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Review Article

An exploratory review on heat transfer mechanisms in nanofluid based heat pipes

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ABSTRACT

The current study reviews the research on nanosuspension-enhanced heat pipe technologies. The reviewed studies are categorized based on the nanosuspension type incorporated in the heat pipe i.e., mono & hybrid. The study attempts to identify the heat transport modes in heat pipes and explore their dominance among each other. The dominance of the identified mechanisms was found to be a strong function of the heat pipe type investigated and get significantly influenced by the operating conditions. The current review paper will aid in properly understanding the thermal mechanisms prevalent in heat pipes filled with nanosuspensions and to further optimizing their thermal response.

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INTRODUCTION

In the current era, a technological revolution has been observed to persist involving the development of new technological solutions and continuous advances in pre-existing technologies to proficiently meet societal requirements. A strong pursuit is prevailing to research and develop effective ways to carry out energy management efficiently. Nanotechnology is one of the most widely discussed areas of research attributed to its appreciable performance enhancement potential across various applications.

Nanotechnology has been evident to be widely discussed across different thermal and heat transfer applications. Nanofluids are basically nano-sized particles suspended in the conventional thermofluidic [1]. The potential of nanofluids based on metallic and carbon-based nanoparticles in base fluids like DI water, alcohols, refrigerants, lubricants, and other conventional working fluids [2]. Figures 1 (a) and (b) illustrate the pictorial representation of the process involved in the one-step and the two-step method respectively.

The major goal in nanofluid synthesis is to achieve a stable nano-suspension avoiding nanoparticle agglomeration and sedimentation within the base fluid [3]. The nanofluids offer attractive thermophysical characteristics in contrast with that offered by conventional working fluids [4]. Two major classes of nanofluids are currently being widely discussed and investigated by researchers. The first is the mono while the other is the hybrid nanosuspension. The

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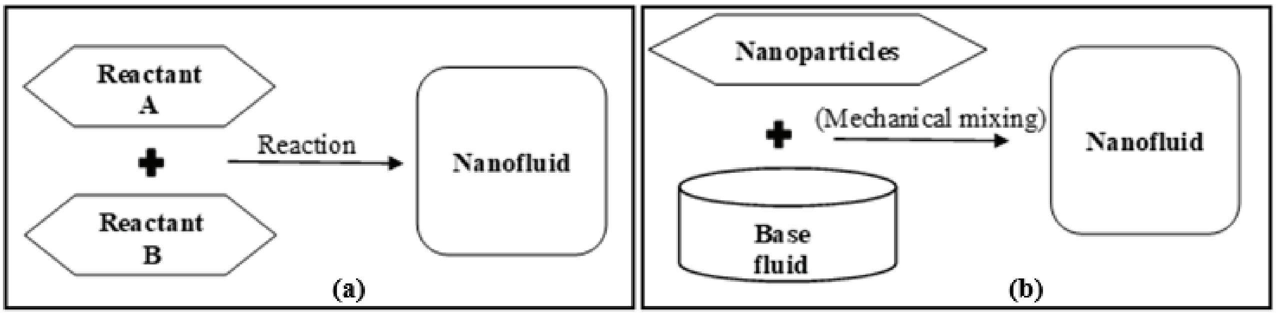

Figure 1. (a) One-step method, (b) Two-step method of nanofluid preparation.

mono nanosuspensions are synthesized by adding a single nanoparticle type while the hybrid nanofluids involve suspending two or more nanoparticle types simultaneously in the base fluid [5].

Both the mono and hybrid nanofluids offer appreciable thermophysical properties in contrast with that offered by conventional working fluids. However, the hybrid nanofluids offer thermal and flow characteristics much superior to that offered by the mono-nanofluids attributed to the synergy achieved between the nanoparticles that further results in a potential combination offering competency to significantly enhance the heat transfer systems [6]. Several researchers have investigated the applicability of nanofluids across different applications. Kilic et al. [7] numerically studied heat transfer from a heated surface employing a swirling jet and nanofluids. They reported that by increasing the Reynolds number (12000 to 21000), an increment of about 51.3% was attained in the average Nusselt number. It was found that using the aqueous CuO nanofluid enhanced the average Nusselt number relative to the TiO_2 and Al_2O_3 nanofluids. Abdulvahitoglu [8] investigated the effectiveness of using aqueous copper and nickel oxide nanosuspensions respectively for engine cooling. Out of all the considered nano-suspensions, the Cu nanofluid was reported to be the best coolant attributed to its superior thermophysical characteristics while the CuO nanofluid was reported as the least preferred choice out of all the considered nanofluids.

The stability of nanofluids is a major issue since it deteriorates the performance of the nanofluids by declining their thermal and flow characteristics [9]. In the last few years, researchers working in the field of nanotechnology have tried to devise several methods to overcome the stability issue of nanofluids to increase their practical applicability. Several mechanical and chemical treatments have been introduced ranging from mechanical agitation to surface modification of nanoparticles to improve the nanofluid stability. However, the stability issue of nanofluids has been encountered to be relatively more in the mono-nanofluids as compared to the hybrid nanofluids.

Heat pipes are special thermal devices used to carry out the transfer of heat energy from a source to a distantly located sink without undergoing any major energy losses [10]. Mesh wick [11], sintered wick [12], grooved [13], oscillating [14], pulsating [15], thermosyphon heat pipes [16], etc. have been employed for numerous applications owing to their high heat transfer capability and robust build.

Some of the interesting applications of heat pipes range from the thermal management of electronic devices to solar, space, HVAC, refrigeration, and air conditioning applications, etc. The heat pipes are lined with a capillary material at its inner surface called the wick structure. The heat pipes are charged at sub-ambient pressures by thermofluids to undergo thermal energy transport without necessitating any external work input [17]. Figure 2 illustrates different working fluids used in heat pipe applications.

Recently, attributed to their attractive thermophysical characteristics, nanosuspensions have been utilized as working fluids. Nanofluid-based heat pipe technologies are being widely investigated for solar thermal applications. Dehaj et al. [18] investigated a heat pipe solar collector using CuO nanosuspensions. The efficiency of the solar collectors got enhanced at higher nanofluid concentrations and flow rates respectively. The researchers carried out another study where they experimented using CuO, Al_2O_3, and MgO nanosuspensions on efficiency. The efficiency was found to enhance using the nanofluids with an improvement rate of up to 20% [19]. Hosseini et al. [20] investigated the effect of nanoparticle surface morphology on solar collector response. Two different samples of aqueous TiO_2 nanofluids were prepared using the spherical and wire-shaped TiO_2 nanoparticles respectively. The wire-shaped TiO_2 nanofluid offered an increment of 21.1% in efficiency while that offered by the spherical TiO_2 nanofluid was found to be 12.2% respectively.

The response of the heat pipes augments appreciably by utilizing nanosuspensions. The thermal transport capacity of the heat pipes enhances considerably while offering augmented thermal conductivity and efficiency when filled with nanofluids. Different nanofluids have been investigated across different experimental and numerical studies. It has been widely proposed that the optimized operating and design parameters can augment the thermal response employing nanofluids [21, 22].

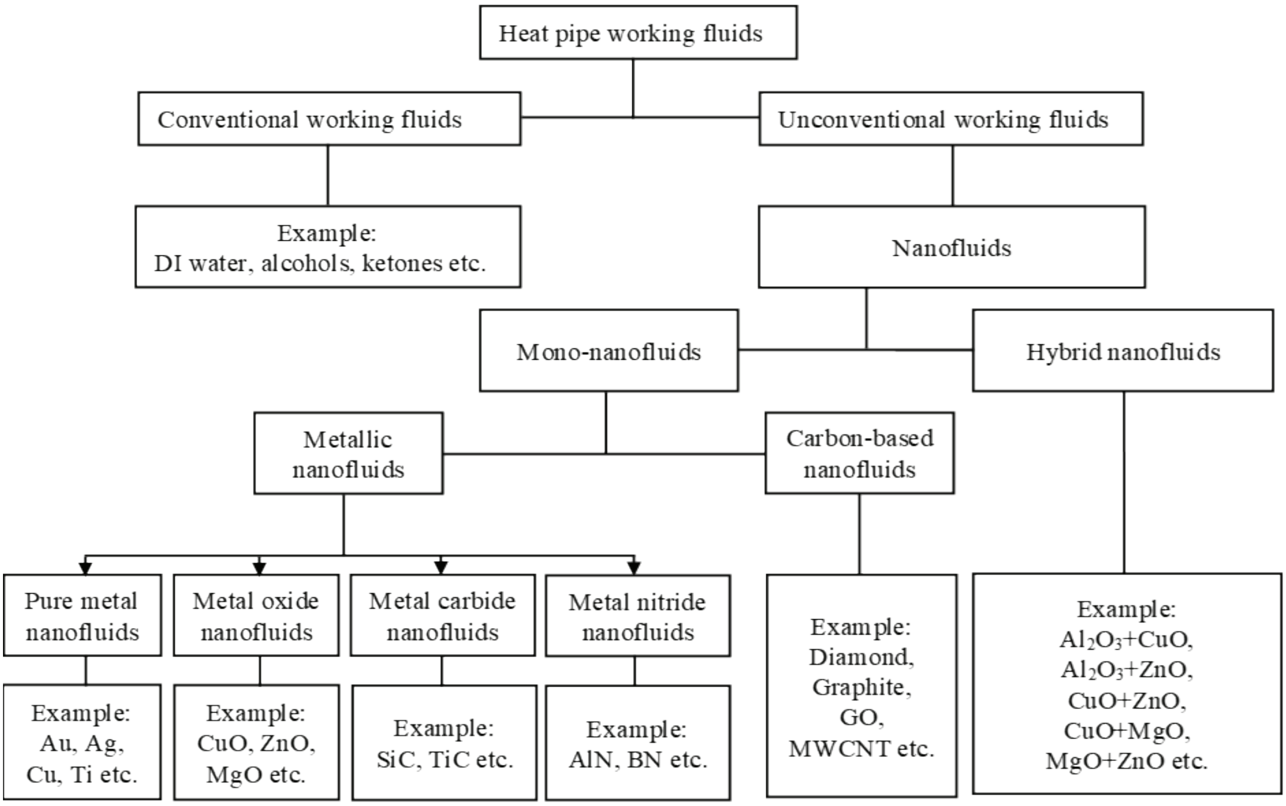

Figure 2. Heat pipe working fluids.

