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A Review of Nanofluid Enhanced Heat Pipes: Performance Improvement, Influencing Parameters and Operating Characteristics

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Abstract
Heat pipes are lightweight heat exchanger devices known for their high cooling capacity and fast response.Using nanofluids,the nanoparticular fluid suspension of material,their performance can be increased tremendously.The performance of the heat pipes are increased due to the distinctive features of nanofluids making it a fascinating topic for researchers although the amount of work done is lesser than expected due to complications in fabrication of such devices.This paper reviews significant and credible recent works in the field of nanofluid application in heat pipes including the experimental performance enhancement results, operation characteristics data collected over time and performance variation trends obtained over the years by many works.At the end future scopes of research in this field are identified.

Keypoints
Nanofluid— HP — Surface Characteristics —Impact Parameters—Wick

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Contents

Introduction

Heat pipes are devices that cool objects, mostly hot electronic components that require fast cooling,by transferring the heat by convective process which can be both single or multiphase.Pulsating Heat Pipes(PHP) and wicked Heat Pipes (wHP) are two of the most commonly used variants of heat pipe.These devices are essential to get the most out of electronic devices as the performance of electronic components decline with increment of heat density.Development of a high performance heat pipe will enhance computational ability by manyfold.

Nanofluids are colloidal suspension of nanoscale particulates or structures(nanotubes,nanosheets or nanofibers) in a base fluid.Due to the presence of condensed nanomaterials,thermophysical properties of the base fluid such as convective heat transfer coefficient,diffusivity, specific heat and thermal conductivity increase significantly.This enhanced characteristics makes them an ideal choice as working fluid for many heat transfer equipment including heat pipe.

Using nanofluids as working fluid in heat pipes ,independent of the operation type, increment in the performance beyond the capability of ordinary fluid can be achieved.This helps us transcend the limitations on heat pipe performance due to physical properties.

Multiphase application of nanofluids creates some problematic issues regarding stability of the nanofluid.This paper discusses some of the recent advancements regarding stability of nanofluids under phase change processes.Also if the nanofluid consists of ferrous material,it can act as a ferrofluid which in turn can enable control over their behaviour using magnetic field interaction.

In recent years the idea of using nanofluids for heat pipe performance enhancement has caught attention of many researchers due to the fact that using nanofluids can result in previously unimaginable levels of improvement of efficiency.Using nanofluids unprecedented successes are being achieved in heat pipe applications which were previously deemed impossible or nonviable. Although previously nanofluid works have been reviewed [1–7] ,their major concern was the properties of nanofluid itself.This review tries to focus on the applicative opportunities, challenges and progressions of nanofluids specifically in heat pipes.Finding crucial challenges related to the current work is another purpose of this article.

1. Regular Heat Pipes

The common setup of heat pipe consists of an array of pipes designed specifically for heat removal purposes.The pipes contain working fluid that carries heat away and in most efficient heat pipes there is a phase transition associated.The flow of the fluid is aided by the capilary action initiated by the presence of sintered wick structure,wire mesh structure or grooved structure inside the pipe.As a result no external mechanism is needed to control the flow.

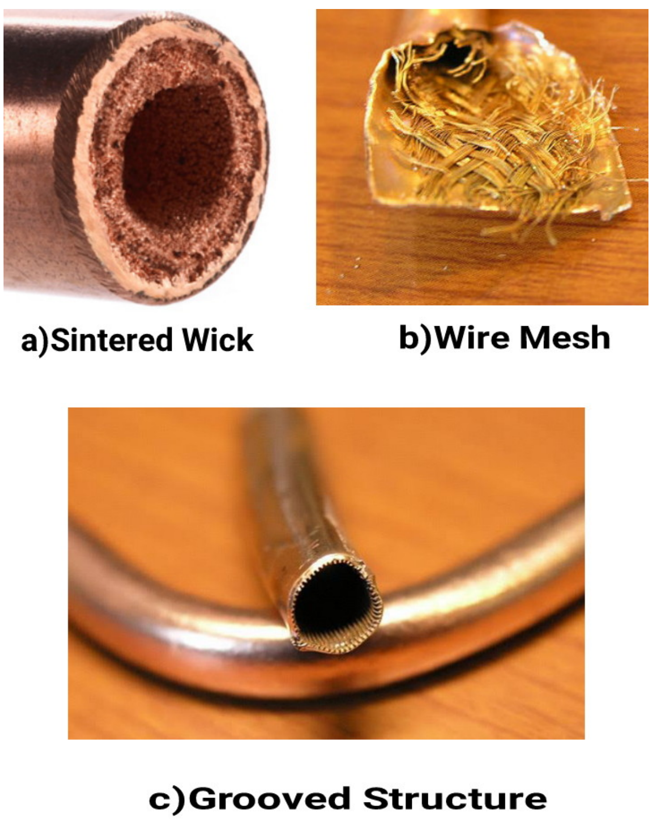


Figure 1. Common capilary structures of heat pipe

Another configuration works with pulses of fluid going in a loop in pulsating manner referred as PHPs.One advantage of this configuration is that it does not require a mesh in the inner surface which makes the fabrication easier. Experiments show that the latter one has greater effectiveness. [8]

