Kerbala Journal for Engineering Science

https://kjes.uokerbala.edu.iq

Review of nanofluids-assisted the thermal performance of heat pipes

*Ali Hakim Mathry, **Fadhel N. Al-Mousawi, ***Nabeel S. Dhaidan, Ahmed A Alammar****
* Department of Mechanical Engineering, College of Engineering, University of Kerbala, Karbala, Iraq
*E-mail: alisonhakim@yahoo.com
** Department of Mechanical Engineering, College of Engineering, University of Kerbala, Karbala, Iraq.
**E-mail: fadhelnor@gmail.com
*** Department of Mechanical Engineering, College of Engineering, University of Kerbala, Karbala, Iraq.
***E-mail: nabeel.sh@uokerbala.edu.iq
****Centre for sustainable cooling, school of chemical engineering, University of Birmingham
****E-mail: a.a.g.alammar@bham.ac.uk

Received: 11 November 2023; Revised: 02 December 2023; Accepted: 24 December 2023.

Abstract

Using nanofluids as a working fluid in heat pipes can increase the ability of heat pipes to transfer thermal energy and improve thermal performance. This paper reviews a group of previous experimental and numerical research that dealt with the impact of nanofluids on the thermal characteristics of heat pipes to understand more about these fluids and their thermal conductivity and to know the difference between using them and using traditional fluids, which are characterized by limited thermal conductivity. Previous researchers have studied the effect of thermal energy input, the type of nanofluid, the size and concentration of the nanoparticles, and the materials from which these nanoparticles are made. In general, nanofluids are characterized by high thermal conductivity when compared to conventional fluids. Therefore, their use in heat pipes leads to a very significant improvement in thermal properties. All of this depends on the operating conditions, the type of nanofluid, the size, and the concentration of the nanoparticles. It was pointed out that the heat pipes attain the highest thermal performance at a certain concentration of nanofluids. In addition, a conflict between the enhancement in the effective thermal conductivity and an increase in viscosity due to the dispersion of nanoparticles should be carefully observed.

Keywords: Heat pipe, Nanofluid, Thermal resistance, Thermal Performance.

Nomenclature	
Al_2O_3	Aluminum oxide
CFD	Computational fluid dynamic
CNT	Carbon Nanotube
CuO	Copper oxide
DI	Deionized
EG	Ethylene glycol
Fe2O3	Iron (III) oxide
FHP	Flat heat pipe
GO	Graphene oxide
HP	Heat pipe
H_2O	Water
MgO	Magnesium oxide
OHP	Oscillating heat pipe
PHP	Pulsating heat pipe
THP	Thermosyphon Heat Pipe
TiO_2	Titanium dioxide
vol%	Volume percentage
wt%	Weight percentage
ZnO	Zinc oxide

1. Introduction

Heat pipes are effective thermal devices for transferring thermal energy and are included in a wide range of thermal applications due to their flexibility in operation, ease of manufacturing, and cheap price. Moreover, they do not need external power to operate, and environmentally friendly, and when they are running, no harmful gas such as carbon dioxide is emitted. Heat pipes have many advantages; they operate within convergent temperature ranges and over long distances and terms. Also, they are regarded as devices that transfer heat from one place to another. They consist of three main parts: the evaporator, the condenser, and the adiabatic section. Heat is gained in the evaporator part from the heat source and released from the condenser part to the heat sink. The adiabatic part is often completely isolated. The process of heat transfer occurs through the evaporation and condensation of the working fluid inside the heat pipe. Conventional fluids are usually used to transfer heat.

Despite the good advantages of heat pipes, they have limitations, which are **[1]**:

1. Sonic limit: The performance of the heat pipes is limited by sonic velocity. Compressibility effects must be considered when calculating the vapour pressure decrease at velocities close to sonic.
2. Viscous limit: Since the condenser pressure cannot be lower than zero, the fluid's lower vapour pressure at low temperatures makes it impossible for the vapour pressure differential to overcome gravitational and viscous forces.
3. Boiling limit: When the radial heat flow in the evaporator reaches a critical value, vapour covers the evaporator surface, and the temperature difference becomes excessive. Until then, the temperature difference is very minor.
4. Capillary limit: The maximum capillary pumping pressure, $\Delta P_{c\,max}$, must be higher than the pipe's overall pressure drops for the heat pipe to function.
5. Entrainment limit: The vapour will provide shear stress to the liquid in the wick at the contact where it meets the wick surface. Shear force entrains liquid droplets and moves them to the condenser end; its strength depends on the vapour's characteristics and velocity.

Given the importance of the working fluid in the heat transfer process, the researchers were keen to investigate a multitude of fluids to obtain high thermal performance for heat pipes. Because thermal conductivity is considered the most significant factor for improving heat transfer to working fluids, researchers have added solid nanoparticles to the base fluid to increase thermal conductivity. Nanofluids attain great importance in heat pipes due to their high ability to transfer heat compared to conventional fluids. Many researchers have presented studies on the behaviour of heat pipes that depend on nanofluids as working fluids. Nanoscience has made it possible to produce multiple types of nanoparticles in different sizes, shapes, and materials. The particles with sizes less than a nanometer have a high potential to enhance base fluid heat transfer. In general, it was found that adding nanoparticles significantly increase the ability of the base fluid to transfer thermal energy **[2-4]**. It must be pointed out the risks of dealing with nanoparticles (nanospheres, carbon nanotubes, etc.), given their smallest size, which can be very easily penetrated through the skin and lungs of humans without knowing their impact on human health. So, nanotechnology workers must take all kinds of precautions to avoid inhaling all kinds of nanomaterials or their contact with human skin.

2. Heat pipes and nanofluids

Tsai et al. **[5]** presented an experimental investigation to evaluate the thermal performance of mesh wick heat pipe with an aqueous solution of various-sized gold nanoparticles as a working fluid. The range of nanoparticle size is 2–35 nm. The test heat pipe made from a copper tube measured 6 mm in inner diameter and 170 mm in length, respectively. There was a 200-mesh screen all across the inside wall. It was realized that using nanoparticles resulted in a 20%–37% reduction in the heat pipe's overall thermal resistance. The heat pipe's total resistance for different particle sizes of nanofluids is displayed in Fig1..

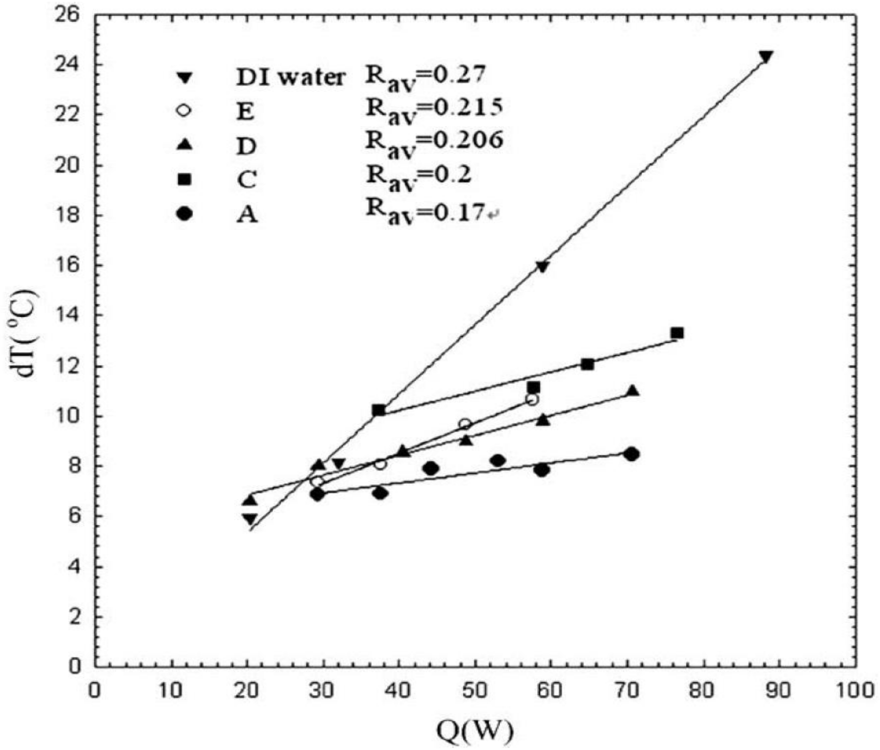

Figure 1. Measured thermal resistance with different particle size nanofluids **[5].**