The authors carried out a search in the google scholar database for the articles reported in the period of 2017-2022 using different keywords. The retrieved search results are illustrated in Figure 3. The trend number of studies on the nanofluid-filled heat pipes reported since 2017 can be observed to be increasing. However, it was noticed by the authors that the number of research studies on nanosuspensions & heat pipes investigating the heat transfer mechanisms is quite low.

It is clear from the generated search results from the Google Scholar database that very few numbers of research studies on heat pipes discussed the reasons behind the exclusive performance. This could be attributed to the fact that the heat transfer mechanisms associated with nanofluid-filled heat pipes are quite complex since all three solid, liquid, and vapor states coexist during their operation. As per the available literature, the authors found that a limited number of studies have attempted to exhaustively identify and investigate mechanisms in different heat pipe types that rationalize the importance and novelty of the current work.

The authors have considered nanofluid-filled thermosyphon, pulsating, oscillating, grooved, and mesh wick heat pipes respectively within the scope of this study. The current study will aid the researchers in the concurrent field in getting aware of the current research perspectives forming a firm understanding of the phenomena involved in the nanofluid-filled heat pipes.

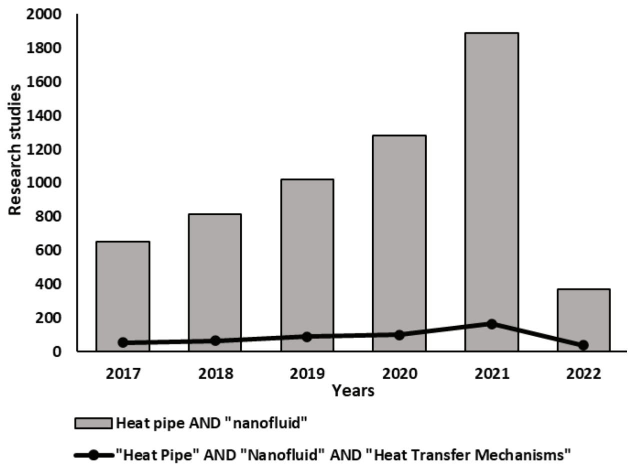

Figure 3. Summary of search results generated from the Google Scholar database.

APPLICATIONS OF MANO NANOFLUIDS

Experimental Researches

The heat pipe is a special type of heat exchanger that is widely being studied owing to its compact build and advanced response. Different heat pipes using various nanosuspensions have been reported in the open literature.

Moradgholi et al. [23] fabricated a thermosyphon system to generate electrical & thermal energy simultaneously. They employed methanol-based Al_2O_3 nanofluids of concentrations 1.0, 1.5, and 2 wt.%. The optimum nanofluid concentration and the filling ratio were reported to be 1.5 wt.% and 50% respectively. Das et al. [24] studied the properties of graphene nanosuspensions. They reported that the conductivity of the graphene nanosuspension was about 29% higher relative to DI water (at 45 °C) which augmented the thermosyphon characteristics.

Sardarabadi et al. [25] utilized multi-wall carbon nanotube (MWCNT) nanosuspensions in a thermosyphon and attained enhanced heat transfer capacity. Sarafraz et al. [26] studied the response characteristics of a thermosyphon using zirconia-acetone nanosuspensions and reported geyser boiling phenomena. Kiseev et al. [27] studied the employability of thermosyphon for LED applications. They utilized Fe_2O_3 nanofluids (0.1 wt.% to 1.0 wt.%) and attained an improved heat transfer coefficient attributed to the nano-sized coating. Cacua et al. [28] studied the effects of nanosuspension stability on thermosyphon response. They prepared aqueous Al_2O_3 nanofluids of concentrations 0.1 wt.% using surfactants and attained a maximum decrement of about 24% in the heat pipe thermal resistance.

Kaya [29] utilized 1.0 wt.% and 2.0 wt.% CuO nanosuspensions in a thermosyphon kept in the vertical position. The performance was found to enhance using CuO nanosuspensions relative to water. Anand et al. [30] prepared Al_2O_3 nanofluids using HFE 7000 & R134a and utilized them in a thermosyphon and reported augmented performance trends. Choi et al. [31] studied the boiling regime of a thermosyphon employing cellulose nanofiber nanofluid. They observed that at lower heat loads, geyser boiling occurred while at higher heat loads, churn boiling occurred.

Shuoman et al. [32] experimented on a thermosyphon utilizing γ-Al_2O_3 nanoparticles of average size 40 nm suspended in distilled water (0.5- 2.0 vol. %) in the heat load range of 500-1250 W in terms of its overall conductivity. At 1000 W, the conductivity was reported to augment by three folds using 2.0% by vol. alumina nanofluid. Xing et al. [33] examined the response of a pulsating heat pipe employing hydroxylated MWCNT nanofluids and attained improved start-up performance. Nazari et al. [34] experimented on a pulsating heat pipe, filled with GO nanosuspensions. The GO nanoparticles were suspended in water to form stable nano-suspensions of concentrations ranging between 0.25 to 1.5 g/lit. At higher concentrations, the heat pipe performance degraded owed to poor flow characteristics of nano-suspension.

Beydokhti et al. [35] experimented on a pulsating heat pipe filled with MWCNT nanosuspensions and reported enhanced convection currents. The surface modification of the MWCNT nanoparticles was carried out through chemical surface and polymer wrapping treatment. Akbari et al. [36] experimented on a pulsating heat pipe utilizing aqueous TiO_2 nanofluid and graphene nanofluid (10 mg/ltr and 1 mg/ltr respectively). They reported that the higher the stability of the nanofluid, the higher will be the enhancement attained in the response.

Chen et al. [37] experimented with a pulsating heat pipe filled with TiO_2 nanofluid for battery cooling. They reported that uniform temperature distribution was achieved with an effective improvement rate of 60% employing TiO_2 nanofluid. Zhou et al. [38] fabricated a pulsating heat pipe using a copper tube bent into three turns. They reported that employing 0.05 wt.% GO nanofluid within the heat pipe improved its thermal performance by about 41%.

Zhang et al. [39] experimentally studied a nanofluid-based pulsating heat pipe. A high-speed camera was used to visualize the flow dynamics. Aqueous-SiO_2 nanofluids (0.5 wt.% to 2.0 wt.%) were used and they reported enhanced phase-transition in the working fluid and increased instantaneous velocity and driving force. Zhou et al. [40] experimented on an oscillating heat pipe using graphene nanoplatelet nanosuspensions (1.2 to 16.7 vol.%). They reported that the favorable nanofluid concentration varied between 2.0 vol.% to 13.8 vol.% at an appropriate fluid fill ratio of 55%, 62%, and 70% respectively.

Meena et al. [41] used silver nanofluid in an oscillating heat pipe at a fluid fill ratio of 50%. They reported augmented performance at the air velocity and temperature of 0.5 m/s and 8 °C respectively. Jin et al. [42] reported that at an optimum fill ratio of 83%, using 3.0 wt.% MWCNT nanosuspension in an oscillating heat pipe the conversion efficiency of about 92% was attained attributed to the higher thermal conductivity of the prepared nano-suspensions.

Monroe et al. [43] examined the performance of an oscillating heat pipe filled with $CoFe_2O_4$ nanosuspension. The surface modification of nanoparticles was carried out using citric acid to improve their suspensibility. It was observed that effective thermal conductivity declined by about 11% relative to that attained in the absence of the externally applied magnetic field attributed to the increased viscosity of the nanofluid owed to nanoparticle magnetization. Davari et al. [44] experimented on an oscillating heat pipe using Fe_3O_4 nanofluid and observed enhanced performance with the corrugated horizontal condenser.

Zhou et al. [45] fabricated a heat pipe and used aqueous-ethanol-based CNT nanofluids (0.05 wt.% to 0.5 wt.%) and reported 0.2 wt.% nanosuspension to offer better heat transfer characteristics relative to the aqueous-ethanol solution. Aly et al. [46] suspended the γ-Al_2O_3 nanoparticles of average size 20 nm in DI water to prepare the 3 vol.% alumina nanofluid and reported increased evaporation and condensation rate and decreased resistance at higher fluid fill ratio. Rui Zhou et al. [47] experimented on a micro-grooved heat pipe filled with CuO nanosuspensions (0.5 wt.% to 1.5 wt.%). The start-up response of the heat pipe slowed while the heat transfer capability improved significantly by utilizing nanosuspensions. Veerasamy et al. [48] utilized graphene nanosuspension in a grooved heat pipe.

The improvement achieved in the response was reported to be a direct function of nanofluid concentration.

