A Review on Application of Nanofluid in Enhancement of Thermal Performance of Various Types of Heat Pipes

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ABSTRACT

Heat pipes are widely used in various applications to remove the heat and control the temperature of various electronics components due to many advantages such as least operating and maintenance cost, accuracy, long service life and environmentally safe. With the decrease in size of electronics components, it becomes necessary to increase the performance of heat pipes. Application of nanofluid is one of the relatively recent developments employed for increasing the heat transfer rate in various heat exchanging devices. Many investigators have employed various types of nanofluids as working medium in different types of heat pipes. In the present paper, recently published literatures and available in open literature have been critically reviewed and future requirements have been identified.

Keywords: *Review, Nanofluid, Thermal Performance, Heat Pipes.*

1. INTRODUCTION

With the advancement in electronics filed, electronics equipmentbecome smarter and smarter with infinite work function ability combined with compactness. With increase in functionality, the rate of heat generation also increases which needs to removed for efficient performance of the electronic equipment. Heat pipes are widely used in the field of electronics cooling due to extremely high effective thermal conductivity as it involves two phase heat transfer. Due to its simplicity in operation and reliability, it has been widely used in other applications su ch as space, medical and health undertakings, and domestic appliances.

R. S. Gauler of General Motors had patented and recommended the application of capillary-driven heat pipes in 1942, but he did not develop it further. George Grover working at Los Alamos National Laboratory had separately developed and patented the most common configuration of present heat pipe in the year 1963. He was the first to use the term "Heat Pipe". Since then investigators have focused on development of various types of heat pipes and increasing the performance e of heat pipes.

The heat pipe consists of three sections viz. (1) evaporator section, (2) adiabaticsection and (3) condenser section. Heat absorption and rejection takes placein the evaporator and condenser sections respectively. Adiabatic section is completely insulated. Generally, heat pipesare evacuated filled up with the working fluid. At the evaporator section, the workingfluid absorbs the heat and evaporated. Evaporated working fluid moves towards the condenser section through adiabatic section. At the condenser section, working fluid releases the heat and gets condensed.Condensed working fluid then returns back to the evaporator section under the action of gravity in case of vertically oriented heat pipe known as thermosyphons. In case other orientation of heat pipe, condensed working fluid returns back to the evaporator section due to thecapillaryaction ofdifferent structures at inner wall of heat pipe such as different types of grooves, different types of wire mesh, sintered powder metal and fiber/spring.Normallytraditional fluids like water, acetone, methanol, ammonia, or sodium are used in heat pipes to remove the heat.But, now-a –days, nontraditional fluids like nanofluid etc. are also used in the heat pipes to increase the performance of the heat pipe. The performance of heat pipe mainly depends on the various parameters such as (1) type of heat pipe, (2) material of heat pipe, (3) orientation of heat pipe, (4) structure at inner wall of heat pipe, (5) different parameters of structures at inner wall of heat pipe etc.

A nanofluid is a mixture of nano-sized particles popularly known as nanoparticles (having less than 100 nm size) and a base fluid. Most commonly used nanoparticles are (1) Pure metals (Au, Ag, Cu, Fe), (2) Metal oxides (CuO, SiO_2, Al_2O_3, TiO_2, ZnO, Fe_3O_4), (3) Carbides (SiC, TiC), (4) Nitrides (AlN, SiN) and (5) Different types of carbon (diamond, graphite, single/multi wall carbon nanotubes). Traditional liquids, such as water, ethylene glycol and engine oil are some examples of base fluids. Nanoparticles are available in various sizes ranges from 1 to 100 nm, in various shapes such as spherical, cylindrical, etc. and they can be mixed with the based fluid in different concentration ratios. Therefore, enhancement of performance using nanoparticles mainly depend upon different criteria such as (1) type of nanoparticles, (2) base fluid, (3) size of nanoparticles, (4) shape of nanoparticles, (5) concentration of nanoparticles in base fluid etc.

Since the 1990s, researchers began to apply nano-material technology to heat transfer field and have achieved many meaningful results on heat transfer enhancement. In 1995, Choi [62] firstly proposed the concept of ''nanofluid'', which is a fluid with some kinds of nanoparticles suspended into a base liquid. The application of nanofluids in heat pipes was firstly published in 2003 by H. T. Chienet. al. [63].

Now-a-days various types of heat pipes are available. Their application in various fields mainly depends upon the range of temperature control, heat flux removal, space available, reliability etc. The most commonly used heat pipes are flat heat pipe (rectangular shaped and/or disc shaped), thermosyphon heat pipe (vertically oriented cylindrical heat pipe), cylindrical heat pipe, rotating heat pipe, oscillating heat pipe, loop heat pipe, pulsating heat pipe, closed loop pulsating heat pipe, open loop pulsating heat pipe and sintered heat pipe.