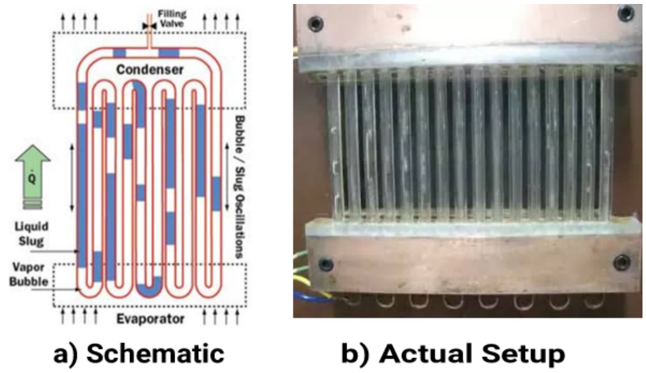


Figure 2. Pulsating Heat Pipes (PHPs)

Both types of heat pipes transfer heat by conducting heat from the pipe wall to the working fluid and removing that by phase change process.Eventually the vaporised working fluid reaches a low temperature end called the condenser and cools down to liquid.The cycle then repeats in a high frequency.The heat in the condenser region is removed afterwards by fins which are air cooled by a fan.This indicates that increasing the thermal conductivity,fluidity,heat capacity and reducing phase transition time of the working fluid is essential for enhancement of heat pipe performance and greater cooling capacity.Nanofluids can provide exactly those features [9] which makes them an excellent choice for heat pipe application.

2. Heat Pipes with Nanofluid Application

Immediately after the extraordinary thermal characteristics of nanofluids were observed various innovative application were conceptualised.The application oriented to heat pipes originated relatively later mostly due to the lack of phase transition data for nanofluid.

Kang et al. [10] presents a comprehensive overview of nanofluid influence on heat pipe behaviour.

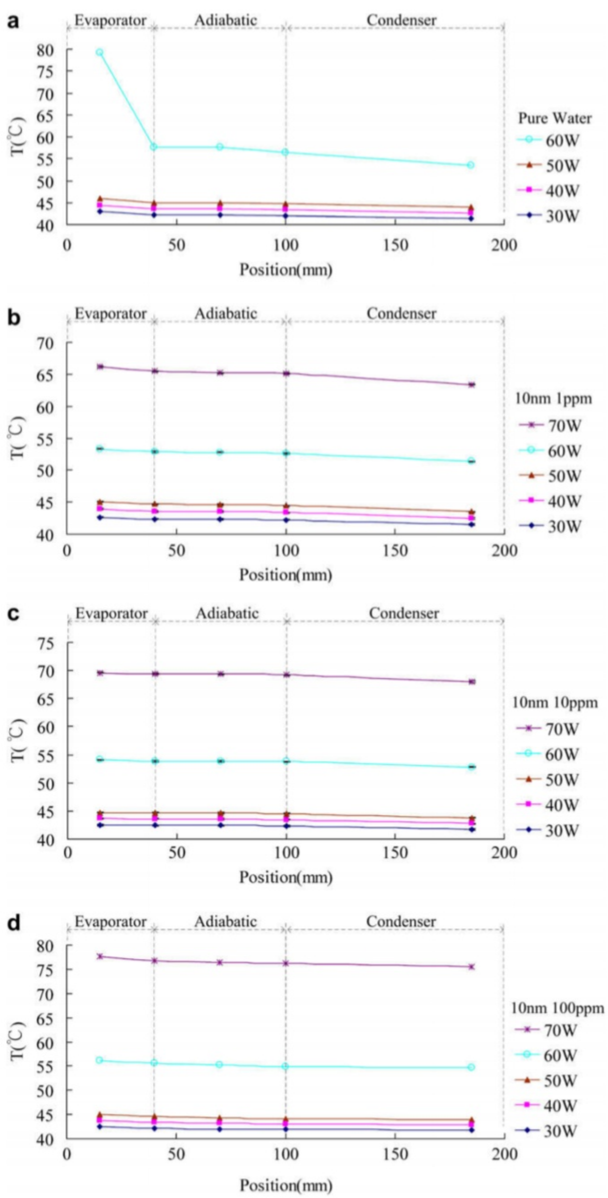


Figure 3. Thermal behaviour of nanofluid enhanced Heat Pipes at different load conditions

The results clearly show that implementation of nanofluid improves thermal performance. Although for lower loads the improvement is not significant.Nanofluids are hence suitable for high thermal load applications.