Wei et al. **[6]** experimentally studied the effect of nanofluid concentration on the thermal performance of grooved heat pipe using a working fluid consisting of pure water and silver nanoparticles with particle sizes of 10 nm and five concentrations of nanoparticles (1, 5, 10, 50, and 100) mg/l. The dimensions of the heat pipe were 200 mm in length and an outer diameter of 60 mm. The filling volume of the working fluid is 51 ml, and the input power is 30, 40, 50, and 60 W. According to the findings, when compared to a heat pipe that uses water, the heat pipe that uses nanofluids may have a total heat resistance of 28% – 44% lower, and the thermal resistance decreases as the concentration of nanoparticles increases, as shown in Fig.2.

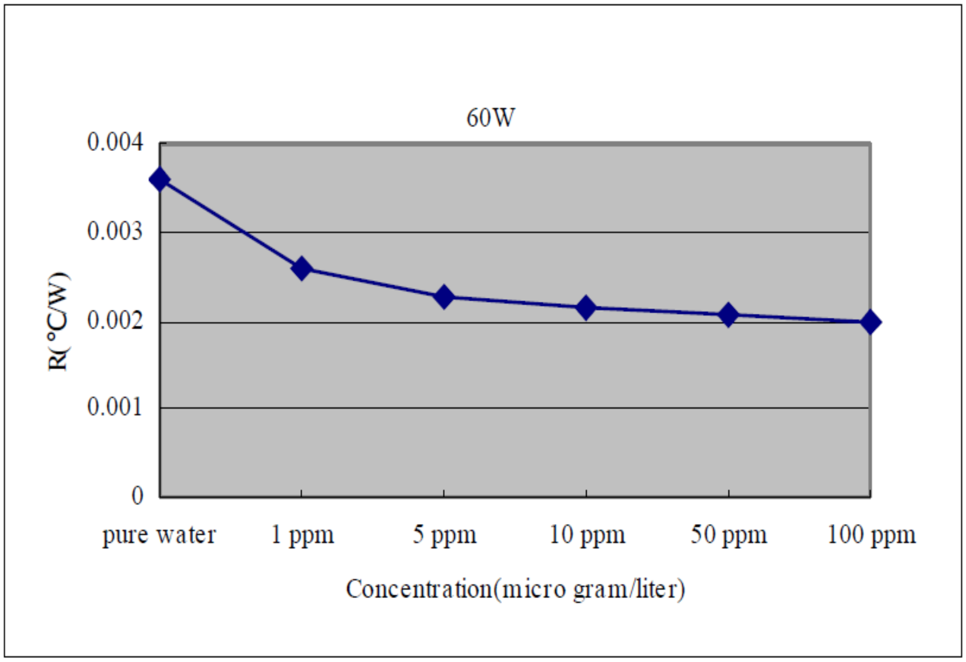

Figure 2. Thermal resistance measurements of heat pipes using pure water and nanofluid produced at varying concentrations **[6].**

Chen et al. **[7]** experimentally explored the thermal resistance of flat heat pipe (FHP) utilizing the nanofluid as a working fluid. The base working fluid was pure water, the nanoparticles were silver with a size of 35 nm, and three concentrations of silver particles were (5, 50, and 100) mg/l. The length and thickness of FHP were 200 mm and 3 mm, respectively. They also used the three values of heat inputs, 20, 30, and 40 W, in their experiment. The results pointed out that the thermal resistance of FHP is lower when using nanofluid compared to heat pipes that use raw water, as shown in Fig.3. In addition, using a high-volume concentration of nanoparticles led to a reduction in heat resistance.

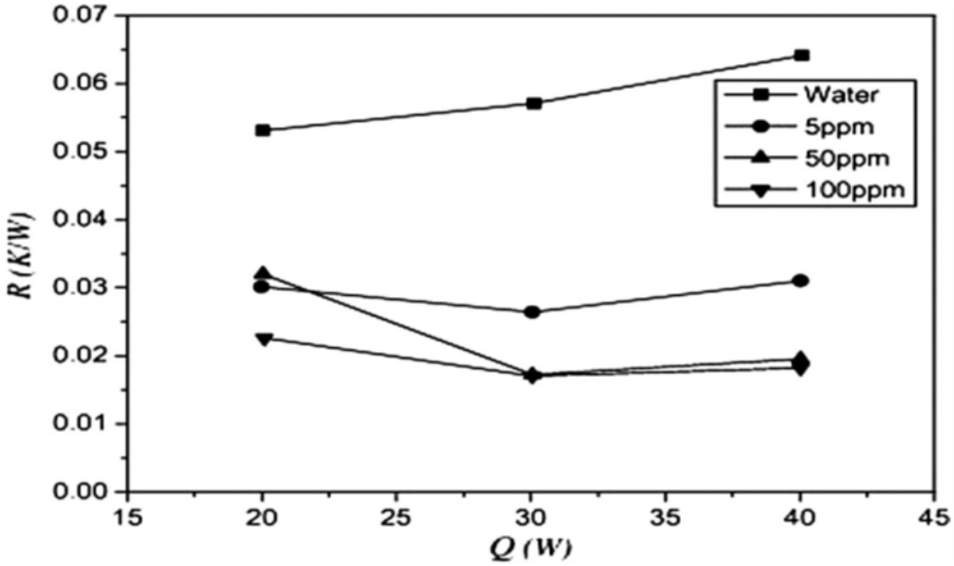

Figure 3. Particle concentration effect on FHP heat resistance at different input powers **[7].**

Lin et al. **[8]** experimentally studied the effect of using water-silver as a working fluid on the thermal performance of a closed-loop oscillating heat pipe as shown in Fig.4. The concentrations of silver nanoparticles were between 100 ppm and 450 ppm, with a size of 20 nm. Operating conditions were heating input (5, 15, 25, 35, 45, 55, 65, 75, and 85 W) and filling ratios (20, 40, 60, and 80%). According to the results, 60% is the ideal fill ratio, while 100 ppm of silver nanofluid is the ideal filled fluid. In comparison to pure water, the thermal resistance is less than 0.092 °C/W at a heat input of 85 W. They also concluded that the nanofluid dissipates more heat due to its increased heat-conduction coefficient, but to a certain extent of particle concentration, as the nanoparticle concentration increases, the viscosity increases, which in turn negatively affects the formation of bubbles.