Bhullar et al. [49] evaluated the temporal performance of aqueous Al_2O_3 nanofluids (0.005 vol.% to 1.0 vol.%.) in heat pipe and attained superior reliability at higher heat loads. The nano-sized coating of Al_2O_3 nanoparticles on mesh caused performance augmentation. The researchers also fabricated a heat pipe with crimped edges to offer extended conduction length [50] and attained thermal resistance of about 22% employing the 1 vol.% Al_2O_3 nanofluid. They reported that the thermal conductivity followed a non-linear relationship with the nanofluid concentration.

Channapattana et al. [51] investigated the influence of the number of screen mesh layers on heat pipe using 1.0wt.% CuO nanofluid. The capability of the heat pipe was reported to improve using a higher number of mesh layers. Gupta et al. [52] experimented on a heat pipe using nanosuspension and nanoparticle coating. The heat pipe was filled with TiO_2 nanofluids. Another heat pipe incorporated in the study was coated with TiO_2 nanoparticles and filled with DI water. They reported that the best thermal performance was attained using TiO_2 nanofluid followed by the nanoparticle-coated water heat pipe. The performance of CeO_2 nanofluid and nanoparticle-coated heat pipes was investigated experimentally. Both the heat pipes were tested under a similar set of conditions and it was found that both the heat pipes offered nearly similar thermal performance hence the nanoparticle-coated heat pipes were proposed as a substitute for conventional heat pipes [53].

Sharuk et al. [54] experimented on an aqueous TiO_2 nanosuspension (0.05 vol.% to 0.25 vol.%) filled mesh heat pipe. They reported that with advancement in nanosuspension concentration and applied heat load, the heat pipe conductivity increased. Anand et al. [55] experimented on a mesh & sintered wick heat pipe respectively. Both the heat pipes were filled with DI water-based Al_2O_3 nanofluid. The maximum enhancement attained in the thermal efficiency in the mesh wick and sintered wick heat pipes using Al_2O_3 nanofluid was found to be about 37.55% and 41.38% respectively.

Gupta et al. [56] experimented on a mesh heat pipe using CuO nanosuspension (0.5 vol.% to 2.5 vol.%) and achieved an efficiency of 66.5% at 150 W using 1.0 vol.% CuO nanofluid owed to its high thermal conductivity. Nizam et al. [57] prepared DI water-based Al_2O_3 nanosuspension (0.5 vol.% to 1.5 vol.%) and employed them in a mesh heat pipe. The characterization of the prepared nano-suspensions was carried out through scanning electron microscopy and transmission electron microscopy. It was found that the nanoparticles were spherical in shape and formed a stable suspension within the base fluid. Sankar et al. [58] examined the employability of graphite nanosuspension (0.5 wt.%) in a mesh heat pipe. The nanosuspensions showcased no sedimentation till 9 weeks and improved the heat transfer coefficient attributed to the low density and high thermal conductivity of graphene nanosuspension.

Numerical Researches

The majority of the numerical studies reported in open literature have attributed the advance thermal and flow characteristics of nanosuspensions responsible for the response improvement of the heat pipes. Some of the numerical studies recently reported by the researchers on the same are discussed in the current study.

Alagappan et al. [59] experimented on a nanofluid-filled thermosyphon following the Box-Behnken Design method. They reported that Fe_3O_4 nanofluid offered better thermal efficiency relative to CeO_2 nanofluid attributed to enhanced convection between the container and nanosuspension. Sarafraz et al. [60] prepared a model of a thermosyphon-assisted solar collector to optimize the operating parameters and maximize efficiency. They reported that utilizing CNT nanofluids promoted nucleate boiling within the working fluid and resulted in enhanced efficiency. Wang et al. [61] prepared a steady-state model of thermosyphon. The nanofluids were reported to reduce the evaporator temperature and further decrease the overall entropy generation.

Xu et al. [62] experimented on a pulsating heat pipe utilizing silver nanofluids. The simulation was carried out on the FLUENT 15.0 software. The 1 vol.% silver nanofluid was found to offer stable thermal performance in the system. Malekan et al. [63] investigated an oscillating heat pipe with artificial intelligence methods using Fe_3O_4 nanofluids considering heat load, the conductivity of nanofluids, and the aspect ratio. They reported that the resistance decrement attained was more utilizing Fe_3O_4 nanofluids relative to γ-Fe_2O_3 nanofluids.

Gupta et al. [64] carried out heat pipe simulation on Ansys FLUENT (14.0) software at heat loads of 10, 15, and 20 kW/m^2. The 1.0 vol.% CeO_2 nanofluid offered the least heat transfer resistance and maximum efficiency out of all the considered nano-suspensions. Maddah et al. [65] studied the characteristics of a heat pipe utilizing an aqueous copper oxide nanofluid. They reported that the residuals of the considered parameters scatter around the zero axis and attainment of response augmentation.

Poplaski et al. [66] carried out a numerical simulation on nanofluid-filled mesh heat pipes to study the influence of nanosuspension concentration. They reported that optimal concentration is different for different nanofluids employed within the heat pipe and was found to be 35% for CuO nanofluid and 25 vol.% for Al_2O_3 and TiO_2 nanofluids considering capillary limit. Herrera et al. [67] numerically studied heat pipe response considering nanoparticle agglomeration and deposition. The capillary limit was reported to augment by about 30 to 40% using nanofluids relative to the base fluid. At high nanosuspension concentrations, the advancement in the capillarity limit was found to be variable and elevated resistance was observed.

Gupta [68] carried out the optimization of a mesh heat pipe using the Taguchi technique. It was found that the heat load has the maximum impact on the efficiency of the heat pipe relative to heat pipe inclination, nanofluid concentration, and fluid fill ratio respectively. Herrera et al. [69] investigated the response of a mesh heat pipe filled utilizing aqueous-Al_2O_3 nanosuspension using a model taking into account the nanoparticle agglomeration. The prepared model predicted that the capillarity augments by about 32% using nanofluid. Reddy et al. [70] prepared a model for a mesh heat pipe using the response surface methodology along with MINITAB-17 software. They reported that the minimum resistance and maximum convection were attained in the heat pipe when kept at an inclination angle of 57.2° under a heat load of 200 W filled with 0.159 vol.% concentration TiO_2 nanofluid.

It is clear from the discussion that the heat pipe response depends on various parameters. The heat pipe type, heat load, inclination angle, and fluid fill ratio significantly control its heat transfer characteristics. The nanofluids have an appreciable ability to enhance the heat-pipe performance owing to their advance and favorable thermophysical properties. All the studies discussed till now (both experimental and numerical studies) are summarized in Table 1.

Table 1. Summary of the studies on the mono nanosuspensions

Literature	Working fluid [MNFs] (Concentration)	Key results
Experimental studies on thermosyphon		
Moradgholi et al. [23]	[Al_2O_3 MNFs] (1.0%-2.0% by wt.)	Temperature decrement of about 14.52 °C in the panel. Increment of about 1.42 W in the power generated by the module. Increment of 27.3% in the total exergy efficiency of the module.
Das et al. [24]	[GNP MNFs] (0.02%-0.1% by wt.)	The viscosity of the 0.10 wt.% graphene nanofluid decreased by about 25% with temperature increment. Reduction of about 13.9% and 72% in the evaporator temperature and resistance.
Sardarabadi et al. [25]	[MWCNT MNFs] (0.4% by wt.)	The operational capability increased from 70 W to 90 W using nanofluids. The MWCNT nanoparticles functionalized with sodium persulfate offered better stability in the base fluid relative to that functionalized by potassium persulfate.
Sarafraz et al. [26]	[Zirconia MNFs] (0.025%-0.1% by wt.)	The nanofluids promoted geyser boiling and enhanced the boiling heat transfer. The optimum inclination angle and charging ratio were found to be 65° and 60% respectively.
Kiseev et al. [27]	[Fe_2O_3 MNFs] (0.5%-2.0% by wt.) [Ir MNFs] (0.1%-1.0% by wt.)	The HTC was enhanced by about 20 to 25% using nanofluids.
Cacua et al. [28]	[Al_2O_3 MNFs] (0.1% by wt.)	The nanofluid added with SDBS offered better stability relative to that added with CTAB. High bubble formation rate achieved using surfactant-aided nanofluids.
Kaya [29]	[CuO MNFs] (1.0%, 2.0% by wt.)	Performance enhancement of about 18.5% attained using 1 2.0 wt.% CuO nanofluids respectively.
Anand et al. [30]	[HFE-based Al_2O_3 MNFs] (0.025%-0.075% by vol.) [R134a-based Al_2O_3 MNFs] (0.5%- 1.5% by vol.)	Heat transfer characteristics of the refrigerants enhance when added with nanoparticles.
Choi et al. [31]	[Cellulose MNFs] (0.075%-0.5% by wt.)	Geyser boiling was attained at lower heat loads. Critical heat flux and heat transfer coefficient enhanced by about 14.3% and 71.74% respectively. Better stability of organic nanofluids.