Furthermore nanofluid evens out the fluctuations in different sections of the heat pipe.This makes them excellent candidate for real life application as CPUs produce fluctuating thermal loads most of the time.

In recent times researchers have focused on such applications notably.Vast majority of them have investigated effect of different parameters on the performance but very few of them actually analyzed the physics of the mechanism.

3. Nanofluid Stability in Heat Pipe Thermal Conditions

One of the major problems with nanofluid phase change is that due to constant agglomeration and separation while the base fluid vaporises,the nanofluid colloidal system equilibrium disrupts resulting in suspention of nanoparticles which decreases nanofluid's special features.To overcome this problem various stability methods are implemented.

3.1 Surfactant addition

Surfactants are dispersive materials consisting of a hydrophobic tail and a hydrophillic polar head which are characterized by Hydrophilic/lipophilic balance (HLB) value where lower HLB values mean higher oil solubilty.They act as binders and hence reduce excessive agglomeration and deposition.Although the process is simple and economic,it can sometimes create problems in practical scenario [11]by increasing thermal resistance by forming resistive coating, contaminating the media and also resulting in foaming upon heating.

3.2 Nanofluid Preparation Method

The basic reason for particle agglomeration is the collision between particles and the chances of cohesion as suggested by Derjaguin, Verway, Landau, and Overbeek (DVLO) theory. [12, 13] .DVLO theory suggests that the stability is determined by the sum of van der Waals attractive and electrical double layer repulsive forces that exist between particles as they approach each other due to the Brownian motion they are continuously undergoing.The stability can be assured by making collisions less frequent which is done by steric or electrostatic stabilization.

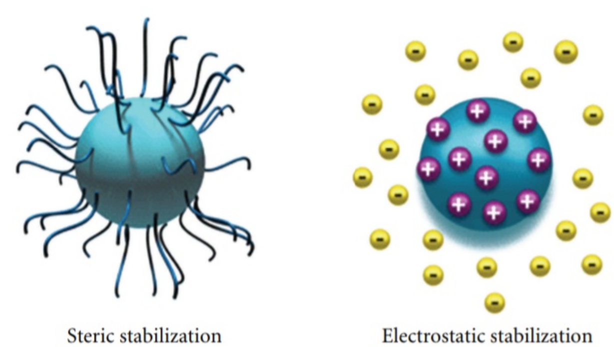


Figure 4. Types of colloidal stabilization

Both processes reduce the ζ potential of the surface to near zero values,one by introducing flagellated additives and the other by charging the particle to form a repellant layer.

3.3 Surface Modification

Use of surface modification techniques by chemical actions lead to variation in collision response as shown by Yang and Liu who worked on the synthesis of functionalized silica (SiO2) nanoparticles by grafting silanes [14] resulting in absence of deposition during a pool boiling process.

Hwang et al. introduced hydrophilic functional groups on the surface of the nanotubes by wet mechanochemical reaction [15] introducing good fluidity, low viscosity, high stability and high thermal conductivity.

Zinc oxide nanoparticles have been modified by polymethacrylic acid (PMAA) in aqueous system [16] enhancing the dispersibility while conserving the crystalline structure of the ZnO nanoparticles.

Such modification methods are being popularized due to their longevity.

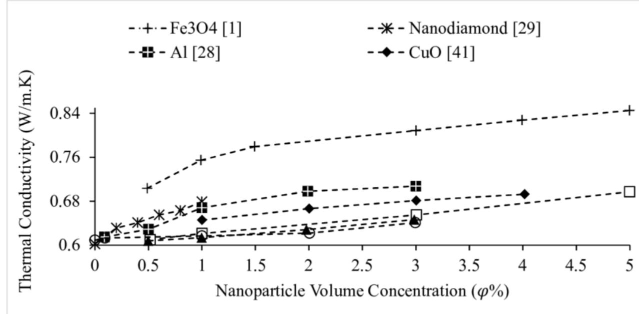


Figure 5. Thermal conductivity trends for common nanofluids

4. Parameters Influencing Performance of Heat Pipes with Nanofluid

PHPs are the most versatile and rapid type of heat pipes due to their simultaneous phase change and heat sweep action.They are suitable for nanofluid application as their is no interfering wick structure present.

Akachi [17] introduced looped PHPs to reduce highly localized heat fluxes and maintain uniformity throughout the object being cooled.