2. REVIEW

In the present paper, the review of recently published investigations and reported in open literature has been carried out on the application of nanofluid in enhancement of thermal performance of heat pipe. The details of the recently published investigations related to different types of heat pipes having various types of nanofluidsas working medium have been arranged in Table 1.The review has been carried out considering three criteria viz. (1) Review of particular nanofluid as working medium in various types of heat pipes, (2) Review of particular heat pipe having different nanofluids as working medium and (3) Review of available literature in terms of outcomes.

2.1 Review of Particular Nanofluid as Working Medium in Various Types of Heat Pipes

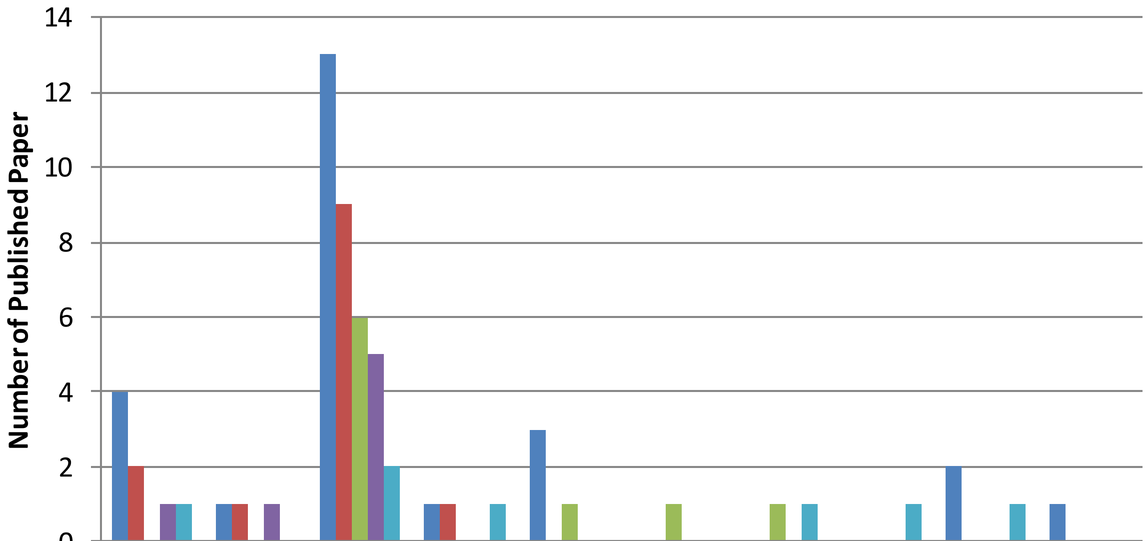
It is observed from the Table 1 that, out of total seventy eight investigations available about application of particular nanofluid as working medium in various types of heat pipes, twenty five researches are related to application of Al_2O_3 nanofluid, thirteen are related to CuOnanofluid, nine are related to silver nanofluid, seven are related to TiO_2 nanofluid, seven are related to Cu nanofluid, two are related to ZnOnanofluid, two are related to SiCnanofluid, one is related to Ti, one is related to Gold, one is related to MgO, two are related to Fe_2O_3, one is related to MWCNT nanofluid, two are related to SiO_2 nanofluid and five are review papers.Most commonly used nanofluids employed in different types of heat pipes are Al_2O_3, CuO, Ag, TiO_2 and Cu. Number of published papers using those nanofluids are shown in Figure 1.

2.2 Review Of Particular Heat Pipe Having Different Nanofluids As Working Medium

It is noted from the Table 1 that, out of total seventy eight investigations available, eight investigations have been carried out using flat heat pipe, three have been carried out using disc shaped heat pipe, forty four have been carried out using cylindrical heat pipe, three have been carried out using rotating heat pipe, six have been carried out using oscillating heat pipe, one have been carried out using pulsating heat pipe, two have been carried out using closed loop pulsating heat pipe, one has been carried out using open loop pulsating heat pipe, four have been carried out using loop heat pipe, one has been carried out sintered (bent) heat pipe and five are review papers. Most frequently employed heat pipes are cylindrical, flat, oscillating, loop, disc shaped and rotating heat pipe. Numbers of published papers using those heat pipes are represented in Figure 2.