Table 1. Summary of the studies on the mono nanosuspensions (continue)

Literature	Working fluid [MNFs] (Concentration)	Key results
Shuoman et al. [32]	[γ-Al_2O_3 MNFs] (0.5%- 2.0% by vol.)	The heat pipe performance improved three folds using nanofluids. The 2.0 vol.% nanofluid offered high thermal performance at 1000 W.
Experimental studies on pulsating heat pipe		
Xing et al. [33]	[MWNT MNFs] (0.1%-1.0% by wt.)	Better start-up performance attained using nanofluids up to the concentration of 0.3 wt.%.
Nazari et al. [34]	[GO MNFs] (0.25-1.5 g/lit)	A resistance decrement of about 42% was attained using GO nanofluids. The 1.5 g/lit GO nanofluid offered deteriorated performance attributed to its high viscosity.
Beydokhti et al. [35]	[MWCNT MNF] (0.2% by wt.)	The least thermal resistance was attained at a fluid fill ratio of 60%.
Akbari et al. [36]	[Graphene MNF] 1 mg/mL [TiO_2 MNF] 10 mg/mL	The nanofluid stability improved the heat pipe response.
Chen et al. [37]	[TiO_2 MNF] 2% by vol.	The maximum temperature of the battery was limited to 42.22 °C.
Zhou et al. [38]	[GO MNFs] (0.02%- 0.1% by wt.)	The start-up response improved using nanosuspensions.
Zhang et al. [39]	[SiO_2 MNFs] (0.5%- 2.0% by wt.)	Adding nanoparticles in the base fluid promotes phase change in the heat pipe working fluid.
Experimental studies on oscillating heat pipe		
Zhou et al. [40]	[GNP MNFs] (1.2%-16.7% by vol.)	At a lower fluid fill ratio, GNP nanofluids reduced the tendency of dry-out.
Meena et al. [41]	[Ag MNF] (N.A.)	The best effectiveness was attained at a hot air temperature of 80 °C.
Jin et al. [42]	[MWCNT MNF] (3.0% by wt.)	A conversion efficiency of 92% improved using nanofluid.
Monroe et al. [43]	[$CoFe_2O_4$ MNF] (15 mg/mL)	The effective thermal conductivity decreased by about 11% in the presence of bias magnets due to the agglomeration of nanoparticles.
Davari et al. [44]	[Fe_3O_4 MNF] (2% by mass)	The horizontal corrugated condenser offered the best system response.
Zhou et al. [45]	[MWCNT MNFs] (0.05% to 0.5% by wt.%)	Maximum decrements of about 80.8% and 18.5% were attained in the thermal resistance and wall temperature respectively.
Experimental studies on grooved heat pipe		
Aly et al. [46]	[Al_2O_3 MNFs] (3% by vol.)	The convection in the heat pipe increased by about 30.4% using nanofluid.
Zhou et al. [47]	[CuO MNFs] (0.5%-1.5% by wt.)	The 0.5 wt.% CuO nanofluid offered minimum resistance.
Veerasamy et al. [48]	[Graphene MNFs] (0.6% and 0.75% by mass)	The wall temperatures of the heat pipe were higher when filled with graphene nanofluid. Graphene nanofluids improved the capillary action.
Experimental studies on mesh heat pipe		
Bhullar et al. [49]	[Al_2O_3 MNFs] (0.005%- 1% by vol.)	Low vapor pressure at 12 W resulted in nanoparticle agglomeration and sedimentation that eventually blocked the wick pores.

Table 1. Summary of the studies on the mono nanosuspensions (continue)

Literature	Working fluid [MNFs] (Concentration)	Key results
Bhullar et al. [50]	[Al_2O_3 MNFs] (0.005%- 1% by vol.)	A maximum enhancement of about 15% was attained in the thermal conductivity of the base fluid when added with Al_2O_3 nanoparticles at a concentration of 1 vol.%.
Channapattana et al. [51]	[CuO MNF] (1% by vol.)	The response improved with an increase in mesh layers.
Gupta et al. [52]	[TiO_2 MMNFs] (0.5%-1.5% by vol.)	A maximum decrement of about 17.3% and a maximum increment of 13.4% were attained in the thermal resistance and thermal efficiency respectively.
Gupta et al. [53]	[CeO_2 MNFs] (0.5%-1.5% by wt.)	The nanoparticle coating offered similar performance as of 1.0 vol.% nanofluid.
Sharuk et al. [54]	[TiO_2 MNFs] (0.05%-0.25% by vol.)	The heat pipe conductivity improved using nanofluids.
Anand et al. [55]	[Al_2O_3 MNFs] (0.5%-3.0% by wt.)	The maximum resistance decrement was observed at a 45° angle.
Gupta et al. [56]	[CuO MNFs] (0.5%-2.5% by vol.)	Maximum thermal efficiency of 66.5% was attained using 1 vol.% CuO nanofluid.
Nizam et al. [57]	[Al_2O_3 MNFs] (0.5%-3.0% by vol.)	The optimum angle was found to be 45°.
Sankar et al. [58]	[Graphite MNF] (0.5% by wt.)	A decrement of about 32.50% was observed in the resistance.
Numerical studies on thermosyphon		
Alagappan et al. [59]	[CeO_2 MNF] (80 mg/lit) [Fe_2O_3 MNF] (80 mg/lit)	Maximum efficiency of 74.3% was observed using Fe_2O_3 nanosuspension.
Sarafraz et al. [60]	[CNT MNFs] (0.1%-0.3% by wt.)	CNT nanoparticles promoted nucleate boiling.
Wang et al. [61]	[Al_2O_3 MNFs] (0%-12% by wt.) [Fe_2O_3 MNFs] (0%-12% by wt.) [Cu MNFs] (0%-12% by wt.)	The overall entropy generation was reduced using Cu nanofluids.
Numerical studies on pulsating heat pipe		
Xu et al. [62]	[Ag MNFs] (0.25%- 1.0 vol.%)	The maximum thermal efficiency and stable operation of the heat pipe were attained using 1.0 vol.% Ag nanofluid.
Numerical studies on oscillating heat pipe		
Malekan et al. [63]	[γ -Fe_2O_3 MNF] (2% by vol.) [Fe_3O_4 MNF] (2% by vol.)	Fe_3O_4 nanofluids offered higher resistance decrement relative to γ-Fe_2O_3 nanofluids.
Numerical studies on mesh heat pipe		
Gupta et al. [64]	[CeO_2 MNFs] (0.5%-1.5% by wt.)	A thermal resistance decrement of 9.30% was observed using 1.0 wt.% nanosuspension.
Maddah et al. [65]	[CuO MNFs] (0.1%-1.5% by vol.)	A resistance decrement of 62.6% was observed.

Table 1. Summary of the studies on the mono nanosuspensions (continue)

Literature	Working fluid [MNFs] (Concentration)	Key results
Poplaski et al. [66]	[CuO MNFs] (N.A) [Al_2O_3 MNFs] (N.A) [TiO_2 MNFs] (N.A)	The optimum concentration of Al_2O_3 and TiO_2 nanofluids was found to be about 25 vol.% while that of CuO nanofluid was found to be 35%.
Herrera et al. [67]	[Al_2O_3 MNFs] (0.1%-1.0% by wt.)	The capillary limit was augmented using the 0.5 wt.% Al_2O_3 nanofluid.
Gupta et al. [68]	[N.A.] (0.5%-1.5% by vol.)	The maximum efficiency of about 72.5% was achieved utilizing 1.0 vol.% nanofluid.
Herrera et al. [69]	[Al_2O_3 MNFs] (0.1%, 0.2% by vol.)	The capillary limit got augmented by about 32% using 0.5 wt.% Al_2O_3 nanofluid.
Reddy et al. [70]	[TiO_2 MNFs] (0.05%-0.25% by vol.)	The 0.159 vol.% TiO_2 nanofluid performed superior.

(MNF means mono-nanofluid), (N.A. means not available)

APPLICATIONS OF HYBRID NANOFLUIDS IN HEAT PIPES

Hybrid nanofluids have been reported to showcase a significant potential for heat transfer fluids applications owing to their advanced thermophysical properties. They offer noteworthy conductivity and stability making them suitable for practical employment. Recently, researchers have tried to explore various nanoparticle combinations to prepare exceptional thermo-fluidics.

Xu et al. [71] experimented on a thermosyphon using mono and hybrid nanosuspensions of Al_2O_3 and TiO_2 nanoparticles and attained the best response using the (25% Al_2O_3+75% TiO_2) hybrid nanofluid. Çiftçi [72] experimented on a thermosyphon and attained a maximum enhancement of about 38.4% in the thermal efficiency and a maximum decrement of about 40.79% in the thermal resistance was attained utilizing (50% AlN+50% ZnO) hybrid nanosuspension. Zufar et al. [73] experimented on a pulsating heat pipe using 0.1 wt.% aqueous hybrid nanofluids of Al_2O_3, SiO_2, and CuO nanoparticles and reported that the SiO_2+CuO hybrid nanofluid performed most appreciable out of all the prepared nano-suspensions attributed to lower flow resistance due to lower dynamic viscosity. It was found that the Al_2O_3+CuO hybrid nanofluid had the highest conductivity and dynamic viscosity [74]. Pandya et al. [75] experimented on a grooved heat pipe utilizing (80% CeO_2+20% MWCNT) nanosuspension (0.25 vol.% to 1.5 vol.%) and attained the best thermal response using the 1.5 vol.% nanosuspension.

Veeramachaneni et al. [76] experimented on a miniature loop heat pipe using Cu+graphene hybrid nanofluid and attained a maximum decrement of about 24.42% and 9.8% was attained in the resistance and the wall temperature respectively. Ramachandran et al. [77] used (25% Al_2O_3+ 75% CuO) hybrid nanofluid to increase the heat transfer capacity of a mesh heat pipe by about 79.35%. Bumataria et al. [78] experimented on a mesh heat pipe and reported that the (75% CuO+25% ZnO) hybrid nanofluid offered appreciable performance. Vidhya et al. [79] experimented on a cylindrical heat pipe using (50% ZnO+50% MgO) hybrid nanosuspensions (0.0125% to 0.1% by vol.). They added CTAB to improve the nanosuspension stability and reported improved convection using the 0.1 vol.% (50% ZnO+50% MgO) hybrid nanofluid. Martin et al. [80] experimented on a conventional heat pipe using (50% Fe+50% CuO) hybrid nanosuspension (2% by mass) and reported the least wall temperatures.