Goodarzi et al [18], Ghofrani et al [19] and Tanshen et al [20] demonstrated significant reduction in thermal resistance in the evaporator side when PHPs are used.

In the last decade numerous research works have been conducted investigating correlation between nanofluid parameters and degree of thermal performance enhancement.The current section presents a comprehensive summary of such works in a categorised manner preceded by a table of summary.

Summary of Research Results on Influencing Parameters (based on 35 papers with credible reputation)

Parameter	+ve dependency	-ve dependency	no dependency
Particle Size	30%	60%	10%
Pipe Surface Porosity	60%	20%	20%
Nanoparticle Fabrication pH	20%	30%	50%
Particle Surface Modification	70%	10%	20%
Agglomeration on Wick	10%	90%	0%

4.1 Different Types of Nanofluid on Same Heat Pipe

Different types of nanofluids behave differently as the colloidal system dynamics is completely different for them.The following discussion analyzes such behaviour specifically for heat pipes.

Simpson's [21] work investigated the thermal performance of different commonly used nanofluids based on water.

The work showed highest performance for ferrofluids and most stable performance for Cu based nanofluids.Also it was found that particle size of 50- 150 nm generally yield better results.

Goshayeshi,Safaei,Goodarzi and Dahari [22] have worked on the influence of ferrous nanofluid (Fe_2O_3/kerosene) in PHP performance.The work was done with γ and α variants of Fe_2O_3 with and without considering magnetic field responses.The results conclusively showed significant reduction in thermal resistance which was unprecedented at the time.Also under magnetic field the performance increased furthermore due to directional assortment of the ferrofluid resulting in faster phase transition.

The semi empirical Nusselt number correlations obtained in Goshayeshi's work were as follows-

$$Nu = 0.20\,Pr^{0.38}Ka^{0.42}Ja^{1.55}d^{1.25} \quad \alpha\text{-}Fe_2O_3\text{, Without magnetic field}$$
$$Nu = 0.22\,Pr^{0.38}Ka^{0.45}Ja^{1.60}d^{1.30} \quad \alpha\text{-}Fe_2O_3\text{, Under magnetic field}$$
$$Nu = 0.35\,Pr^{0.38}Ka^{0.42}Ja^{1.55}d^{1.25} \quad \gamma\text{-}Fe_2O_3\text{, Without magnetic field}$$
$$Nu = 0.37\,Pr^{0.38}Ka^{0.45}Ja^{1.60}d^{1.30} \quad \gamma\text{-}Fe_2O_3\text{, Under magnetic field}$$

The correlations clearly show increased heat transfer as the coefficients are way higher for ferrofluids compared to that of regular fluids.

Mehrali [23] has investigated nanofluid PHP application with NDG/Water based nanofluids. The results show excellent performance under very high heating loads. NDG(Nitrogen Doped Graphene) provides much higher thermal conductivity compared to regular Pristine Graphene nanostructures.The work also shows incremental nature of conductivity with temperature which makes heat removal at severe and fluctuating cases much easier.

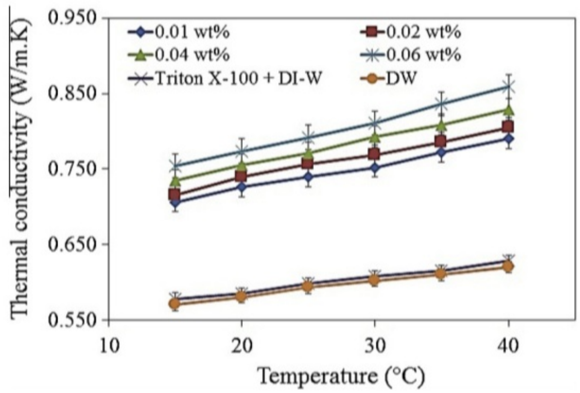


Figure 6. NDG conductivity response with temperature

Mehrali's work also shows significant decrement in viscosity with temperature for NDG/Water nanofluids which makes them excellent candidate for heat pipes with longer effective length or convoluted structure.

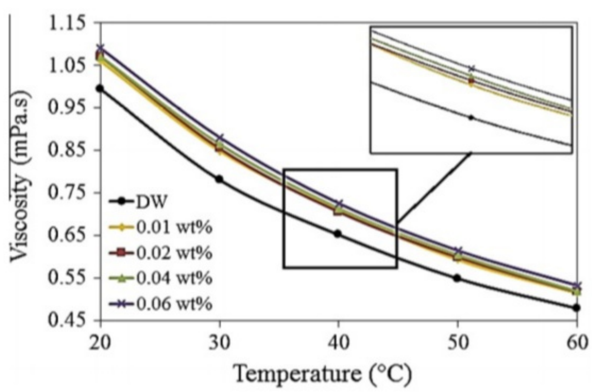


Figure 7. NDG viscosity variation with temperature

Nazari [24] worked with a similar setup with Graphene oxide/Water nanofluid reporting 42% thermal resistance decrease.The work was validated both experimentally and using regression model simulations.