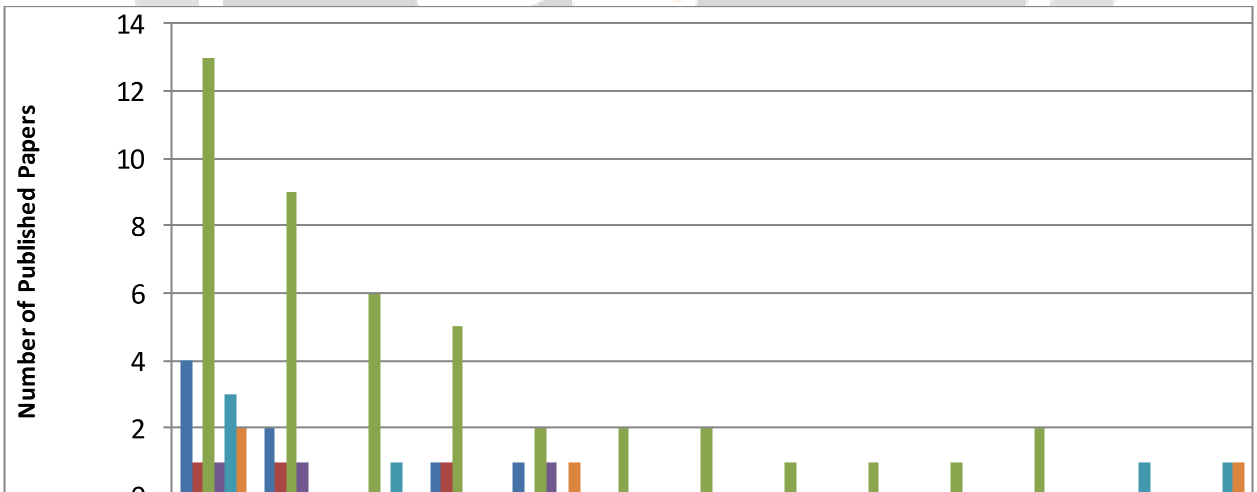
Table 1: Details of the Recently Published Investigations Related to Different Types of Heat Pipes Having Various Types of Nanofluids

Nanofluid / Type of Heat Pipe	**Number of Published Papers**													
	Al_2O_3	**CuO**	**Silver**	**TiO_2**	**Cu**	**ZnO**	**SiC**	**Ti**	**Gold**	**MgO**	**Fe_2O_3**	**MWCNT**	**SiO_2**	**review**
Flat	4[3,26,38,53]	2[3,38]		1[38]	1[3]									
Disc Shaped Heat Pipe	1[38]	1[38]		1[38]										
Cylindrical including Thermosyphons	13[5,8,10,11,12, 15,25,31,36,43, 46,51,55]	9[13,16, 19,35,39,45, 49,50,55]	6[4,17, 29,37,56,60]	5[2,11,12,36, 55]	2[18,30]	2[32,36]	2[1,6]	1[58]	1[61]	1[10]	2[23,44]			
Rotating Heat Pipe	1[7]	1[7]			1[7]									
Oscillating Heat Pipe	3[41,42,54]		1[48]									1[27]	1[41]	
Pulsating Heat Pipe			1[59]											
Close Loop pulsating Heat Pipe			1[20]		1[20]									
Open Loop Pulsating Heat Pipe					1[34]									
Loop Heat Pipe	2[21,22]				1[14]								1[28]	
Sintered Heat Pipe (Bent)	1[33]													
Review Paper														5[9,24,40,47, 53]



	Flat	Disc Shaped Heat Pipe	Cyllindrical	Rotating Heat Pipe	Oscillating Heat pipe	pulsating heat ipe	Close loop pulsating Heat pipe	Open loop pulsating heat pipe	Loop Heat Pipe	Sintered Heat Pipe (Bent)
Al2O3	4	1	13	1	3	0	0	0	2	1
CuO	2	1	9	1	0	0	0	0	0	0
Ag	0		6	0	1	1	1	0	0	0
TiO2	1	1	5	0	0	0	0	0	0	0
Cu	1	0	2	1	0	0	1	1	1	0

Figure 1: Number of Published Papers Related to Particular Nanofluid at Working Medium



	Al2O3	CuO	Silver	TiO2	Cu	ZnO	SiC	Ti	Gold	MgO	Fe2O3	MWCNT	SiO2
Flat	4	2	0	1	1	0	0	0	0	0	0	0	0
Disc Shaped	1	1		1	0	0	0	0	0	0	0	0	0
Cyllindrical	13	9	6	5	2	2	2	1	1	1	2	0	0
Rotating	1	1	0	0	1	0	0	0	0	0	0	0	0
Oscillating	3	0	1	0	0	0	0	0	0	0	0	1	1
Loop	2	0	0	0	1	0	0	0	0	0	0	0	1

Figure 2: Number of Published Papers Related to Particular Heat Pipe

2.3 Review of Available Literature in Terms of Outcomes

In the present section, recent investigations in the field of application of nanofluid in enhancement of thermal performance of heat pipe have been critically reviewed in terms of input variables, targeted variables, methodology adopted and results obtained chronologically.

Ghanbarpour, M. et. al.[1] have carried out an experimental study to investigate the thermal performance of cylindrical copper heat pipesusingSiC/waternanofluid as the working fluidat different concentrations andinclination angles. They reported reduction in thermal resistance of heatpipes by 11%, 21% and 30% with SiC nanofluids containing 0.35 wt.%, 0.7 wt.% and 1.0 wt.% SiC nanoparticles as compared with water and the lowest thermal resistance belongs to the inclination angle of 60◦ in all concentrations. They concluded that the maximum heat removal capacity of the heat pipeincreases by 29% with SiCnanofluids at nanoparticle mass concentration of 1.0 wt.%.Colla, L. et. al. [2] have studied the effect of water-based TiO_2nanofluid under laminar, forced and mixed flow conditions in a uniformly heated pipe. They found increase in convictive heat transfer rate as compared to water.Hamdy Hassan andSouadHarmand [3] have carried out experimental and numerical study on cooling of an electronic component using flat heat pipe having water based Cu, CuO and Al_2O_3 nanoparticles as working fluid. They have considered the effects of diameter of nanoparticles, volume fraction, wick porosities and wick thicknesses on performance of heat pipe.They showed that the maximum temperature of the heat pipe decreases by using nanofluids at different wick porosities and thicknesses. The temperature of the heat pipe decreases with decreasing the diameter and with increasing the volume fraction of the solid nanoparticles.