It is clear post-discussion that the hybrid nanofluids offer tremendous enhancement in the heat pipes since they offer superior thermophysical properties accompanied by appreciable stability which favors their applications in the heat pipes. Hybrid nanofluids perform much superior relative to mono-nanofluids. However, the full potential of hybrid nanofluids is not yet discovered completely since not many studies have been reported. Hence, it gets crucial to substantially focus on hybrid nanofluids across various applications like heat pipes, heat exchangers, etc. by carrying out experimental and numerical studies. Studies focused on the prospective combinations of different nanoparticles should be carried out to achieve hybrid nanofluids as efficient and competent heat transfer fluids. The research studies discussed on hybrid nanosuspensions are summarized in Table 2.

Table 2. Summary of the studies on the hybrid nanosuspensions

Literature	Working fluid		Key results
	[HNFs] (Concentration)	Proportions	
Studies on thermosyphon			
Xu et al. [71]	[Al_2O_3+TiO_2] (0.2% by vol.)	a) (25:75) b) (50:50) c) (75:25)	The (25% Al_2O_3+75% TiO_2) hybrid nanofluid performed the best. A maximum decrement of about 26.8% was attained in the thermal resistance. A maximum increment of about 26.8% and 10.6% were attained in the heat transfer coefficient and thermal efficiency.
Çiftçi [72]	[AlN+ZnO] (2.0% by vol.)	a) (25:75) b) (50:50) c) (75:25)	An increment of about 34.8% and a decrement of about 40.79% were attained in the efficiency and resistance respectively using the 50:50 combination.
Studies on pulsating heat pipe			
Zufar et al. [73]	[Al_2O_3+CuO] (0.1% by wt.) [SiO_2+CuO] (0.1% by wt.)	(50:50)	The SiO_2+CuO hybrid nanofluid offered the best response attributed to its lower dynamic viscosity.
Zufar et al. [74]	[Al_2O_3+CuO] (0.1% by wt.) [SiO_2+CuO] (0.1% by wt.)	(50:50)	The performance deteriorated using the Al_2O_3+CuO hybrid nanofluid attributed to its high dynamic viscosity.
Studies on grooved heat pipe			
Pandya et al. [75]	[CeO_2+MWCNT] (0.25%-1.75% by vol.)	(80:20)	The operational capacity improved using the 1.5 vol.% nanosuspension.
Veeramachaneni et al. [76]	[Cu+graphene] (0.01%, 0.02% by vol.)	a) (30:70) b) (70:30)	The capillary limit and the conductivity got improved using the 0.02 vol.% (30:70) hybrid nanofluid.
Studies on mesh heat pipe			
Ramachandran et al. [77]	[Al_2O_3+CuO] (0.1% by vol.)	a) (50:50) b) (25:75)	The hybrid nanofluids were found to increase the heat transfer capacity.
Bumataria et al. [78]	[CuO+ZnO] (0.1% by wt.)	a) (25:75) b) (50:50) c) (75:25)	The best performance was attained using (75:25) hybrid nanofluid at an inclination of 60°.
Vidhya et al. [79]	[ZnO+MgO] (0.0125%-0.1% by vol.)	(50:50)	The 0.1 vol.% hybrid nanofluid performed best.
Martin et al. [80]	[Fe+CuO] (2% by wt.)	(50:50)	A maximum decrement of about 16.91% was attained in the resistance.

HEAT TRANSFER MODES IN HEAT PIPES

A major share of the published studies on heat pipes is on the utilizing of conventional nanosuspensions in the heat pipes relative to hybrid nanosuspensions that report performance augmentation. The authors have noticed during the literature survey that the crucial factors for heat pipe improvement are an aspect of research that is still not very much discussed with a firm understanding and remains hidden. The heat transfer modes found to be acting in such scenarios are summarized as follows:

- The Mechanism-(A) of augmentation in the thermophysical characteristics employing nanoparticles acts in the nanofluid-filled heat pipes. Such augmentation is achieved mainly in conductivity owed to the high aspect ratio of the nanoparticles that improves the heat transfer across the resulting nano-suspension.
- The Mechanism-(B) of increased capillary action also plays a crucial role owing to the reduced interface angle

that enhances the wettability & further improves the capillary pumping pressure.

- The Mechanism-(C) of Brownian motion of the nanoparticles leading to enhanced operation i.e., highly randomized movement by virtue of their high surface activity. Such randomized movement of the nanoparticles leads to inter-collisions and thermal energy exchange.
- The Mechanism-(D) of vapor bubble puncture due to nanoparticle activity also occurs in the heat pipes. During the heat pipe operation, vapor bubbles form at the inner wall which eventually hinders thermal exchange. In the case of nanofluid-filled heat pipes, the nanoparticles suspended in the base fluid under the action of externally supplied heat energy initiate chaotic motion. Such chaotic motion of nanoparticles bombards the aforementioned bubbles degrading the resistance.
- The Mechanism-(E) of nanoscale deposition on the inner surface of the container has been reported widely. The nanoparticles suspended in the base fluid lose their stability, start to sediment on the inner wall surface and form a nano-scale deposition. Such nanoparticle deposition results in numerous nano-sized nucleation sites which further results in vapor bubble formation of smaller size with high departure rates further reducing the resistance.
- The Mechanism-(F) of high mixing fluctuations within the nanofluid-filled heat pipe also had been observed in several research studies. The supplied heat energy progresses the mixing fluctuations within the nanofluids. Such increased mixing in the nanofluid leads to enhanced heat transfer when filled within the heat pipes.
- The Mechanism-(G) of nanoparticle thermophoresis across the base fluid has been evident to occur in the nanofluid-filled heat pipes such that a thermal gradient establishes. Such temperature gradient results in nanoparticle migration under the action of the discussed temperature gradient which further enhances the thermal exchange.
- The Mechanism-(H) of diffusiophoresis of the nanoparticles also has been observed to prevail in the heat pipes. The nanoparticles migrate across a density gradient resulting in heat exchange between them. However, this also results in nanoparticle agglomeration which further deteriorates the thermal exchange if the size of the agglomerates formed gets exceptionally large and blocks the wick pores.
- The Mechanism-(I) of ballistic transport of the nanoparticles also has been evident to act in the heat pipes owed to externally supplied heat energy carrying out phonon heat transfer which changes from scattered to ballistic transport resulting in increased conductivity.
- The Mechanism-(J) of the interfacial phenomena in nanofluids also prevails. The nanosuspensions are basically composites where the nanoparticles form the core structure while the base fluid acts as a matrix. This leads to a formation of a region where the intermediate of their properties is attained called the interfacial layer. The interfacial layer resembles a multi-phase system that offers high thermophysical characteristics. Such availability of high thermophysical properties results in enhanced heat transfer and efficient performance.
- The Mechanism-(K) of enhanced heat transfer area availability owed to the nanoparticle deposition has been reported across several experimental studies on heat pipes. The nanoparticle deposition reasoned as in the aforementioned mechanism (E) leads to a porous nanoparticle coating on the wick and inner wall resulting in an increment in thermal transport while allowing the smooth condensate return.
- The Mechanism-(L) of favorable increment in the viscosity using nanoparticles has been reported to prevail. Nanoparticles added to the base fluid cause advanced conductivity (favorable) and viscosity (opposing). So, it gets essential that a trade-off is attained between them. It can also be declared as a reason that researchers have reported the optimum nanofluid concentrations for best performance.
- The Mechanism-(M) of improvement in the critical heat flux due to nanofluids has been reported to act. The nanofluids filled offer high convection further improving the critical heat flux. An increase in the critical heat flux eventually results in improved heat pipe capacity.
- The Mechanism-(N) of gravitational influence on heat pipe performance has been reported in several research studies on heat pipes. The gravity force interacts with the capillary force altering the fluid flow. In the gravity-assisted positions, the gravity favors the condensate flow towards the evaporator while in the gravity-opposed positions, the gravity opposes the same.
- The Mechanism-(O) of synergy achieved between the suspended nanoparticles has been reported to act in the heat pipes. The synergetic combination of dissimilar nanoparticles is attained such that superior thermophysical characteristics are attained as compared to that attained using mono-nanofluids of the counterparts. This results in improved stability, flow, and performance.

Figures 4 (a)-(e) illustrate the percentage of studies in which the identified mechanisms A to N were reported based on the type of heat pipe incorporated. Figure 4 (a) shows the variation of the reported thermal exchange modes in thermosyphons. Mechanism A of thermophysical augmentation of base fluid has been reported in the majority followed by mechanisms E, K, and C with the dominance of 97%, 67%, 61%, and 59% respectively in the thermosyphon. The rest of the reported mechanisms were reported in less than 50% of the reviewed studies such that the mechanisms D, L, M, J, N, G, F, I and H had dominance of 43%, 38%, 29%, 22%, 17%, 12%, 8%, 7%, and 5% respectively in the nanofluid-filled thermosyphon heat pipes. Out of all the identified mechanisms, mechanism B was not reported in thermosyphon attributed to the absence of capillary phenomena.

