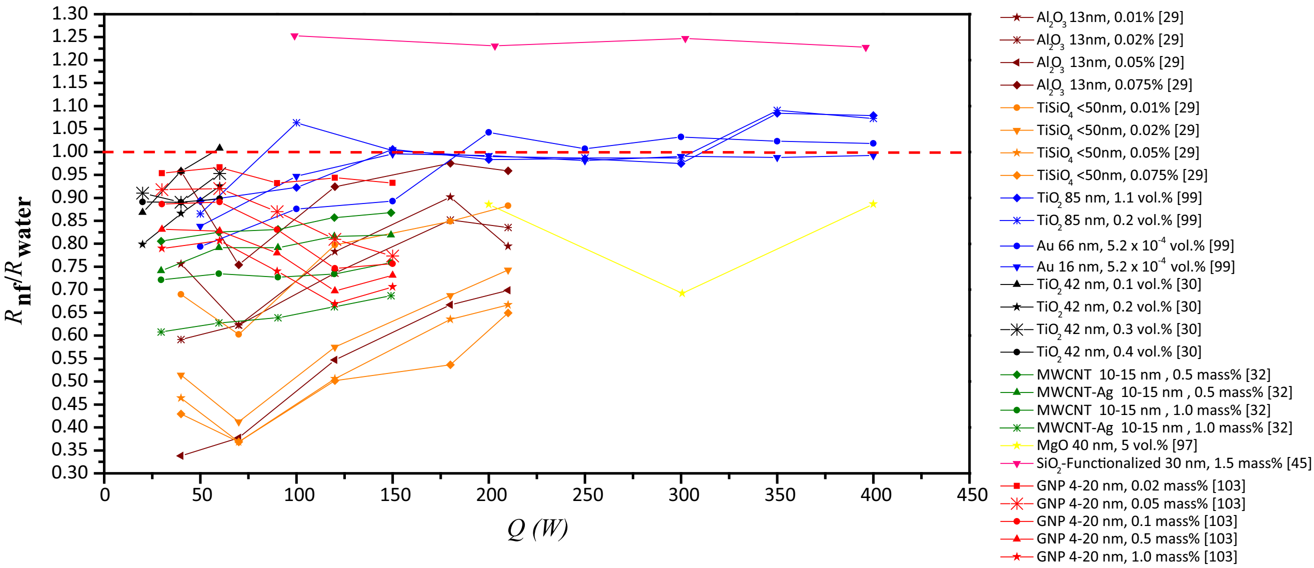

Fig. 2 Relative thermal resistance as a function of applied power for various nanofluids used in TPCTs

evaporation surface but also improve the surface wettability and capillary wicking performance. In the same way, Putra et al. [42] argued that this coating layer in a screen mesh wick improves the surface wettability by reducing the contact angle and increasing the surface roughness, which in turn increases the critical heat flux. This observation was complemented by Asirvatham et al. [43] who showed evidence of the formation of a thin porous silver nanoparticles coating layer at screen mesh wick at the evaporation region. The coating layer on the mesh wick surface provided an additional evaporating surface where high heat transfer rates occur. This drastically reduces the thermal resistance of the mesh wicked heat pipe and increases the capillary pumping ability.

A mathematical description of the heat pipes performance enhancement with the use of nanofluids was attempted by Qu et al. [126], who described that the thermal resistance due to nucleate boiling at the evaporator can be written as shown in Eq. 1:

$$R_{\mathrm{evp}} = \frac{1}{2N_{\mathrm{b}}D_{\mathrm{b}}^{2}\sqrt{f\pi k_{\mathrm{nf}}\rho_{\mathrm{nf}}C_{\mathrm{p,nf}}}} \qquad (1)$$

where k_{nf} is the thermal conductivity, ρ_{nf} is the density, $C_{p,nf}$ is the specific heat, N_b is the active nucleation site, D_b is the bubble release diameter, and f is the bubble release frequency. In nanofluids with low concentration, the product $k_{nf}\rho_{nf}C_{p,nf}$ is less changed compared to the base fluid. It is rather the increase of the active nucleation site density N_b, the bubble release diameter D_b, and the bubble release frequency f that decreases the thermal resistance at the evaporator.

High wettability and roughness increases also were used by Ramachandran et al. [29] to explain the reduction of 44.25% of the thermal resistance of the hybrid Al_2O_3/CuO nanofluid compared to deionized water in a cylindrical screen mesh heat pipe, and by Sadeghinezhad et al. [30] who found a maximum reduction in the thermal resistance of 48.4% with 0.1 mass% of graphene nanoplatelets nanofluid compared with distilled water in a sintered wick heat pipe. On the other hand, the thermal performance decrease has been explained based on the reduction in the nucleation sites density due to the nanoparticles' deposition [46, 47].

A possible explanation to the contradictory results was exposed in the review presented by Fang et al. [127], who claim that there is an optimum value of nanoparticles' concentrations to enhance the heat transfer with nanofluids. The authors proposed that at concentration under the optimum value, the nanoparticles deposited layer may create active cavities, increase nucleation sites, and modify the surface wettability. On the other hand, at concentrations higher than the optimal value, nanoparticles deposited may block nucleation sites.

Summary and conclusions

Most experimental studies about heat pipes using nanofluids provided a few details about the preparation and dispersion of nanofluids, whose stability was reported only before being used, under rest conditions. Furthermore, during nanofluid preparation, it is common to use chemical additives such as surfactants to improve nanoparticle dispersion. However, the effects of the type of chemical additive and its concentration on the thermophysical properties of nanofluids and heat pipes performance are not commonly studied.

In addition, stability issues of nanofluids after operation cycles are not studied in depth. Some researchers reported that the hydrodynamic diameter of agglomerates was increased and that a porous layer was formed on the evaporator surface during heat pipe operation. This suggests that nanofluid stability on rest changed during heat pipe operation due to different thermal loads, phase changes, movement, and maybe functionality loss of chemical additives used during their preparation. The main issue to resolve is the reproducibility of the operation of a thermosyphon using nanofluids for a long time.

The reported performances of nanofluids in heat pipe have commonly been attributed to a porous layer formed on the evaporator surface during cycle operation. Increases or decreases in nucleation sizes and modifications in wettability during boiling on the evaporator surfaces, wicks, and grooves have been presented as responsible for the performance changes of heat pipes. Nevertheless, additional studies on the formation of the porous layer must be conducted in order to determine the effects of nanoparticle type, morphology, size, base fluid, concentration, and experimental conditions during heat pipe operation.

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