Although numerous nanofluid based heat pipe researches were carried out in the last decade, majority of them focused on practical performance and heat transfer characteristics based on first law efficiency.Sheikholeslami [25] investigated the fundamental thermodynamic nature of nanofluids in heat pipes including parametric relationships between thermophysical properties and nanofluid specification by using finite volume formulation.This CFD based study has provided a rich amount of information including second law efficiency and exergy loss expressions for nanofluids in a heat pipe for future works and has established a solid criteria for selection of suitable nanofluid for different heat pipes.

4.2 Effect of Heat Pipe Surface Fabrication

Depending on the type of application heat pipes are manufactured with different surface characteristics.Grooved,sintered wick,wire mesh etc are popular surface structures.

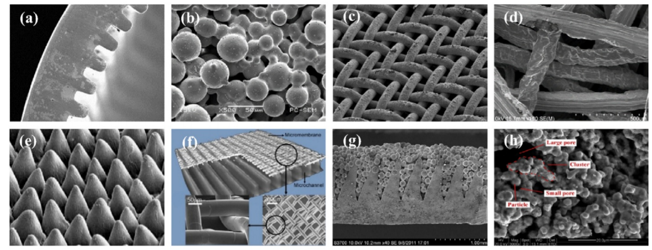


Figure 8. Wick structures of heat pipes:(a)micro grooves,(b)sintered powders,(c)woven mesh,(d)sintered fibres,(e)grooved porous structure ,(f) combined grooves with sintered mesh,(g)combined grooves with sintered powder and (h)biporous wick

Enerton group [26] R&D division have investigated the effect of this structural variation on heat transfer.

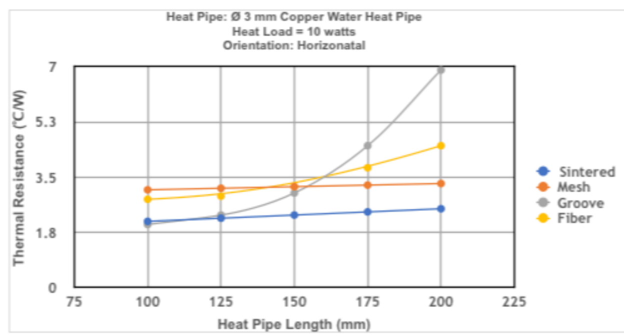


Figure 9. Effect of wick structure on thermal resistance

The variation results due to interference of flow with wick and the heat blockage fue to wick material.Data in this field for nanofluid enhanced pipes is very rare.

4.3 Heat Pipe Performance Variation Due to Particle Size

Nanofluids show enhanced thermal behaviour in heat pipes due to the presence of nanoparticles.Therefore size of the nanoparticle actively controls it's properties.

Past data on the effect of particle size on the thermal conductivity of nanofluids are limited and inconsistent.

Xie et al [27] reported an increase followed by a decrease in the thermal conductivity with increasing particle size for alumina nanofluids in ethylene glycol and pump oil containing five different sizes of alumina particles (12–302 nm).

Other studies have reported monotonic increment in the thermal conductivity with decreasing particle size, attributed to Brownian motion [28, 29] or decrement due to interfacial thermal resistance [30–32].

The thermal conductivity enhancement in two of the most common base fluids, water and ethylene glycol dispersed with alumina particles of 8 to 282 nm size [31] was reported to decrease as the particle size decreased below about 50 nm, which the authors attributed to phonon scattering at the solid–liquid interface.

Timofeeva [33] worked on size effect on same type of nanofluid(SiC-Water) with different particle sizes.

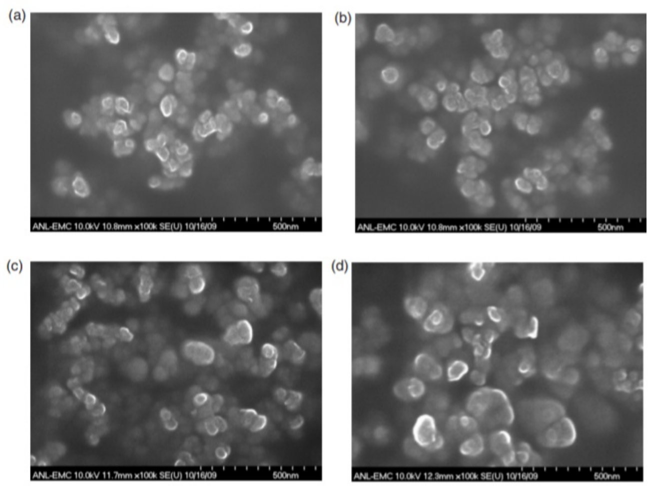


Figure 10. TEM images of size variation in SiC-water nanofluid samples

The results showed decrement of viscosity with larger particle sizes attributed to interface interaction by the authors.