Ghanbarpour, M. et. al.[4] have experimentally investigated the effect of water based silver nanofluidwith mass concentrations of 0.25%, 0.5% and0.75% as working fluids on thermal performance of inclined screen mesh heat pipe containing two layers of screen mesh and located at four inclination angles of 0°, 30°, 60° and 90°incooling applications. They found that at inclination angle of 60°, the average effectivethermal conductivity of the heat pipe increases about 11% comparedwith the horizontal heat pipe.Ghanbarpour, M. et. al.[5] have studied the effect of water based Al_2O_3 nanofluidwith mass concentrations of 5% and 10% on thermal performance of screen mesh copper heat pipein cooling applications at different heat inputs experimentally. They showed that that using 5wt.% of Al_2O_3nanofluidimproves the thermal performance of the heat pipe for increasing and decreasing heatfluxes compared with distilled water, while utilizing 10 wt.% of Al_2O_3nanofluid deteriorates the heat pipethermal performance.

Kyung Mo Kimet. al. [6] have compared the thermal performances of water-filled and 0.01 and 0.1 vol.% SiC/waternanofluids-filled heat pipes with a screen mesh wick and water-filled heat pipe with a SiCnanoparticles-coated screen mesh wick in order to investigate the effects of nanoparticlesdepositions on inner surface structures of heat pipes experimentally. They reported that the overall thermalresistances of the heat pipes with the SiC/water nanofluids and SiC-coated wick were similar with thoseof the heat pipe charged with water.Hamdy Hassan and SouadHarmand [7] have experimentally studied the effect of using water based Cu, CuO and Al_2O_3(at different nanoparticles radiuses and volume fractions)nanofluids on the performance of rotating heat pipe. They reported that the heat transfer by rotating heat pipe increases with increase in temperature difference and volume fraction and radius of solid nanoparticles and with decrease condenser taper angle. They concluded that rotating heat pipes with Cu–water nanofluid(volume fraction 0.04 and radius 5 nm)have maximum heat transfer compared with CuO–water and Al_2O_3–water nanofluids.

Hassan, M. I. et. al. [8] have studied the impact of nanoparticles deposition on the vacuumed copper heat pipe wick porosity after several use of nanofluid (1, 2 and 3 vol.% alumina nanoparticles in water) as a working medium. They reported that at the beginning, the heat pipe performance showed a significant enhancement for using the nano fluids over the pure water, but this enhancement is later depreciated after several use.Menlik, T. et. al. [10] have investigated the effect of MgO/water nano-fluid (5 %vol., filling ratio 33.3 % of volume of heat pipe, input power as 200 W, 300 W and 400 W and flow rates of cooling water 5, 7.5 and 10 g/s) on thermal performance of a two-phase closedthermo-syphon cylindrical copper heat pipe at various states of operation. They concluded that the thermal performance of the MgO containing nano-fluid was better than that of deionized water and the highest improvement inefficiency was determined as 26% at 200 W heating power and 7.5 g/s flow rate. Morteza Ghanbarpour and Rahmatollah Khodabandeh [11] have studied the entropy generation in cylindrical miniature grooved heat pipes having distilled water and water based TiO_2 and Al_2O_3 nanofluids of different concentration as working fluids analytically and compared the results with experimental results. They reported that 3–13.5% reduction of entropy generation in heat pipes are found for nanofluids concentrations of 1–5 vol.% while heat pipes with Al_2O_3 nanofluids have lower entropy generation that heat pipes with TiO_2 nanofluids.

P. R. Mashaei and M. Shahryari [12] have studied the performance of pure water and water based Al_2O_3 and TiO_2 nanofluids (2, 4 and 8 % particle concentration and size of 10, 20, and 40 nm) in a cylindrical heat pipe with two heat sources for the application of heat dissipating in satellite equipment cooling experimentally. Their results reveal that applying nanoparticle with smaller size and higher concentration level increases heat transfer coefficient remarkably by reducing thermal resistance. They have also found that the presence of nanoparticles in water can lead to a reduction in weight of heat pipe.Venkatachalapathy, S. et. al. [13] have presented the experimental study on enhancement of thermal performance of cylindrical copper mesh wick heat pipe using water based CuOnanofluids of various concentration at different inclination angle and heat input. They found that thermal efficiency of heat pipe increases withthe addition of CuO nanoparticles and the increment is proportional with heat load. They reported that maximumimprovement in thermal efficiency is 32.9% at 140 W compared with that of 20 W heat load. Zhenping Wanet. al. [14] have analyzed the thermal performance of miniature loop heat pipe with water based Cu nanoparticles having average diameter of 50 nm and mixed with water at different concentrations experimentally. They found that reductions of 12.8% and 21.7% are achieved in the evaporator wall temperature and total thermal resistance, respectively, while the heat transfer coefficient of the evaporator increases 19.5% when substituting the nanofluid with 1.0 wt.% of deionized water at a heat load of 100 W.