Figure 4 (b) illustrates the domination of different mechanisms in the case of pulsating heat pipes. The action of mechanism A dominated followed by mechanisms F, K, and E with the dominance of 93%, 71%, 65%, and 59% respectively. The rest of the discussed mechanisms were reported in less than 50% of the reviewed studies such that the mechanisms C, L, J, G, M, N, H and I had dominance of 49%, 41%, 28%, 15%, 14%, 13%, 9% and 4% respectively. Similar to thermosyphon, mechanism B was also reported to be absent in pulsating heat pipes owed to the absence of capillarity. Mechanism D was also not reported owing to the fluid flow dynamics of the pulsating heat pipes.

Figure 4 (c) shows the domination of different mechanisms in oscillating heat pipes. Mechanism A of thermophysical augmentation of base fluid has been reported in the majority of the studies followed by mechanisms F, K, E, and C with the dominance of 89%, 84%, 72%, 69%, and 62% respectively. The rest of the reported mechanisms were reported in less than 50% of the studies such that the mechanisms L, J, G, N, M, I, and H had dominance of 44%, 34%, 24%, 17%, 12%, 9% and 4% respectively. Mechanism B was not reported in oscillating heat pipes attributed to the absence of capillary phenomena in them.

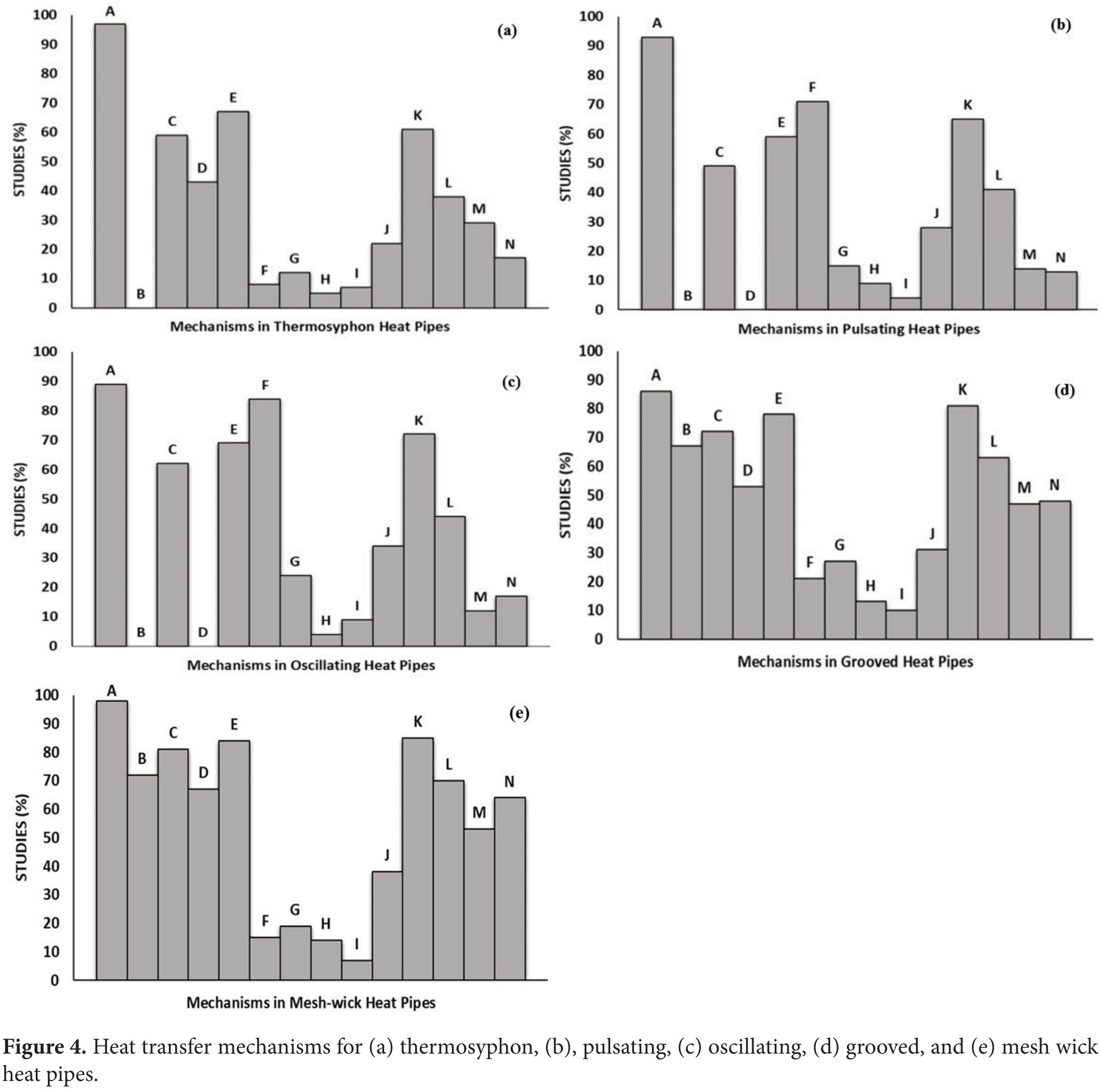

Figure 4. Heat transfer mechanisms for (a) thermosyphon, (b), pulsating, (c) oscillating, (d) grooved, and (e) mesh wick heat pipes.

Figure 4 (d) shows the variation of domination of different mechanisms in grooved heat pipes. Mechanism A of thermophysical augmentation of base fluid has been reported in the majority of the studies followed by mechanisms K, E, C, B, L, and D with the dominance of 86%, 81%, 78%, 72%, 67%, 63%, and 53% respectively. The rest of the reported mechanisms were reported in less than 50% of the studies such that the mechanisms N, M, J, G, F, H and I had dominance of 48%, 47%, 31%, 27%, 21%, 13% and 10% respectively.

Figure 4 (e) shows the variation of domination of different mechanisms in mesh heat pipes. Likewise, for other heat pipes, mechanism A has been reported in the majority of the studies followed by mechanisms K, E, C, B, L, D, N, and M with the dominance of 98%, 85%, 85%, 81%, 72%, 70%, 67%, 66% and 53% respectively. The rest of the reported mechanisms were reported to act in less than 50% of the studies such that the mechanisms J, G, F, H and I had dominance of 38%, 19%, 15%, 14%, and 7% respectively in the nanofluid-filled mesh wick heat pipes.

Figure 5 illustrates the percentage of studies attributing the mechanisms A to N to be acting during heat pipe operation irrespective of the type of heat pipe investigated. It is clear from the plot shown in Figure 5 that mechanism A of thermophysical augmentation due to nanoparticle addition has been reported significantly while mechanism I of nanoparticle ballistic phonon-based heat transfer has been reported in the least of the reviewed studies. The mechanism O of the synergy effect between the nanoparticles has been reported for hybrid nanosuspensions but it has not been reported widely owing to the scarcity of studies.

Mechanisms A, K, E, C, and L have been reported to act in about 92%, 73%, 71%, 65%, and 51% of the total reviewed studies respectively. Contrary to them, the mechanisms F, D, N, M, and J were reported to act in about 40%, 33%, 32%, 31%, and 30% respectively. Mechanisms B, G, H, and I were reported to act in the least of the reviewed studies. All the discussed thermal exchange modes act simultaneously.

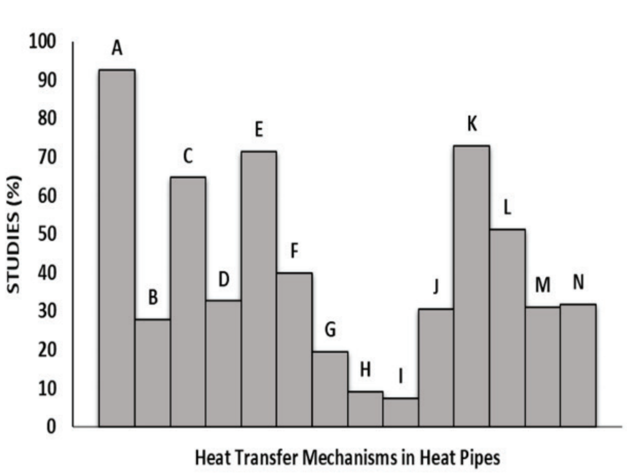

Figure 5. Thermal exchange modes in heat pipes.

The identified thermal exchange modes have their respective contributions that vary with the operating conditions & their dominance depends on several other parameters which are yet to be identified.

CONCLUSION

A review of the studies reported on the heat pipe technologies was carried out and categorized on the basis of the type of nanofluid incorporated. The thermal exchange modes were identified and their dominance over each other was presented in different heat pipes. The key conclusions are as follows:

- The performance of the heat pipe-based technologies augments appreciably when filled with nanosuspensions where the hybrid nanosuspension offers better heat transfer characteristics relative to mono nanosuspensions.
- The thermal exchange modes are highly controlled by fluid-flow dynamics within the container.
- The thermal exchange mode attributed with the highest dominance is the property augmentation of the base fluid when added with the nanoparticles.
- The heat transfer mechanisms pertaining to the nanoparticle Brownian motion and their deposition are widely accepted modes attributed to heat transfer augmentation.
- The synergy between the different nanoparticles enhances the thermal exchange across the hybrid nanosuspensions.
- The thermal exchange mode of nanoparticle thermophoresis & diffusiophoresis, and ballistic transport have not been much discussed in the open literature and are required to be further investigated to properly understand their dominance over other heat transfer mechanisms.

FUTURE RESEARCH SCOPE

The dominance of the heat transfer mechanisms in the pipes depends on various heat pipe parameters which are required to be investigated in terms of their quantitative influence by carrying out experimental and theoretical studies. Further research work can be carried out to optimize the heat pipes using artificial intelligence and machine learning.