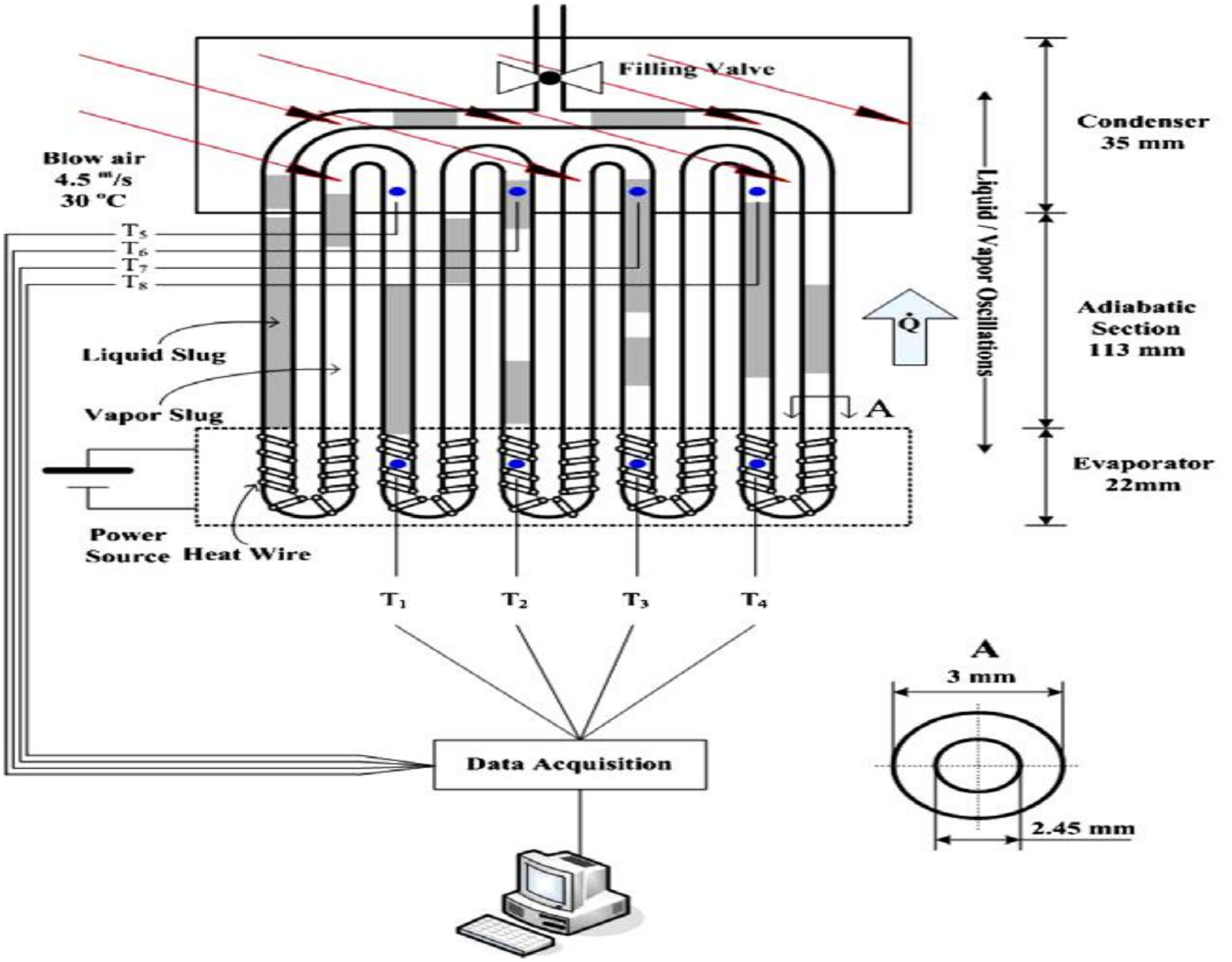

Figure 4. Schematic of the experimental setup **[8].**

The influence of fill ratios, mass fractions of spherical Al2O3 particles, and heat input on the thermal performance of the oscillating heat pipe (OHP) was experimentally tested by Qu et al. **[9]**. The working fluids are alumina nanofluids with a diameter of 56 nm and five distinct mass fractions: 1.2%, 0.1%, 0.3%, 0.6%, and 0.9%. The OHP has a 2 mm inner and 3 mm outer diameter. It was three meters long overall and featured six turns. Three filling ratios utilize 50%, 60%, and 70%, and the heat input range is between 20 and 140 W. It was found that when the power input was 58.8 W, the maximum drop in thermal resistance was 0.14 °C/W (or 32.5%) compared to pure water. This happened at a 70% filling ratio and a 0.9% mass fraction.

Senthilkumar et al. **[10]** explained how the copper nanofluid impacts the heat pipe effectiveness. The purpose of this research was to get a better understanding of how a heat pipe that makes use of copper nanofluid as its working fluid would be able to attain a higher thermal rise. A mixture of de-ionized water was subjected to ultrasonic homogenization so that copper nanoparticles dispersed throughout the fluid with a concentration of 100 mg/l and an average size of particles of 40 nm. According to the findings of several experiments, nanoparticles have a high capacity for heat transmission, which makes them superior to more traditional forms of cooling medium in different contexts. Fig.5 shows the variation in thermal resistance results with different working fluids.

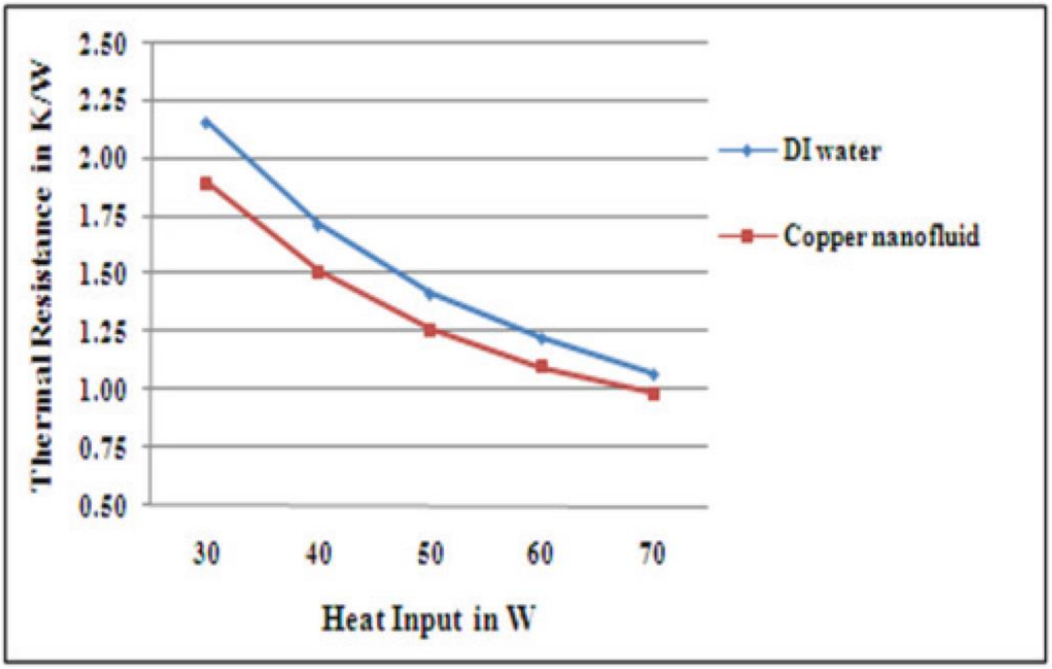

Figure 5. Thermal Resistance of heat pipe for 90o inclinations **[10].**

Putra et al. **[11]** tested the thermal behaviour of wick heat pipes utilizing Al_2O_3-water, Al_2O_3–ethylene glycol, TiO_2–water, TiO_2–ethylene glycol, and ZnO-ethylene glycol as working fluids experimentally. Between 1% and 5% of the base fluid's volume, the nanoparticle concentration was adjusted. It was found that the lowest thermal resistance of the heat pipes tested was when using an Al_2O_3–water nanofluid with a 5% volume concentration, as shown in Table 1. The potential of nanofluids as an alternative to traditional working fluids was demonstrated by the increased thermal performance of heat pipes charged with nanofluids.