M.M. Sarafraz and F. Hormozi [15] have investigated the thermal performance and thermal efficiency of a cylindrical thermosyphon heat pipe with Al_2O_3-water/EG and Al_2O_3-water/DEG nanofluid. Their results demonstrated that heat transfer coefficient of the heat pipe significantly increases, when nanofluids are used as possibleworking fluid and have a significant positive influence on the enhancement of thermal efficiency of the heat pipe. They have also reported that tilt angle had a strong effect on thermal performance of heat pipe such that when tilt angle increases, due to the strong influence of gravitational force on the flowing of working fluid, particularly on the nanoparticles, the heat pipe efficiency increases. Kumaresan, G. et. al. [16] have studied the thermal performance of sintered and mesh wick heat pipe by using different working fluid (water and water based CuOnanofluid), inclination angle and heat input. They reported that that the heat transport capacity of sintered wick heat pipe is 14.3%more comparedwithmeshwick heat pipe under the same operating conditions and a higher reduction in the surface temperature of 27.08% is observed for the sintered wick heat pipe with 1.0wt.% of CuO/DI water nanofluids compared with mesh wick heat pipe.Based on the observed results, they concluded that the thermal performance of sintered wick heat pipe is better than that of the mesh wick heat pipe.

M. M. Sarafrazet. al. [17] have investigated the thermal performance of wickless thermosyphon heat pipe having water based silver nanofluids prepared using green synthesis under different operating parameters such as heat flus, filling ratio, inclination and concentration experimentally. They reported that at filling ratio of 0.65 and inclination of 55°, the best thermalperformance of heat pipe is obtained at wt.% = 0.4 of Ag/waternanofluids.Brusly Solomon, A. et. al. [18] have compared the thermal performance of heat pipe having water based Cu naofluid with the same having water as working fluid for different operating conditions. They found that the addition of nanoparticles leads to the reduction in wall temperature and total resistance of the heat pipe; thus, increases theheat transfer of the heat pipe at the same heat load. They have also observed that the decreasedpore size of the wick due to the addition of nanoparticles increases the effective thermal conductivityof the wick structure which acts as a coating layer and enhances the heat transfer capability of the heatpipe. Kumaresan, G. et. al. [19] have experimentally studied the effect of heat input, tilt angle and weight concentration on thermal performance of copper sintered wick heat pipe having surfactant free CuO nanoparticles dispersed in mineral water. They reported a reduction in the thermal resistance of66.1% and enhancement in the heat transfer coefficient and thermal conductivity of 29.4% and 63.5% isrespectively, observed for 1.0 wt.% of CuO/DI water nanofluid at 45^{O}inclination angle compared with horizontal heat pipe.

Karthikeyan, V. K. et. al. [20] have analyzed the effect of copper and silver colloidal nanofluid on the performance of closed loop pulsating heat pipe.They showed that the nanofluid charged closed loop pulsating heat pipe enhances the heat transfer limit by 33.3% and have lower evaporator wall temperature compared to that of DI water.Putra, N. et. al. [21] have described the effect of water based Al_2O_3 nanofluid on performance of loop heat pipe having biomaterial as a wick experimentally and compared the results with sintered copper powder wick. They concluded that the biomaterial (Collar) and nanofluids as wick and working fluid increases the performance of loop heat pipe. Gunnasegaran, P. [22] have examined the effect of water based alumina nanoparticles (0 to 3% mass concentration) on the thermal performance of loop heat pipe experimentally. They reported that nanofluid yields lower wall temperature difference between evaporate and condenser and steady state condition is achieved quickly using nanofluid.

Gabriela Huminic and Angel Huminic[23] have experimentally analyzed the effect of water based γ-Fe_2O_3 nanoparticles (2 and 5.3 vol. %) on the thermal performance of thermosyphon at four operating temperatures (60, 70, 80 and 90 ^{O}C) and compared the results with numerical results. They concluded that thermosyphon heat pipe using the nanofluid has better heat transfer characteristics than the thermosyphon heat pipe using water. Yousefi. T. et. al. [25] have analyzed the heat transfer performance of CPU cooling heat pipe when Al_2O_3 nanofluid is utilized as working fluid at different parameters such as inclination angle, concentration of nanoparticles in water and heat input. They concluded that using 0.5 wt. % Al_2O_3 nanoparticles based nanofluid reduces thermal resistance and at 10 W heat input nanofluid reduces the thermal resistance by 15 %. Zhang, J. et. al. [26] have studied the heat recovery characteristics of flat micro heat pipe array heat exchanger using δ-Al_2O_3-R141b nanofluids as working fluids.Theyconcluded that heat recovery efficiency is enhanced by using 0.01% volume fraction nanofluid as working fluid, and the maximum growth rate of effectiveness can reach 110%.