NOMENCLATURE

PV/T system	Photovoltaic Thermal system
LED	Light Emitting Diode
SDBS	Sodium Dodecyl Benzene Sulfonate
CTAB	Cationic Cetyl Trimethyl Ammonium Bromide
GNP	Graphene Nanoplatelet
CNT	Carbon Nanotube

VOF	Volume of Fluid method
CFD	Computational Fluid Dynamics
MNFs	Mono Nanofluids
N.A.	Not Available
HNFs	Hybrid Nanofluids

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Choi SUS. Enhancing thermal conductivity of fluids with nanoparticles. ASME Eng Fluids Eng Div 1995;231:99−105.

[2] Senthil Kumar R, Vaidyanathan S, Sivaraman B. Effect of copper nanofluid in aqueous solution of long chain alcohols in the performance of heat pipes. Heat Mass Transf 2015;51:181−193. [CrossRef]

[3] Guo Z. A review on heat transfer enhancement with nanofluids. J Enhanc Heat Transf 2020;27:1−70. [CrossRef]

[4] Choi SUS. Nanofluid technology: current status and future research. Energy 1998;26:1−26. [CrossRef]

[5] Bumataria RK, Chavda NK, Panchal H. Current research aspects in mono and hybrid nanofluid based heat pipe technologies. Heliyon 2019;5:e01627. [CrossRef]

[6] Wang X, Luo L, Xiang J, Zheng S, Shittu S, Wang Z, et al. A comprehensive review on the application of nanofluid in heat pipe based on the machine learning: Theory, application and prediction. Renew Sustain Energy Rev 2021;150:111434. [CrossRef]

[7] Kilic M, Abdulvahitoğlu A. Numerical investigation of heat transfer at a rectangular channel with combined effect of nanofluids and swirling jets in a vehicle radiator. Therm Sci 2018;2018:3627−3637. [CrossRef]

[8] Abdulvahitoglu A. Using analytic hierarchy process for evaluating different types of nanofluids for engine cooling systems. Therm Sci 2018;2018:3199−3208. [CrossRef]

[9] Nine MJ, Chung H, Tanshen MR, Osman NABA, Jeong H. Is metal nanofluid reliable as heat carrier? J Hazard Mater 2014;273:183−191. [CrossRef]

[10] Abo El-Nasr A, El-Haggar SM. Effective thermal conductivity of heat pipes. Heat Mass Transf 1996;32:97-101. [CrossRef]

[11] Hassan MI, Alzarooni IA, Shatilla Y. The effect of water-based nanofluid incorporating Al_2O_3 nanoparticles on heat pipe performance. Energy Proced 2015;75:3201−3206. [CrossRef]

[12] Kumaresan G, Venkatachalapathy S, Godson L, Wongwises S. Comparative study on heat transfer characteristics of sintered and mesh wick heat pipes using CuO nano fluids. Int Commun Heat Mass Transf 2014;57:208−215. [CrossRef]

[13] Do KH, Kim SJ, Garimella SV. A mathematical model for analyzing the thermal characteristics of a flat micro heat pipe with a grooved wick. Int J Heat Mass Transf 2008;51:4637−4650. [CrossRef]

[14] Goshayeshi HR, Goodarzi M, Dahari M. Effect of magnetic field on the heat transfer rate of kerosene/Fe_2O_3 nanofluid in a copper oscillating heat pipe. Exp Therm Fluid Sci 2015;68:663−668. [CrossRef]

[15] Zhang XM, Xu JL, Zhou ZQ. Experimental study of a pulsating heat pipe using FC-72, ethanol, and water as working fluids. Exp Heat Transf 2004;17:47−67. [CrossRef]

[16] Yang XF, Liu ZH. Flow boiling heat transfer in the evaporator of a loop thermosyphon operating with CuO based aqueous nanofluid. Int J Heat Mass Transf 2012;55:7375−7384. [CrossRef]

[17] Zuo ZJ, Faghri A. A network thermodynamic analysis of the heat pipe. Int J Heat Mass Transf 1998;41:1473−1484. [CrossRef]

[18] Shafiey Dehaj M, Zamani Mohiabadi M. Experimental study of water-based CuO nanofluid flow in heat pipe solar collector. J Therm Anal Calorim 2019;137:2061−2072. [CrossRef]

[19] Shafiey Dehaj M, Ahmadi M, Zamani Mohiabadi M. Assessment of a heat pipe solar collector with nanofluids. Environ Sci Pollut Res 2021;28:5316−5331. [CrossRef]

[20] Hosseini SMS, Shafiey Dehaj M. Assessment of TiO_2 water-based nanofluids with two distinct morphologies in a U type evacuated tube solar collector. Appl Therm Eng 2021;182:116086. [CrossRef]

[21] Mozumder AK, Akon AF, Chowdhury MSH, Banik SC. Performance of heat pipe for different working fluids and fill Ratios. J Mech Eng 2010;41:96−102. [CrossRef]

[22] Liu Z, Li Y, Bao R. Thermal performance of inclined grooved heat pipes using nano fluids. Int J Therm Sci 2010;49:1680−1687. [CrossRef]

[23] Moradgholi M, Mostafa Nowee S, Farzaneh A. Experimental study of using Al_2O_3/methanol nanofluid in a two phase closed thermosyphon (TPCT) array as a novel photovoltaic/thermal system. Sol Energy 2018;164:243−250. [CrossRef]

[24] Das S, Giri A, Samanta S, Kanagaraj S. Role of graphene nanofluids on heat transfer enhancement in thermosyphon. J Sci Adv Mater Devices 2019;4:163−169. [CrossRef]

[25] Sardarabadi H, Zeinali Heris S, Ahmadpour A, Passandideh-Fard M. Experimental investigation of a novel type of two-phase closed thermosyphon filled with functionalized carbon nanotubes/water nanofluids for electronic cooling application. Energy Convers Manag 2019;188:321−332. [CrossRef]

[26] Sarafraz MM, Pourmehran O, Yang B, Arjomandi M. Assessment of the thermal performance of a thermosyphon heat pipe using zirconia-acetone nanofluids. Renew Energy 2019;136:884−895. [CrossRef]

[27] Kiseev V, Sazhin O. Heat transfer enhancement in a loop thermosyphon using nanoparticles/water nanofluid. Int J Heat Mass Transf 2019;132:557−564. [CrossRef]

[28] Cacua K, Buitrago-Sierra R, Pabón E, Gallego A, Zapata C, Herrera B. Nanofluids stability effect on a thermosyphon thermal performance. Int J Therm Sci 2020;153:106347. [CrossRef]

[29] Kaya M. An experimental investigation on thermal efficiency of two-phase closed thermosyphon (TPCT) filled with CuO/water nanofluid. Eng Sci Technol Int J 2020;23:812−820. [CrossRef]

[30] Anand RS, Jawahar CP, Solomon AB, Koshy JS, Jacob JC, Tharakan MM. Heat transfer properties of HFE and R134a based Al_2O_3 nano refrigerant in thermosyphon for enhancing the heat transfer. Mater Today Proc 2020;27:268−274. [CrossRef]

[31] Choi D, Lee KY. Experimental study on confinement effect of two-phase closed thermosyphon and heat transfer enhancement using cellulose nanofluid. Appl Therm Eng 2021;183:116247. [CrossRef]

[32] Shuoman LA, Abdelaziz M, Abdel-Samad S. Thermal performances and characteristics of thermosyphon heat pipe using alumina nanofluids. Heat Mass Transf 2021;57:1275−1287. [CrossRef]

[33] Xing M, Yu J, Wang R. Performance of a vertical closed pulsating heat pipe with hydroxylated MWNTs nanofluid. Int J Heat Mass Transf 2017;112:81−88. [CrossRef]

[34] Nazari MA, Ghasempour R, Ahmadi MH, Heydarian G, Shafii MB. Experimental investigation of graphene oxide nanofluid on heat transfer enhancement of pulsating heat pipe. Int Commun Heat Mass Transf 2018;91:90−94. [CrossRef]

[35] Kazemi-Beydokhti A, Meyghani N, Samadi M, Hajiabadi SH. Surface modification of carbon nanotube: Effects on pulsating heat pipe heat transfer. Chem Eng Res Des 2019;152:30−37. [CrossRef]

[36] Akbari A, Saidi MH. Experimental investigation of nanofluid stability on thermal performance and flow regimes in pulsating heat pipe. J Therm Anal Calorim 2019;135:1835−1847. [CrossRef]

[37] Chen M, Li J. Nanofluid-based pulsating heat pipe for thermal management of lithium-ion batteries for electric vehicles. J Energy Storage 2020;32:101715. [CrossRef]

[38] Zhou Y, Yang H, Liu L, Zhang M, Wang Y, Zhang Y, et al. Enhancement of start-up and thermal performance in pulsating heat pipe with GO/water nanofluid. Powder Technol 2021;384:414−422. [CrossRef]

[39] Zhang D, He Z, Guan J, Tang S, Shen C. Heat transfer and flow visualization of pulsating heat pipe with silica nanofluid: An experimental study. Int J Heat Mass Transf 2022;183:122100. [CrossRef]

[40] Zhou Y, Cui X, Weng J, Shi S, Han H, Chen C. Experimental investigation of the heat transfer performance of an oscillating heat pipe with graphene nanofluids. Powder Technol 2018;332:371−380. [CrossRef]

[41] Meena P, Sangmart A. Heat transfer of a heat pipe on fins using silver nanofluid. J Phys Conf Ser 2018;1144:012121. [CrossRef]