Table 1. The heat pipe thermal resistances while using different operating fluids **[11].**

No	Working fluids	Thermal resistance (C/W)		
		10 W	20 W	30 W
1	Ethylene glycol	2.44	2.28	2.16
2	Water	2.36	2.20	2.11
3	Al_2O_3–ethylene glycol	2.18	2.02	1.86
4	TiO_2–ethylene glycol	2.38	2.23	2.11
5	ZnO–ethylene glycol	1.82	1.67	1.55
6	Al_2O_3–water	0.51	0.36	0.26
7	TiO_2–water	0.76	0.63	0.54

Asirvatham et al. **[12]** conducted experiments to estimate the effect of nanoparticle concentrations on the behaviour of heat pipes. Water is the base fluid in which silver nanoparticles are suspended with concentrations of 0.003%, 0.006%, and 0.009%; 58.35 nm is the average nanoparticle diameter. The experiments were conducted at input power (20, 40, 60, 80, and 100 W). The findings showed that adding silver nanoparticles might raise the thermal conductivity and thermal coefficient of the heat pipes. Using silver-water nanofluid reduced the heat pipe's thermal resistance, which raised the effective thermal conductivity by 42.4%, 56.8%, and 73.5% at concentrations of 0.003, 0.006, and 0.009 vol%, respectively. Fig.6 shows the Schematic diagram of the experimental setup.

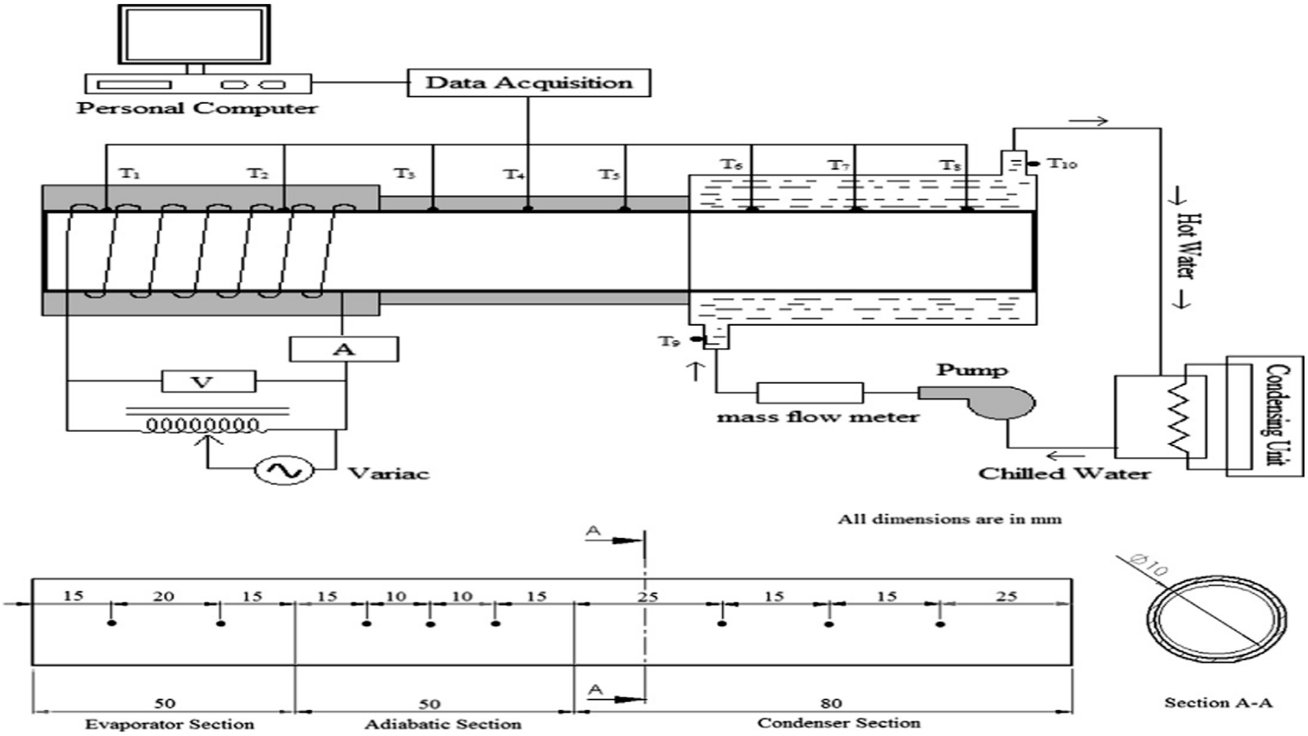

Figure 6. Schematic diagram of the experimental set up **[12].**

Park et al. **[13]** experimentally evaluated using a chemical reformation operation in which nanofluid has been formulated with hydroxy radicals coupled with oxidized multi-walled CNTs to improve nanoparticle dispersion stability to improve the heat-transfer utility of the heat pipe in a solar collector. Tests were carried out to identify the optimal nanoparticle mixture proportion by analyzing the relationship between temperature and the thermal expansion & viscosity of distilled water. The oxidized MWCNTs showed an increase in their thermal conductivity when the volume percentage & temperature were raised to higher levels. The viscosity climbed gradually until it reached a concentration of 0.01%, at which point it surged dramatically; nevertheless, it decreased when the temperature rose.

Huminic et al. **[14]** numerically examined the thermal behaviour of the thermosyphon and the effect of nanofluids on its thermal properties. Water is the base fluid, and iron (III) oxide nanoparticles with a size of 4-5 nm and a concentration of nanoparticles (0, 2, and 5.3) vol.% The findings of the numerical study showed that the thermal resistance of thermosyphon heat pipes using the water-Fe2O3 nanofluid was less than that of those that use pure water. It was also noted that the higher the nanoparticle concentration and the lower the thermal resistance lead to an increase in the thermal efficiency of the thermosyphon.

Asmaie et al. **[15]** presented a numerical study to verify the thermal performance of the thermosyphon and the effect of using CuO/water nanofluid as a working fluid. A thermosyphon heat pipe's phase variations in gas/liquid flow and heat transmission were studied using a two-phase computational fluid dynamics (CFD) model. The nanoparticle concentration adopted in this study is 0.1, 0.5, and 1 vol%. According to the result, the heat transfer rate of the thermosiphon increased by 49% when using CuO/water nanofluid compared to using water under the same conditions, and the best concentration of CuO nanoparticle was 1%.

Sarafraz et al. **[16]** employed the silver nanoparticles dispersed into the DI water as the base fluid for thermosyphon. The heat pipe's length was 280 mm, and its outer and inner dimensions were 10.7 mm and 12mm, respectively. An electrical cartridge burner was used to provide uniform heat flux in the evaporator portion. The experiment was conducted at the fluid medium loading ratio and heat capacity (30-75) %, (100-600) W, respectively, at different concentrations of 0.1, 0.2, 0.3, and 0.4 wt%. The findings demonstrated that heat pipes' thermal performance was enhanced when nanoparticles were used. At a filling ratio of 0.65, the best thermal performance of HP. Additionally, increasing the concentration of nanofluids leads to a decrease in thermal resistance, as shown in Fig.7.