Md. RiyadTanshenet. al [27] have analyzed the effect of multi-walled carbon nanotube based aqueous nanofluid (0.05 wt. %, 0.1 wt. %, 0.2 wt. % and 0.3 wt. %) on thermal performance of multi-loop oscillating heat pipe at 60 % filling ratio. They concluded that the 0.2 wt.% MWCNTs based aqueous nanofluids obtain low thermal resistance at any evaporator power input. Gunnasegaran, P. et. al. [28] have experimentally inspected the performance of loop heat pipe using SiO_2-H_2O based nanofluid for heat input range from 20 W to 100 W.They reported that the average decrease of 28%–44% in thermal resistance at heat input ranging from 20 W to 100 Wof loop heat pipe using SiO_2–H_2O nanofluid as compared with pure water.

Asirvatham, L. G. [29] have experimentally investigated the improvement in heat transfer characteristics of heat pipe using water based silver (58.35 nm size and 0.003 % to 0.009 %volume concentration) nanofluid for heat input ranging from 20 W to 100 W. They have reported that the thermalresistance of heat pipe decreases with the use of silver–waternanofluid, which in turn increases the effective thermal conductivityby 42.4%, 56.8% and 73.5% respectively for 0.003, 0.006 and 0.009 vol.% concentrations. Madhusree Kole and T. K. Dey [30] have investigated the thermal performance of screen mesh wick heat pipe using stable and surfactant free copper nanoparticles mixed with water at different inclination angle of heat pipe.They concluded that averagewall temperature of the evaporatorreduces by 14^{O} C when water is replaced by 0.5 wt.% Cunanofluid at an input power of 100Wfor heat pipe inclined at90^{O} andthe thermal resistance of the vertically mounted heat pipe with0.5 wt.% of Cudistilled water nanofluid as working fluid is reducedby 27%.

Yi-HsuanHung et. al. [31] have analyzed the thermal performance of heat pipe filled with Al_2O_3 nanofluid at different parameters such as filling ratio (20%, 40%, 60%, and 80%), inclination angle (10, 40, 70, and 90), heat pipe length, heat input power (20W, 30W and 40W) and weight concentration. Their experimental results showed that at a heating power of 40 W, the optimal thermal performance forAl_2O_3/water nanofluid heat pipes measuring 0.3 m, 0.45 m, and 0.6 m was 22.7%, 56.3%, and 35.1%,respectively, better than that of pipes using distilled water as the working fluid. Saleh, R. et. al. [32] have prepared the ZnO nanoparticles and evaluated the thermal performance of screen mesh wick heat pipe using EG based ZnOnanofluid at different operating parameters such as different concentration (0.025 to 0.5 vol.%), size of nanoparticles (18 or 23 nm) and different heat input. They concluded that presence of nanoparticles in theworking fluid led to a reduction of the heat pipe wall temperature and thermal resistance. Mostafa Keshavarz Moraveji and Sina Razvarz [33] have investigated the effect of using aluminum oxide nanofluid (pure water mixed with Al_2O_3 nanoparticlewith 35 nm diameter) on the thermal efficiency enhancement of a wick sintered heat pipe on the different operatingstates. They concluded that when more Al_2O_3 nanoparticles were dispersed in the working fluid, the performance of heat pipe enhances.

Roger R. Riehl and Nadjara dos Santos [34] have tested an experimental open loop pulsating heat pipe with water-copper nanofluid, with an addition of 5% by mass of copper nanoparticles. They observed improvements on the overall device's operation when using the nanofluid with lower temperatures.Ping-Yang Wanget. al. [35] have analyzed the thermal performance of inclined miniature mesh heat pipe using water based CuO nanofluid (1% mass concentration) at different operating conditions.Their resultsshow that the inclination angle has a strong effect on the heat transfer performance of heat pipes usingboth water and the nanofluid and at the inclination angle of 45◦ best thermal performancefor heat pipes is obtained using both water and the nanofluid. Putra, N. et. al. [36] have experimentally investigated the effect of different nanofluids (Al_2O_3–water, Al_2O_3–ethylene glycol, TiO_2–water,

TiO_2–ethylene glycol and ZnO–ethylene glycol) and nanofluid concentration (1% to 5%) on thermal performance of screen mesh wick horizontal cylindrical heat pipe.They found that the screen mesh wick heat pipe shows the best performance when Al_2O_3–water nanofluid with 5% volume concentration is used.