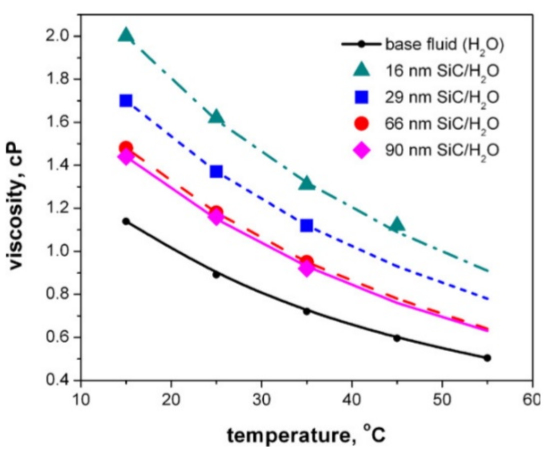


Figure 11. Viscosity variation with size of nanoparticles

The work could not conclusively find a general trend for thermal conductivity but observed increasing trend for their samples.

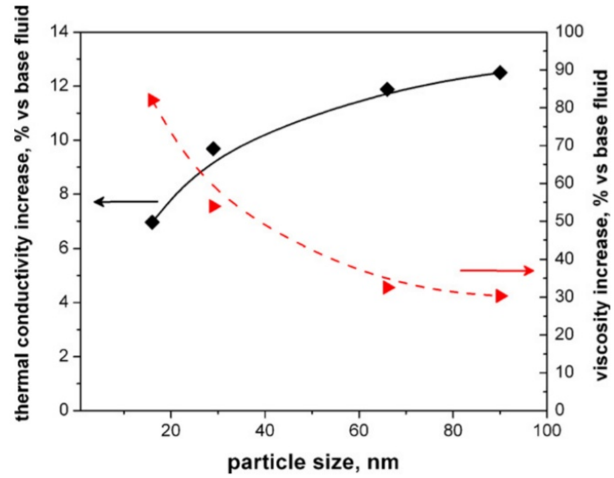
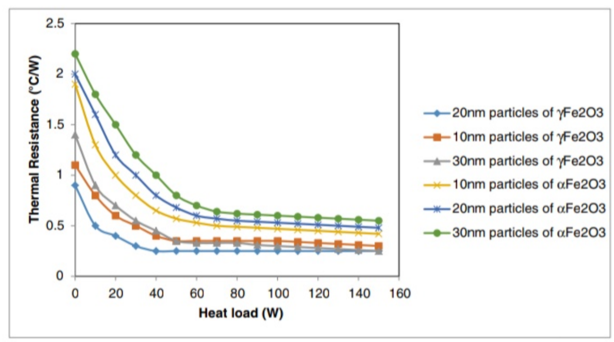
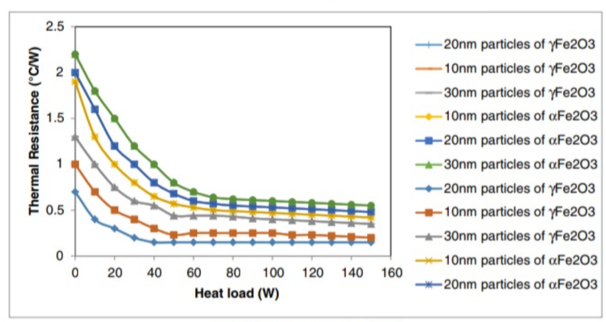


Figure 12. Variation of thermal conductivity with size change

Goshayeshi [22] has worked with similar objectives with the exception being the use of ferrofluid as the sample.The results showed generally increasing trends.



(a) Without magnetic field.



(b) Under magnetic field.

Figure 13. Variation of thermal resistance with particle size

Size effects are being studied extensively for different nanofluids to gather individual data as no general trend is found yet.

4.4 Effect of Nanofluid Fabrication Method

Physiochemical conditions at which a nanofluid us prepared affects it's performance.

Tsai [34] worked on the variation in properties due to different chemical mediums used as nanofluid fabrication stock.

Volumes of materials used in different synthesis conditions

Condition	Na_3 citrate (ml)	Tannic acid (ml)	$HAuCl_4$ (ml)
A	0.2	2.5	3
B	0.2	5	6
C	3	0.1	1
E	3	2.5	6
G	3	0.1	3

This resulted into difference in configuration of the structural groups formed in the nanofluids inside the heat pipe.