[42] Jin H, Lin G, Zeiny A, Bai L, Cai J, Wen D. Experimental study of transparent oscillating heat pipes filled with solar absorptive nanofluids. Int J Heat Mass Transf 2019;139:789−801. [CrossRef]

[43] Monroe JG, Kumari S, Fairley JD, Walters KB, Berg MJ, Thompson SM. On the energy harvesting and heat transfer ability of a ferro-nanofluid oscillating heat pipe. Int J Heat Mass Transf 2019;132:162−171. [CrossRef]

[44] Davari H, Goshayeshi HR, Öztop HF, Chaer I. Experimental investigation of oscillating heat pipe efficiency for a novel condenser by using Fe3O4 nanofluid. J Therm Anal Calorim 2020;140:2605−2614. [CrossRef]

[45] Zhou Z, Lv Y, Qu J, Sun Q, Grachev D. Performance evaluation of hybrid oscillating heat pipe with carbon nanotube nanofluids for electric vehicle battery cooling. Appl Therm Eng 2021;196:117300. [CrossRef]

[46] Aly WIA, Elbalshouny MA, Abd El-Hameed HM, Fatouh M. Thermal performance evaluation of a helically-micro-grooved heat pipe working with water and aqueous Al_2O_3 nanofluid at different inclination angle and filling ratio. Appl Therm Eng 2017;110:1294−1304. [CrossRef]

[47] Zhou R, Fu S, Li H, Yuan D, Tang B, Zhou G. Experimental study on thermal performance of copper nanofluids in a miniature heat pipe fabricated by wire electrical discharge machining. Appl Therm Eng 2019;160:113989. [CrossRef]

[48] Veerasamy A, Balakrishnan K, Surya Teja Y, Abbas Z. Efficiency improvement of heat pipe by using graphene nanofluids with different concentrations. Therm Sci 2020;24:447−452. [CrossRef]

[49] Bhullar BS, Gangacharyulu D, Das SK. Temporal deterioration in thermal performance of screen mesh wick straight heat pipe using surfactant free aqueous nanofluids. Heat Mass Transf 2017;53:241–251. [CrossRef]
[50] Bhullar BS, Gangacharyulu D, Das SK. Augmented thermal performance of straight heat pipe employing annular screen mesh wick and surfactant free stable aqueous nanofluids. Heat Transf Eng 2017;38:217–226. [CrossRef]
[51] Channapattana SV, Raut SB, Pawar AA, Campli S, Sarnobat SS, Dey T. Heat transfer performance analysis of screen mesh wick heat pipe using CuO nano fluid. Eur J Sustain Dev Res 2018;3:1–10. [CrossRef]
[52] Gupta NK, Tiwari AK, Ghosh SK. Experimental study of thermal performance of nanofluid-filled and nanoparticles-coated mesh wick heat pipes. J Heat Transfer 2018;140:102403. [CrossRef]
[53] Gupta NK, Tiwari AK, Verma SK, Rathore PKS, Ghosh SK. A comparative study of thermal performance of a heat pipe using water and nanofluid, and a nanoparticle-coated wick heat pipe using water. Heat Transf Res 2019;50:1767–1779. [CrossRef]
[54] Sharuk B, Reddy PL, Reddy ES. Thermal performance enhancement of cylindrical heat pipe using Tio2 nanofluid. Int J Mech Prod Eng Res Dev 2019;9:433–444.
[55] Anand EV, Andhare A. Performance analysis of inclined heat pipe using alumina nanofluid. Indian J Sci Technol 2019;12:1–8. [CrossRef]
[56] Gupta NK, Verma SK, Rathore PKS, Sharma A. Effects of CuO/water nanofluid application on thermal performance of mesh wick heat pipe. Heat Transf Res 2020;51:837–850. [CrossRef]
[57] Nizam AR, Gupta NK, Alam P. Experimental Investigation of Thermal Performance of Mesh Wick Heat Pipe Using Nanofluid. IOP Conf Ser Mater Sci Eng 2020;998:012034. [CrossRef]
[58] Jyothi Sankar PR, Venkatachalapathy S, Asirvatham LG. Thermal performance enhancement studies using graphite nanofluid for heat transfer applications. Heat Transf 2020;49:3013–3029. [CrossRef]
[59] Alagappan N, Karunakaran N, Rathnasabapathy CS. Performance of two phase copper thermosyphon operated with cerium IV oxide and iron II, III oxide nano fluid using box-behnken design. Mater Today Proc 2019,24:2094–2107. [CrossRef]
[60] Sarafraz MM, Tlili I, Tian Z, Bakouri M, Safaei MR. Smart optimization of a thermosyphon heat pipe for an evacuated tube solar collector using response surface methodology (RSM). Phys A Stat Mech Its Appl 2019;534:122146. [CrossRef]
[61] Wang WW, Cai Y, Wang L, Liu CW, Zhao FY, Sheremet MA, et al. A two-phase closed thermosyphon operated with nanofluids for solar energy collectors: Thermodynamic modeling and entropy generation analysis. Sol Energy 2020;211:192–209. [CrossRef]
[62] Xu H, Zhang P, Yan L, Xu D, Ma W, Wang L. Thermal characteristic and analysis of microchannel structure flat plate pulsating heat pipe with silver nanofluid. IEEE Access 2019;7:51724–51734. [CrossRef]
[63] Malekan M, Khosravi A, Goshayeshi HR, Assad MEH, Garcia Pabon JJ. Thermal resistance modeling of oscillating heat pipes for nanofluids by artificial intelligence approach. J Heat Transfer 2019;141:072402. [CrossRef]
[64] Gupta NK, Barua A, Mishra S, Singh SK, Tiwari AK, Ghosh SK. Numerical study of CeO_2 /H_2O nanofluid application on thermal performance of heat pipe. Mater Today Proc 2019;18:1006–1016. [CrossRef]
[65] Maddah H, Ghazvini M, Ahmadi MH. Predicting the efficiency of CuO/water nanofluid in heat pipe heat exchanger using neural network. Int Commun Heat Mass Transf 2019;104:33–40. [CrossRef]
[66] Poplaski LM, Benn SP, Faghri A. Thermal performance of heat pipes using nanofluids. Int J Heat Mass Transf 2017;107:358–371. [CrossRef]
[67] Herrera B, Chejne F, Mantelli MBH, Mejía J, Cacua K, Gallego A. Population balance for capillary limit modeling in a screen mesh wick heat pipe working with nanofluids. Int J Therm Sci 2019;138:134. [CrossRef]
[68] Gupta NK. Thermal performance optimization of heat pipe using Taguchi method. Lect Notes Mech Eng 2021:499–508. [CrossRef]
[69] Herrera B, Chejne F, Mantelli MBH, Mejía J, Cacua K. Modelling of a screen mesh wick heat pipe using Al_2O_3 nanofluids. IOP Conf Ser Mater Sci Eng 2021;1139:012006. [CrossRef]
[70] Reddy P, Reddy B, Govindarajulu K. Thermal performance prediction of heat pipe with TiO_2 nanofluids using RSM. Therm Sci 2022;26:641–651. [CrossRef]
[71] Xu Q, Liu L, Feng J, Qiao L, Yu C, Shi W, et al. A comparative investigation on the effect of different nanofluids on the thermal performance of two-phase closed thermosyphon. Int J Heat Mass Transf 2020;149:119189. [CrossRef]
[72] Çiftçi E. Distilled water-based AlN + ZnO binary hybrid nanofluid utilization in a heat pipe and investigation of its effects on performance. Int J Thermophys 2021;42:1–21. [CrossRef]
[73] Zufar M, Gunnasegaran P, Kumar HM, Ng KC. Numerical and experimental investigations of hybrid nanofluids on pulsating heat pipe performance. Int J Heat Mass Transf 2020;146:118887. [CrossRef]
[74] Zufar M, Gunnasegaran P, Ng KC, Mehta HB. Evaluation of the thermal performance of hybrid nanofluids in pulsating heat pipe. CFD Lett 2019;11:13–24.
[75] Pandya NS, Desai AN, Kumar Tiwari A, Said Z. Influence of the geometrical parameters and particle concentration levels of hybrid nanofluid on the thermal performance of axial grooved heat pipe. Therm Sci Eng Prog 2021;21:100762. [CrossRef]

[76] Veeramachaneni S, Pisipaty SK, Vedula DR, Solomon AB, Harsha VS. Effect of copper-graphene hybrid nanoplatelets in a miniature loop heat pipe. J Therm Anal Calorim 2021;147:5985–5999. [CrossRef]

[77] Ramachandran RN, Ganesan K, Asirvatham LG. The role of hybrid nanofluids in improving the thermal characteristics of screen mesh cylindrical heat pipes. Therm Sci 2016;20:2027–2035. [CrossRef]

[78] Bumataria RK, Chavda NK, Nalbandh AH. Performance evaluation of the cylindrical shaped heat pipe utilizing water-based CuO and ZnO hybrid nanofluids. Energy Sources Part A Recover Util Environ Eff 2020. doi: 10.1080/15567036.2020.1832628. [Epub ahead of print]. [CrossRef]

[79] Vidhya R, Balakrishnan T, Kumar BS. Investigation on thermophysical properties and heat transfer performance of heat pipe charged with binary mixture based ZnO-MgO hybrid nanofluids. Mater Today Proc 2020;37:3423–3433. [CrossRef]

[80] Martin K, Sözen A, Çiftçi E, Ali HM. An experimental investigation on aqueous Fe-CuO hybrid nanofluid usage in a plain heat pipe. Int J Thermophys 2020;41:1–21. [CrossRef]