Hajian, R. et. al. [37] have experimentally analyzed the thermal performance of medium sized cylindrical meshed heat pipe using water based silver nanofluid at various concentrations of 50, 200 and 600 ppm and heat inputs in the range of 300-500 W. They concluded that by applying 50 ppm nanofluid,the thermal resistance and the response time of the heat pipedecreases by 30% and about 20%, respectively, compared toDI-water. Alizad, K. et. al. [38] have studied the thermal performance of flat shaped heat pipes and disk shaped heat pipes using CuO, Al_2O_3 and TiO_3 nanofluid. They have reported enhancement in the heat pipe performance whileachieving a reduction in the thermal resistance for both flat-plate and disk-shaped heat pipes while using nanofluids and they have shown that a higher concentration of nanoparticles increases the thermalperformance of either the flat-plate or disk-shaped heat pipes.

Senthilkumar, R. et. al. [39] have investigated the enhancement of thermal performance of cylindrical heat pipe using copper nanofluid (100 mg/lit) as working fluid at various inclination angle. They concluded that thenanofluids have a great potential for heat transfer which makes them suitable foruse in many applications than the conventional cooling mediums.JianQu and Huiying Wu [41] have compared the thermal performance of two same oscillating heat pipes charged with SiO_2/water (0–0.6 wt.% and 50 % filling ratio) and Al_2O_3/water (0–1.2 wt.% and 50% filling ratio)nanofluids, respectivelyexperimentally.They concluded that within the experimental range, using the alumina nanofluid instead of pure water enhances the heat transfer of the oscillating heat pipe (reduces the evaporator wall temperature and thermal resistance of the oscillating heat pipe), while using the silica nanofluid instead of pure water deteriorated the thermal performance of the oscillating heat pipe.

YulongJiet. al. [42] have analyzed the thermal performance of oscillating heat pipe using Al_2O_3 nanofluid withaverage diameters of 50 nm, 80 nm, 2.2 μm, and 20 μm. They reported that when the oscillating heat pipe was charged with water and 80 nm Al_2O_3 particles, the oscillating heat pipe achieves the best heat transfer performance among four particles investigated. Mousa, M. G. [43] has experimentally evaluated the thermal performance of circular heat pipe using pure water and water based Al_2O_3 nanofluid. They concluded that thermal resistance decreases withincreasing Al_2O_3-water based nanofluid compared to that of pure water. Huminic, G. et. al. [44] havestudied the behavior of thermosyphon heat pipe when using iron oxide nanofluid (0%, 2%, and 5.3% concentration) as working medium. Their results show that the addition of 5.3% (by volume) of iron oxide nanoparticles in water improves thermal performance of thermosyphon heat pipe compared with the operation with DI-water.

Zhen Hua Liu and QunZhi Zhu [45] have investigated the thermal performance of horizontal mesh heat pipe using deionized water and CuO nanoparticles with an average diameter of 50 nm as working fluid experimentally. They observed that the maximum heat flux increases with theincrease of the mass concentration when the mass concentrationis less than 1.0 wt.% and after then begin to decrease slowly. Kyu Hyung Doet. al. [46] have evaluated the thermal performance of circular screen mesh wick heat pipe using water-based Al_2O_3 nanofluids with thevolume fraction of 1.0 and 3.0 Vol.%. They concluded that the thermal resistance of theheat pipe using the water-based Al_2O_3 nanofluids with the volume fraction of 3.0 vol.%reduces by about 40% at the evaporator-adiabatic section and the water-based Al_2O_3 nanofluids as the working fluid instead of DI water can enhance themaximum heat transport rate of the heat pipe.

N. Bhuwakietkumjohn and S. Rittidech [48] have studied the internal flow patterns and heat transfer characteristics of a closed loop oscillating heat pipe with check valves using ethanol and a silver nano-ethanol mixture as working fluid at a filling ratio of 50 % volume of tube. They reported that the silver nano-ethanol mixture gives higher heat flux than ethanol. Guo-Shan Wanget. al. [49] have examined the performance of cylindrical miniaturegrooved heat pipe using aqueous CuOnanofluid as the working fluid. They experimentally showed that substituting the nanofluid for water as the workingfluid can apparently improve the thermal performance of the heat pipe for steady operation and the totalheat resistance and the maximum heat removal capacity of the heat pipe using nanofluids can maximallyreduce by 50% and increase by 40% compared with that of the heat pipe using water, respectively.

Zhen-Hua Liu et. al. [50] have examined the thermal performance of inclined miniature grooved heat pipe using water base CuOnanofluid as working fluid. Their experimental results showed that the inclination anglehas a strong effect on the heat transfer performance of heat pipes.Tun-Ping Teng et. al. [51] have experimentally evaluated the thermal performance of straight copper heat pipe using water based Al_2O_3 nanofluidwith three different concentrations (0.5, 1.0 and 3.0 wt.%).Their experimental results shows that the optimum condition of heat pipe is when nanoparticles being at 1.0 wt.% and at this condition, the thermal efficiency is 16.8%, which is higher than that of heatpipe charged with distilled water. Kyu Hyung Do and Seok Pil Jang [52] have analyzed the thermal performance of flat micro heat pipe with a rectangular grooved wick using water based Al_2O_3 nanofluid. They concluded that the thermal resistanceof the nanofluid heat pipe tends to decrease with increase inthe nanoparticle size.