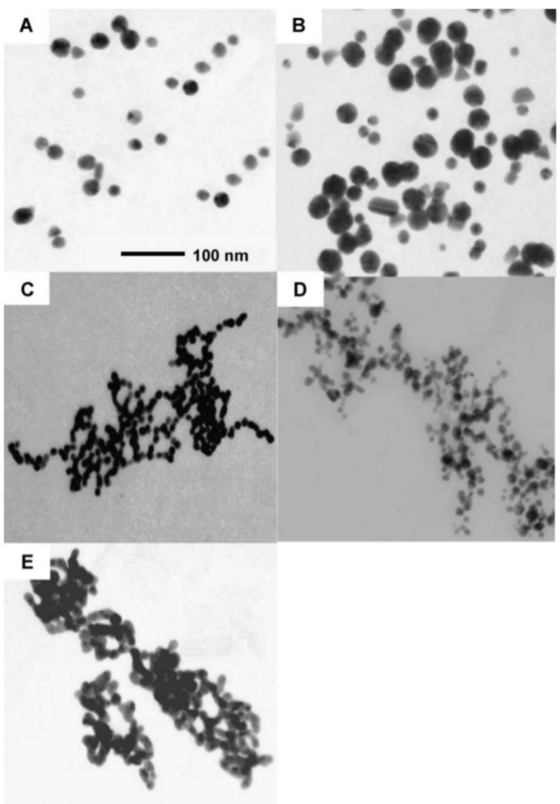


Figure 14. SEM images of configuration variation due to fabrication medium difference

His study shows that this configuration change affects the thermal resistance of the fluid severely creating significant variation in heat flux on the pipe.

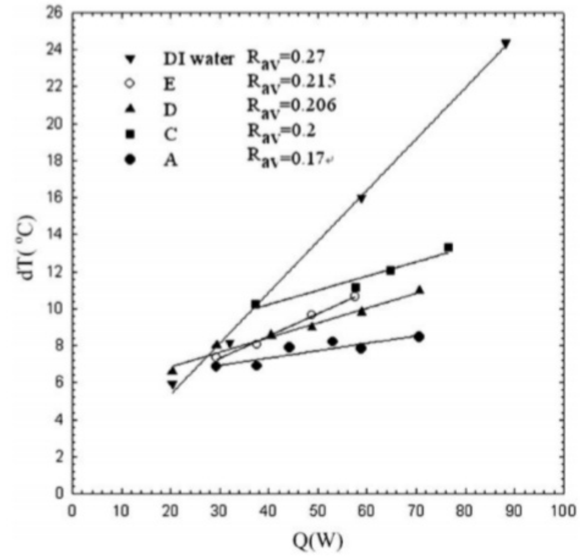


Figure 15. Variation in resistance due to fabrication medium distinction

Tsai's work conclusively showed that thermal resistance of nanofluids is a controllable parameter.

Another research was done by Timofeeva [33] which showed the pH dependency of nanofluid viscosity and zeta potential.

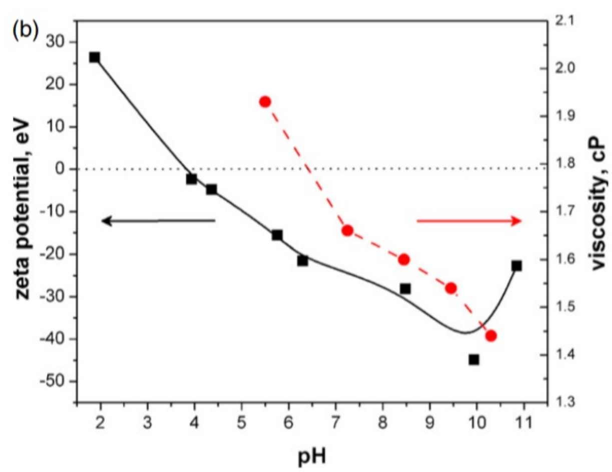


Figure 16. Nanofluid property response to pH variation

These ideas are helpful in engineering the nanofluid based on need which enables the possibility to design high performance heat pipes.

4.5 Long Term Performance of Heat Pipe

Nanoparticles are solid particulates which never quite dissolve in the base fluid.Rather they are dispersed throughout the fluid and form a colloidal system.The problem is as this system is subjected to heat,the particles start to agglomerate and deposit rather than remaining dispersed.This makes it difficult to use them for a long time period and eventually the heat pipe ceases to work.Different researchers have tried to figure out trends of this behaviour with time and the optimum temperature ranges in which they show highest lifetime.This data is crucial for long term application of the nanofluids especially in heat pipes as they work in a steady range for a large number of cycles.