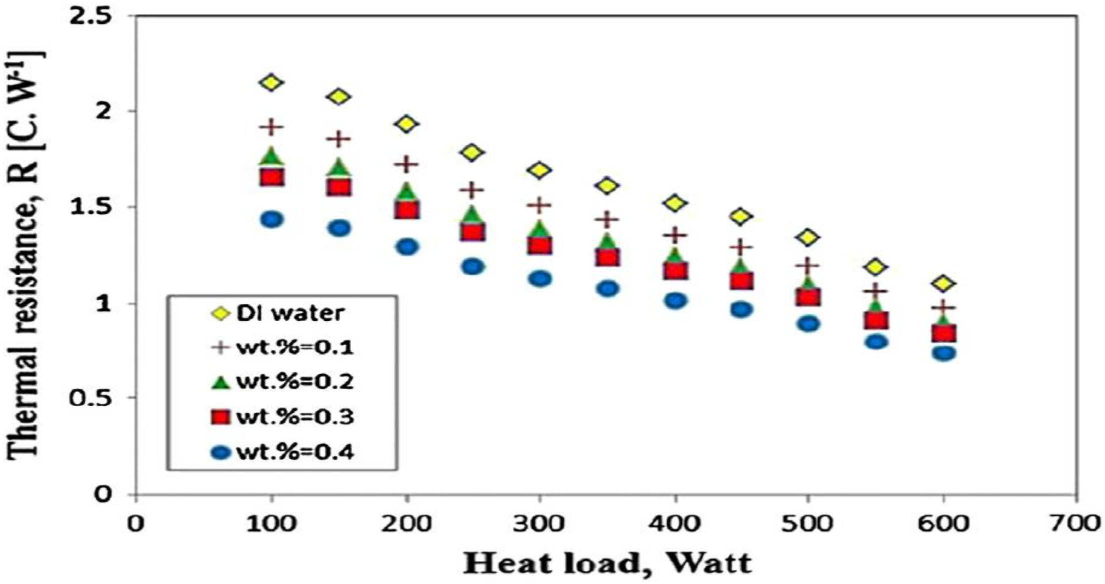

Figure 7. Impact nanofluid concentration on HP's thermal resistance **[16].**

Gajalakshmi et al. **[17]** discussed the practical examination of grooved heat transfer pipes employing nanofluids. A practical exam was carried out in this study to establish the efficiency of a grooved heat transfer pipe Fig.8. Deionized (DI) water and Iron Oxide nanoparticles, of an average diameter of around 50 nm and a concentration of 100 mg/lit, were used as nanofluids. The experiments were conducted at different inclination angles between 0° to 90° with 15° intervals. The effectiveness & thermal properties of a grooved heat transfer pipe have been investigated, and it has been discovered that Fe2O3 nanofluids deliver superior outcomes than Deionized Water, as well as the heat pipe with a 45° inclination improves performance.

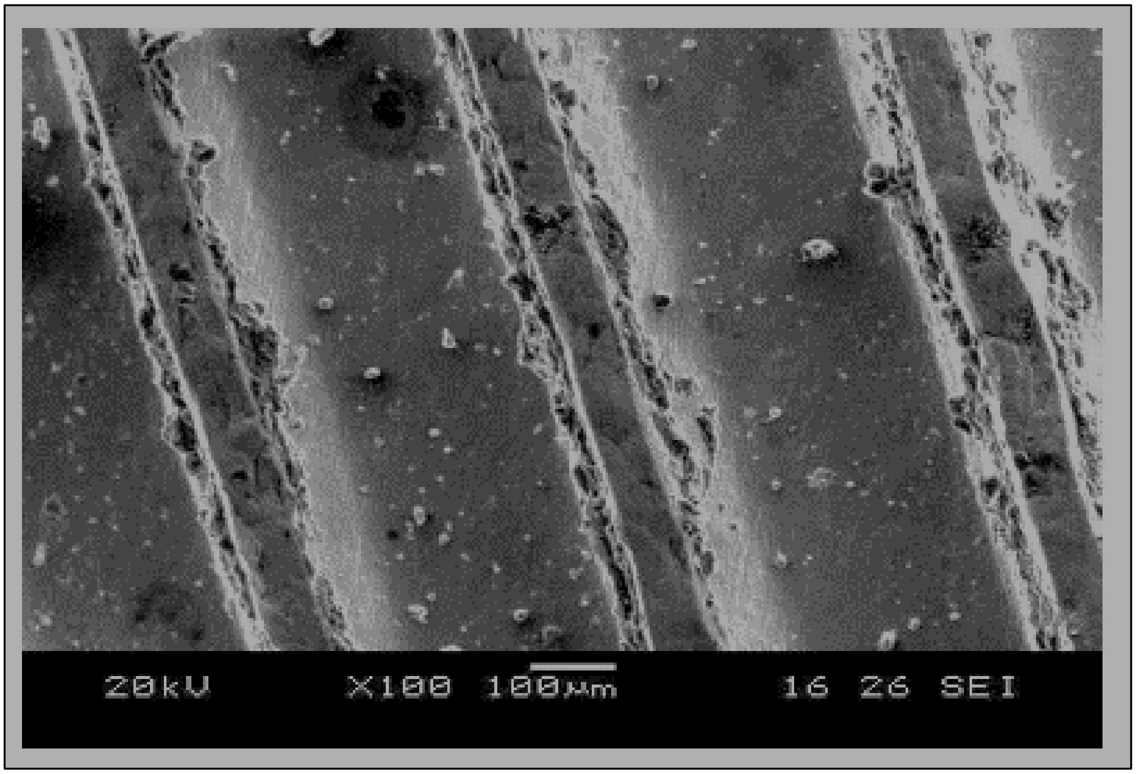

Figure 8. Microstructure of a grooved heat transfer pipe [**1**7]

Nazari et al**. [18**] improved the thermal performance of the pulsating heat pipes using graphene oxide nanosheets with a base fluid (water) as a working fluid with different concentrations (0.25, 0.5, 1, and 1.5 g/lit) and a filling ratio of 50%. According to the results, the highest decrease in thermal resistance was 40% at the lowest concentration of 0.25 g/lit. Furthermore, a rise in concentration degrades the PHP's thermal performance, which is linked to a rise in the working fluid's dynamic viscosity.

Sözen et al. **[19]** studied experimentally and numerically the performance of thermosyphon by using nanofluid as a working fluid utilizing a copper tube with both outer & inner diameters of 0.013 & 0.015 mm consecutively. De-ionized water & aqueous clinoptilolite nanofluid with a concentration of 2% wt. were used to examine the efficiency of thermosyphon. In each test, the capacity of the thermosyphon was only one-third loaded with the working fluid. Maximum increases in heat transmission and thermal resistance were 9.5% and 26.31%, respectively, as shown in Fig.9, as the aqueous clinoptilolite nanofluid was the operating medium in the HP.