JianQu, Hui-ying Wu and Ping Cheng [54] have investigated the thermal performance of an oscillating heat pipe using base water and spherical Al_2O_3 particles of 56 nm in diameter at different mass fraction and filling ratio. They found that the maximal thermal resistance decreases by 0.14 °C/W (or 32.5%) when the power input is 58.8 W at 70% filling ratio and 0.9% mass fraction compared to water.Shafahi, M. et. al. [55] have investigated the effect of Al_2O_3, CuO, and TiO_2nanofluid on thermal performance of cylindrical heat pipe at different concentration and nanoparticle size experimentally. They concluded that the thermalresistance decreases as the concentration increases or as the nanoparticlediameter decreases. Shung-Wen Kang et. al. [56] have investigated the thermal performance of wick type sintered circular heat pipe with water based silver nanoparticles (10 and 35 nm and 1, 10 and 100 mg/l) as working fluid. They reported the increase in thermal performance of heat pipe with silver nanofluid as compared to the heat pipe with water as working medium.

Naphon, P. et. al. [57] have investigated the thermal characteristics of straight tube copper heat pipe using titanium nanoparticles of 21 nm diameter mixed with refrigerant, R11 at different filling ratio, and inclination angle. They reported that for the used pure refrigerants working fluid, the heat pipe at the tilt angle of 60^{O}, working fluid charge amount of 50% gives thehighest efficiency and at that optimum condition for the pure refrigerant, the heat pipe with 0.1% nanoparticlesconcentration gives efficiency 1.40 times higher than that with pure refrigerant. Naphon, P. et. al. [58] have analyzed the effect of three working mediums i.e. de-ionic water,alcohol, and nanofluids (alcohol and titanium nanoparticles with 21 nm diameter) on the performance of straight copper cylindrical heat pipe at different filling ratio, inclination angle and volume concentration. They concluded that for the heat pipe with 0.10%nanoparticles volume concentration, the thermal efficiency is 10.60%higher than that with the based working fluid.

Yu-Hsing Linet. al. have experimentally investigated the thermal performance of copper pulsating heat pipe using 20 nm silver nanofluid at different concentration (100 ppm and 450 ppm) and various filled ratio (20%, 40%, 60%, 80% respectively), also applying with different heating power (5 W, 15 W, 25 W, 35 W, 45 W, 55 W, 65 W, 75 W, 85 W respectively). They concluded that the midterm value (i.e. 40%, 60%) of filled ratio shows better and at 60% of filled ratio, heat dissipation result is better than 40%, and the best filled fluid is 100 ppm in silver nano-fluid. They also found that when the heating power is 85 W, the average temperature difference and the thermal resistance of evaporator and condenser are decreases by 7.79 °C and 0.092 °C/W, respectively. Shung-Wen Kang et. al. [60] have analyzed the effect of aqueous solution of 35 nm size silver nanoparticles (1 mg/l to 100 mg/l) on the performance of deep grooved circular heat pipe. They concluded that at a same filling ratio, the measured nano-fluid filled heat pipe temperature distribution demonstrated that the thermal resistance decreases 10–80% compared to DI-water at an input power of 30–60 W and the thermal resistances ofthe heat pipe decreases as the silver nano-particle size and concentration increase. Tsai, C. Y. et. al. [61] have experimentally investigated the performance of circular heat pipe using aqueous solution of various sized gold nanoparticles.They found that thermalresistance of the heat pipes with nanoparticle solution islower than that with DI water.

Five literatures [9, 24, 40, 47 and 53] are available in open literature related to the review of application of various types of nanofluid in enhancement of performance of various types of heat pipes. Sarkar, J. et. al. [9] have reviewed the recent researches in the field of hybrid nanofluids and their applications. Matthias H. Buschmann[24] has overviewed the application of nanofluids in thermosyphons and heat pipes. Zhen-Hua Liu and Yuan-Yang Li [40] have carried out review in the field of nanofluid application heat pipes. Alawi, O. A. et. al. [47] have presented a review on effect of fluid flow and heat transfer characteristics of nanofluid in heat pipes. Sureshkumar, R. et. al. [53] have reviewed the heat transfer characteristics of nanofluids in heat pipes.

3. CONCLUSION AND SCOPE FOR FUTURE WORK

From the exhaustive literature review, it is observed that heat pipe is most developing and widely used heat transfer device for various applications such as electronics cooling, space application, medical applications etc. With the advancement in electronics devices, it is very essential to cool the component effectively and efficiently using less space. Therefore there seems to be essential to increase the performance of heat pipes using different alternatives. Application of various nanofluids in enhancement of performance of heat pipe is the relative recent and one of the alternative available for this. Yet it requires extensive experimentations on various types of heat pipes along with various types of nanofluids.

The present review of literatures available in open literature identifies the present status of investigation and future requirement of the investigations in the field of heat pipes with nanofluid as working medium. Gaps in the Table 1 need to be fulfilled by carrying out researches using those nanofluids in particular heat pipes.

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