Hordy [35] showed that different base fluids with same nanoparticle(CNT) have different agglomeration trend.Propylene glycol and ethylene glycol maintain almost constant concentration for a long period of time.Water has a decreasing trend but the behaviour can be improved by stabilization techniques discussed in the previous section.

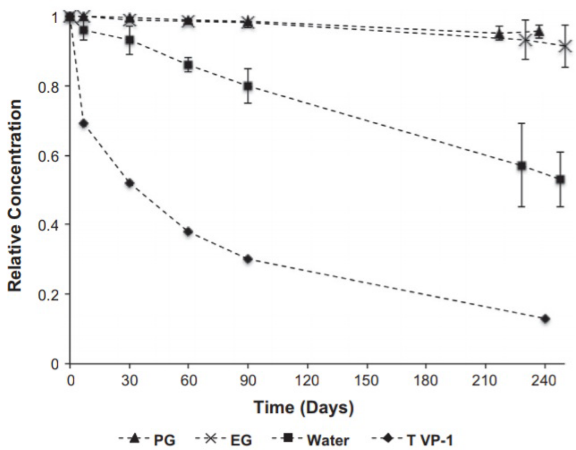
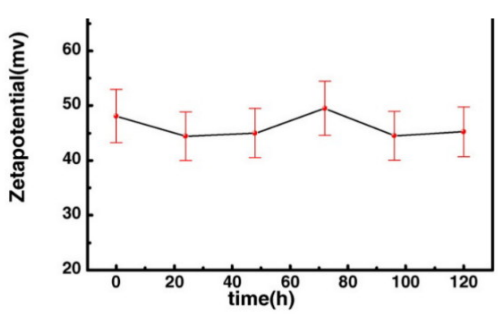


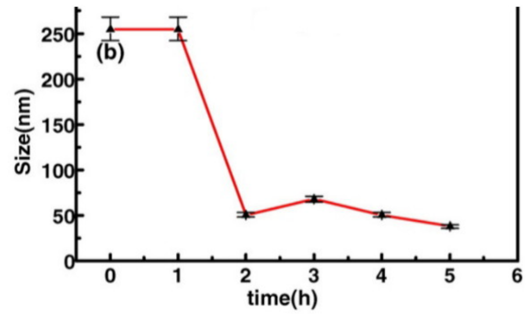
Figure 17. Concentration variation with time for nanofluids with same nanoparticles and different base fluids

Although water doesn't maintain a fairly constant concentration for long time,due to it's availability and large working range of temperatures compared to PG and EG it is the most used base fluid.

Anushree [36] worked with different nanoparticles in the same basefluid(water) and found trends of zeta potential and particle size variation with time using spectroscopic absorbance analysis.



a) Variation of zeta potential



b) Particle size variation

Figure 18. Transient characteristics of nanofluids with same basefluid but different nanoparticles

Her work also provides a comparative data between long term behaviour of all three nanofluids used which shows γ variants of nanoparticle crystals are the most stable.

S.·no	Properties	Time dependent changes of water based nanofluids		
		γ-Al_2O_3 (stable)	α-Al_2O_3 (unstable)	TiO_2 (unstable)
1	Absorbance variation	Almost remained same	Decrease	No regular trend
2	Size	Same	Decrease	Decrease
3	Zeta potential	Same	–	Decrease
4	Microscopy	Clear	Micron sized aggregates	Micron sized aggregates
5	Visual inspection	No phase separation	Faster phase separation	Slower phase separation

Further works on long term stability involving other fluids are still underway.

5. Conclusion and Future Works

Nanofluids being one of the newest and most interesting topic have been explored throughout the last decade.Very few of them were focused on their application in compact heat exchangers such as heat pipes.But in the last five years some of the most significant works have been done regarding nanofluid application in heat pipes especially by researchers in Iran and China .

During the review process some specific lackings were spotted related to the current topic.

Major factors influencing nanofluid performance are yet to be distinguished as different researchers have reported different results.The key to this could be understanding the dispersion mechanism better.

Also behaviour of nanofluid at very high temperatures is not researched much.This data is needed for usage in severe cases.

Interaction of wick and nanofluid is not at all researched as all credible works have focused in PHP.This could be a crucial work ensuring control of nanoparticular dispersion as the nanofluid flows.

These sectors require significant work for successfully creating next generation heat pipes.This proves the potential and need of research in the current topic.

Acknowledgments

Although this paper is an original piece of intellectual work with information from about 30 papers related to the topic,the work and presentation is heavily influenced by the 2012 nanofluid review paper by Wei Yu and Huaqing Xie. [1]

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