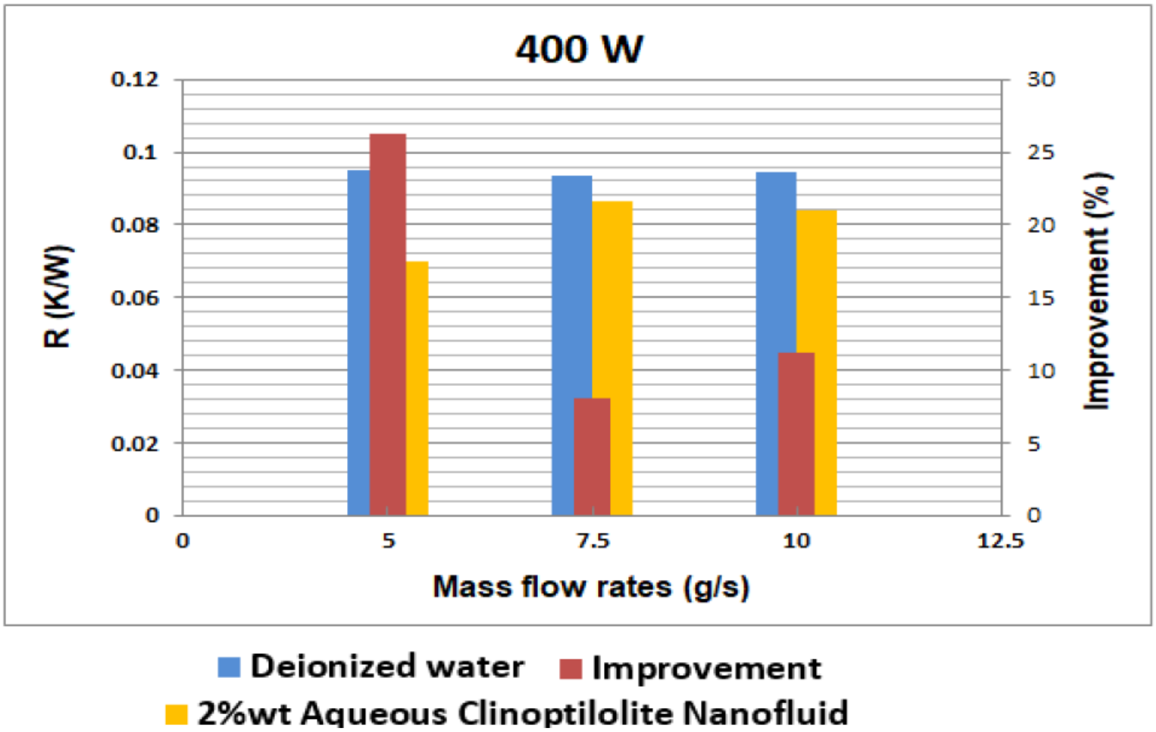

Figure 9. Thermal resistance of the heat pipe for both working fluids 400 W power input **[19]**.

Reji et al. **[20]** used both deionized water & aluminium nanofluid as the working fluid for the thermosyphon heat pipe with a mass concentration of 1.0%. The heat input values between 40W and 200W, and tilt angle of 0°, 30°, 60°, and 90°. According to the results, when a nanofluid was employed as the working fluid in a thermosyphon heat pipe, the performance increased by 41% over a range of experimentally manipulated inclination angles than DI water. Moreover, an effectiveness of 88% has been achieved at an inclination angle of 60°.

The modification of an L-shaped pipe using water/SiO2 nanofluids was experimentally studied by Khajehpour et al. **[21]**. The experiments used two different dimensions for nanoparticles (11-14 nm & 60-70 nm), two different amounts of nanoparticle content (0.11% & 0.5%), two different angles for the heat pipe (90 degrees and 0 degrees), and three different evaporation particle sizes (80%, 90%, & 100%), & three power inputs (5, 10, & 15 W). According to the results, the thermal resistance decreased as nanoparticle diameter increased from 11 to 70 mm. The ideal conditions for low thermal resistance were 11 nm and 0.5%wt, and details were provided in comparison to pure water.

Vidhya et al. **[22]** experimented to evaluate the impact of using hybrid nanofluids on the thermal conductivity of heat pipes. Magnesium oxide and zinc oxide nanoparticles were used with a base solution of a mixture of water and ethylene glycol (40:60%) as a working fluid, with six concentrations (0%, 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%). It was shown that the heat transfer coefficient of nanofluids improved by 28.9% and decreased by 4.07% in the thermal resistance of heat pipes compared to a base fluid. The temperature and nanoparticle concentration of ZnO and MgO hybrid nanofluids improved their thermal conductivity at 50 °C and 0.1% particle volume concentration, as shown in Fig.10. It is also discovered that the viscosity rises with increasing volume concentration and falls with rising temperature. It is around 67.4% higher than the base fluid at 80°C with a 0.1% volume concentration. as shown in Fig. 11.

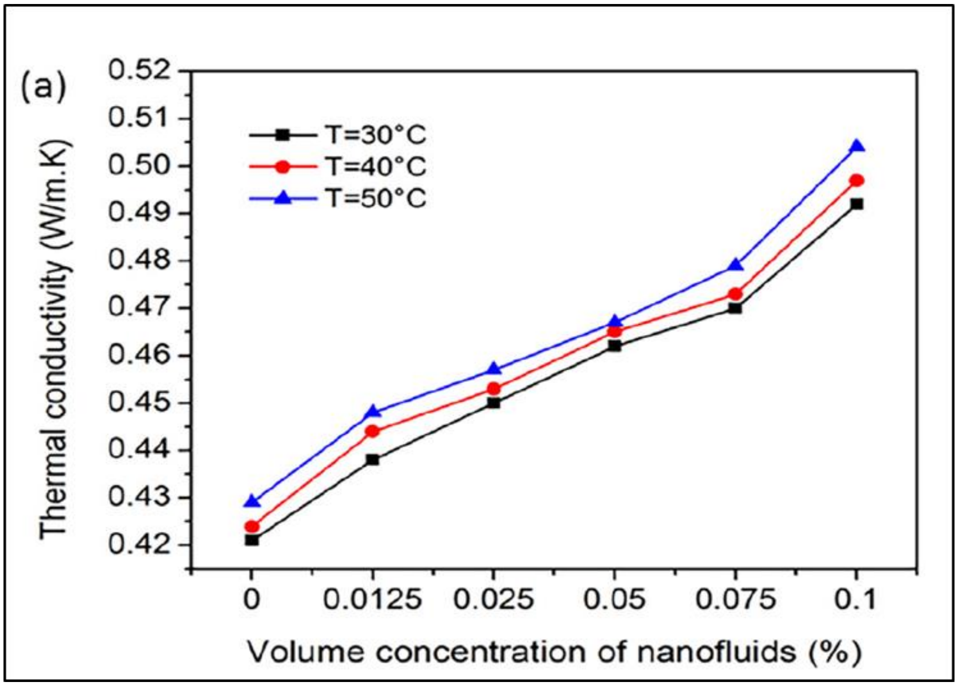

Figure 10. Thermal conductivity changes versus temperature and concentration of ZnO-MgO **[22].**

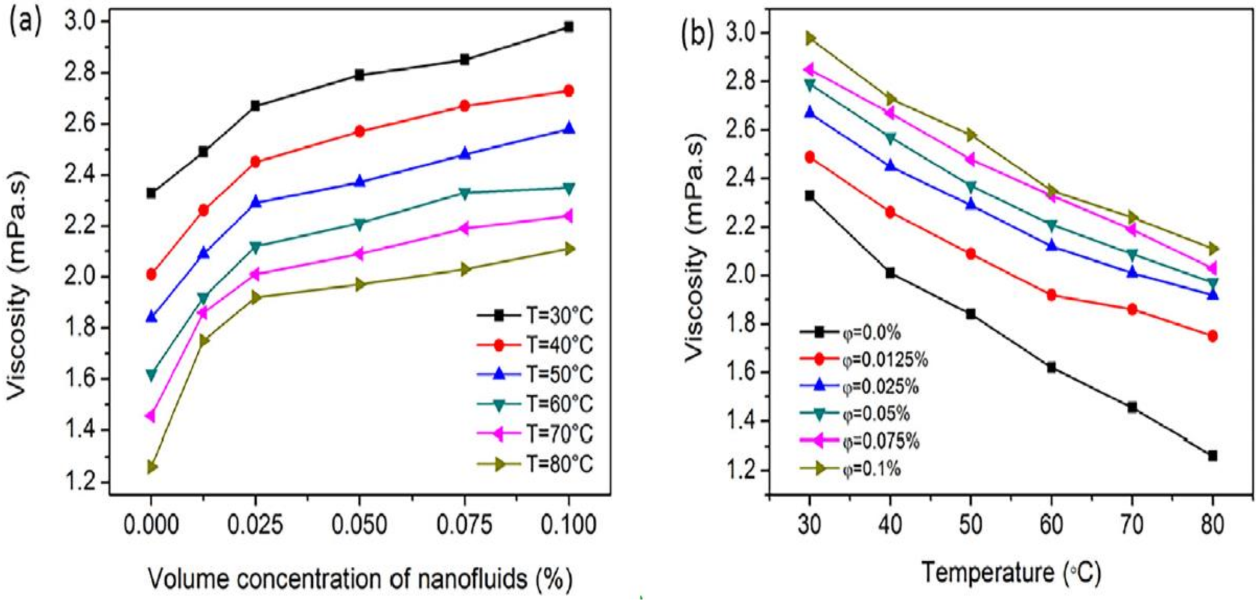

Figure 11. (a) Variation of viscosity of ZnO-MgO nanofluids for different volume concentrations (b) Effect of temperature on viscosity of nanofluids. **[22].**

Wang et al. **[23]** experimentally studied a thermosyphon heat pipe at 50°, 60°, 70°, 80°, and 90°. The experiments were carried out to find the influence of the single and hybrid nanofluids, where the single nanofluid is TiO_2–H_2O and Al_2O_3–H_2O, and the hybrid nanofluid is $Al_2O_3+TiO_2$–H_2O, with a volume fraction of 5%. The results indicated that heat pipe works more efficiently when using single or hybrid nanofluid compared to its performance with water, as they recorded the efficiency of thermosyphon heat pipe with nanofluid at about 70% to 85%. In addition, comparing single nanofluids (TiO_2–H_2O and Al_2O_3–H_2O) and hybrid nanofluids ($Al_2O_3+TiO_2$–H_2O), it can be said that at an angle of 60°, heat transfer in $Al_2O_3+TiO_2$–H2O is better than that in TiO_2–H_2O and Al_2O_3–H_2O, while at an angle of 70°, TiO_2–H_2O and Al_2O_3–H2O are better than $Al_2O_3+TiO_2$–H_2O.

Chilbule et al. **[24]** conducted experiments to estimate the effect of nanofluid concentration, nanoparticle size, filling ratio, and heat pipe diameter on the performance of thermosyphon heat pipes. CuO-water nanofluid is used as a working fluid with three different sizes of copper nanoparticles (30–50, 50–80, and 80–100 nm), 0.05 to 0.3% wt of concentrations of nanoparticles in water, and three diameters of heat pipe (8, 10, and 12) mm. The filling ratios used in the experiment were (15, 30, and 45%). The experimental findings showed that adding nanoparticles might raise the thermal conductivity and thermal coefficient of the heat pipes. The best thermal performance of the heat pipe was obtained under the following conditions: 0.3 (wt%) nanofluid concentration, 45% filling ratio, 30 nm nanoparticle size, and 8 mm heat pipe diameter.

Table 2. Summarizes all the research mentioned in this paper.

Authors	Type of nanofluid	Concentrations of nanoparticles	Results/Outlines
Tsai et al. [5]	Water-gold nanoparticles		20%–37% reduction in the heat pipes' overall thermal resistance.
Wei et al. [6]	Water-silver nanoparticles	1, 5, 10, 50, and 100) mg/l	Compared to a heat pipe that uses water, the heat pipe that uses nanofluids may have a total heat resistance of 28% – 44% lower.
Chen et al. [7]	Water-silver nanoparticles	(5, 50, and 100) mg/l	If there are more nanoparticles in the volume concentration range under test, the more the heat resistance will be reduced.
Lin et al. [8]	Water-silver nanoparticles	100 ppm and 450 ppm	In comparison to pure water, the thermal resistance is less than 0.092 °C/W
Jian Qu et al. [9]	Water-alumina	1.2%, 0.1%, 0.3%, 0.6%, and 0.9%.) wt.%	The drop in thermal resistance was 0.14 °C/W (or 32.5%) compared to pure water
Senthilkumar, R. et al [10]	copper nanofluid	100 mg/l	Significant decrease in the thermal resistance of heat pipes with nanofluid compared to water
Putra et al. [11]	Al_2O_3-water, Al_2O_3–ethylene glycol, TiO_2–water, TiO_2–ethylene glycol, and ZnO-ethylene glycol	(1%, 2%, 3%, 4%, and 5%) volume fraction	The lowest thermal resistance of the heat pipes tested was when using an Al_2O_3–water nanofluid with a 5% volume concentration
Asirvatham et al. [12]	Water-silver nanoparticles	(0.003%, 0.006%, and 0.009%) wt.%	Raises the effective thermal conductivity by 42.4%, 56.8%, and 73.5% at concentrations of 0.003, 0.006, and 0.009 vol%, respectively.
Park, S.S. [13]	hydroxy radicals coupled with oxidized multi-walled CNTs		The viscosity climbed gradually until it reached a concentration of 0.01%, at which point it surged dramatically; nevertheless, it decreased when the temperature was raised.
Huminic et al. [14]	Water- Fe2O3	(0, 2, and 5.3) vol.%	The thermal resistance of thermosyphon heat pipes using the water-Fe2O3 nanofluid was less than that of those that use pure water.
Asmaie et al. [15]	Water- CuO	0.1, 0.5, and 1 vol%	The heat transfer rate increased by 49% when using CuO/water compared to using water, also the best concentration was 1%.
Sarafraz, M.[16]	Water-silver nanoparticles	0.1, 0.2, 0.3, 0.4 wt.%	Heat pipes' thermal performance was enhanced when nanoparticles were used, and increasing the concentration of nanofluids leads to a decrease in thermal resistance.
Gajalakshmi, S.K. et al [17]	Water-Oxide of the Iron	100 mg/l	Fe2O3 nanofluids deliver superior outcomes than Deionized Water.
Nazari, M.A et al**.** [18**]**	Water- graphene oxide nano sheets	0.25, 0.5, 1, and 1.5 g/l	The highest decrease in thermal resistance was 40% at the lowest concentration of 0.25 g/lit.
Sözen, A. et al.[19]	Water- aqueous clinoptilolite	2% wt	Maximum increases in heat transmission (9.5%) and thermal resistance (26.31%).

Reji, A.K. et al.[20]	Water- aluminum	0.1 Wt.%	Increases performance by 41% more than DI water.
Khajehpour, E. et al.[21]	Water- SiO2	(0.11% & 0.5%) wt.%	The ideal conditions for low thermal resistance are 11 nm and 0.5%wt.
R. Vidhya. [22]	ZnO and MgO with blend of ethylene glycol and water (60:40%)	0%, 0.0125%, 0.025%, 0.05%, 0.075%, and 0.1%) wt. %	Decreased by 4.07% the thermal resistance of heat pipes compared to a base fluid.
Zhaoxiao W. [23]	TiO_2–H_2O and Al_2O_3–H_2O and the hybrid nanofluid is Al_2O_3+TiO_2–H_2O		The efficiency of thermosyphon heat pipe with nanofluid is about 70% to 85%.
Pawan C. et al. [24]	copper oxide	0.05 to 0.3% wt	The best thermal performance of the heat pipe was under the following conditions: nanofluid concentration of 0.3 (Wt.%)

3. Conclusions

This paper provides an overview of the results of previous research related to studying the thermal behaviour of heat pipes that use nanofluids as working fluids. The results showed that it is possible to improve the thermal performance of nanofluid heat pipes. The following conclusions can be summarized:

1. Nanoparticles added to the base fluid increase the conductivity of the working fluid.

2. Nanofluids improve the thermal performance and reduce the thermal resistance of heat pipes.

4. Nanoparticle concentrations may increase the viscosity of the working fluid, thus negatively affecting thermal performance. So, there is a certain concentration that is best.

3. Comparing hybrid nanofluids to pure nanoparticle nanofluid systems, the former proved to be more efficient under certain operating conditions.

4. Challenges and future trends

The results of all studies showed an improvement in the thermal performance of nanofluid heat pipes, and some of them proved that increasing the concentration increases the ability of the heat pipe to transfer heat. However, increasing the concentration to a certain extent shows a negative reaction to the thermal performance as a result of an increase in the viscosity of the working fluid and thus an increase in tension surfactant and that there is a certain ideal concentration. Therefore, it is necessary to conduct studies to reduce the use of surfactants to prevent agglomeration and sedimentation of nanoparticles.

References

[1] D. A. Reay, P. A. Kew, and R. J. McGlen, "Heat transfer and fluid flow theory," in Heat Pipes, 2014, pp. 64-15

[2] Tiara, A.M., Chakraborty, S., Sarkar, I., Ashok, A., Pal, S.K. and Chakraborty, S., 2017. Heat transfer enhancement using surfactant-based alumina nanofluid jet from a hot steel plate. Experimental Thermal and Fluid Science, 89, pp.295-303.

[3] Das, P.K., Mallik, A.K., Ganguly, R. and Santra, A.K., 2018. Stability and thermophysical measurements of TiO2 (anatase) nanofluids with different surfactants. Journal of Molecular liquids, 254, pp.98-107.

[4] Das, P.K., Islam, N., Santra, A.K. and Ganguly, R., 2017. Experimental investigation of thermophysical properties of Al2O3–water nanofluid: Role of surfactants. Journal of Molecular Liquids, 237, pp.304-312.

[5] Tsai, C.Y., Chien, H.T., Ding, P.P., Chan, B., Luh, T.Y. and Chen, P.H., 2004. Effect of structural character of gold nanoparticles in nanofluid on heat pipe thermal performance. Materials Letters, 58(9), pp.1461-1465.

[6] Wei, W.C., Tsai, S.H., Yang, S.Y. and Kang, S.W., 2005. Effect of nanofluid concentration on heat pipe thermal performance. IASME Trans, 2(8), pp.1432-1439.

[7] Chen, Y.T., Wei, W.C., Kang, S.W. and Yu, C.S., 2008, March. Effect of nanofluid on flat heat pipe thermal performance. In 2008 Twenty-fourth Annual IEEE Semiconductor Thermal Measurement and Management Symposium (pp. 16-19). IEEE.

[8] Lin, Y.H., Kang, S.W. and Chen, H.L., 2008. Effect of silver nano-fluid on pulsating heat pipe thermal performance. Applied thermal engineering, 28(11-12), pp.1312-1317.

[9] Qu, J., Wu, H.Y. and Cheng, P., 2010. Thermal performance of an oscillating heat pipe with Al2O3–water nanofluids. International Communications in Heat and Mass Transfer, 37(2), pp.111-115.

[10] Senthilkumar, R., Vaidyanathan, S. and Sivaraman, B., 2012. Effect of inclination angle in heat pipe performance using copper nanofluid. Procedia Engineering, 38, pp.3715-3721.

[11] Putra, N., Septiadi, W.N., Rahman, H. and Irwansyah, R., 2012. Thermal performance of screen mesh wick heat pipes with nanofluids. Experimental thermal and fluid science, 40, pp.10-17.

[12] Asirvatham, L.G., Nimmagadda, R. and Wongwises, S., 2013. Heat transfer performance of screen mesh wick heat pipes using silver–water nanofluid. International journal of heat and mass transfer, 60, pp.201-209.

[13] Park, S.S. and Kim, N.J., 2014. A study on the characteristics of carbon nanofluid for heat transfer enhancement of heat pipe. Renewable energy, 65, pp.123-129.

[14] Huminic, G. and Huminic, A., 2013. Numerical study on heat transfer characteristics of thermosyphon heat pipes using nanofluids. Energy Conversion and Management, 76, pp.393-399.

[15] Asmaie, L., Haghshenasfard, M., Mehrabani-Zeinabad, A. and Nasr Esfahany, M., 2013. Thermal performance analysis of nanofluids in a thermosyphon heat pipe using CFD modeling. Heat and Mass Transfer, 49, pp.667-678.

[16] M. M. Sarafraz, F. Hormozi, and S. M. Peyghambarzadeh, "Thermal performance and efficiency of a thermosyphon heat pipe working with a biologically ecofriendly nanofluid," International Communications in Heat and Mass Transfer, vol. 57, pp. 297-303, 2014, doi: 10.1016/j.icheatmasstransfer.2014.08.020.

[17] R. S. Senthamarai Kannan Gajalakshmi*1 and a. G. Sasikumar3, "Experimental investigation of grooved heat pipe using nanofluids," Chemical and Pharmaceutical Research, 2016.

[18] Nazari, M.A., Ghasempour, R., Ahmadi, M.H., Heydarian, G. and Shafii, M.B., 2018. Experimental investigation of graphene oxide nanofluid on heat transfer enhancement of pulsating heat pipe. International Communications in Heat and Mass Transfer, 91, pp.90-94.

[19] A. Sözen, M. Gürü, A. Khanlari, and E. Çiftçi, "Experimental and numerical study on enhancement of heat transfer characteristics of a heat pipe utilizing aqueous clinoptilolite nanofluid," Applied Thermal Engineering, vol. 160, 2019, doi: 10.1016/j.applthermaleng.2019.114001.

[20] A. K. Reji, G. Kumaresan, A. Sarathi, A. G. P. Saiganesh, R. Suriya Kumar, and M. M. Shelton, "Performance analysis of thermosyphon heat pipe using aluminum oxide nanofluid under various angles of inclination," Materials Today: Proceedings, vol. 45, pp. 1211-1216, 2021, doi: 10.1016/j.matpr.2020.04.247.

[21] E. Khajehpour, A. R. Noghrehabadi, A. E. Nasab, and S. M. H. Nabavi, "Experimental investigation of the effect of nanofluids on the thermal resistance of a thermosiphon L-shape heat pipe at different angles," International Communications in Heat and Mass Transfer, vol. 113, 2020, doi: 10.1016/j.icheatmasstransfer.2020.104549.

[22] Vidhya, R., Balakrishnan, T. and Kumar, B.S., 2021. Investigation on thermophysical properties and heat transfer performance of heat pipe charged with binary mixture based ZnO-MgO hybrid nanofluids. Materials Today: Proceedings, 37, pp.3423-3433.

[23] Wang, Z., Zhang, H., Yin, L., Yang, D., Yang, G., Akkurt, N., Liu, D., Zhu, L., Qiang, Y., Yu, F. and Xu, Q., 2022. Experimental study on heat transfer properties of gravity heat pipes in single/hybrid nanofluids and inclination angles. Case Studies in Thermal Engineering, 34, p.102064.

[24] Chilbule, P.V., Dhole, L.P. and Chavhan, G.R., 2023. Optimization of heat pipe charged with CuO nanofluid using Taguchi technique. Materials Today: Proceedings.

مراجعة السوائل النانوية التي ساعدت على الأداء الحراري لأنابيب الحرارية

الخلاصة: إن استخدام السوائل النانوية كمائع عمل في الأنابيب الحرارية يمكن أن يزيد من قدرة الأنابيب الحرارية على نقل الطاقة الحرارية وتحسين الأداء الحراري.يستعرض هذا البحث مجموعة من الأبحاث التجريبية والعددية السابقة التي تناولت تأثير الموائع النانوية على الخصائص الحرارية للأنابيب الحرارية لفهم المزيد عن هذه الموائع وموصليتها الحرارية ومعرفة الفرق بين استخدامها واستخدام الموائع التقليدية التي تتميز بالتوصيل الحراري المحدود. وقد قام باحثون سابقون بدراسة تأثير مدخلات الطاقة الحرارية، ونوع السائل النانوي، وحجم الجسيمات النانوية وتركيزها، والمواد التي تصنع منها هذه الجسيمات النانوية. بشكل عام، تتميز السوائل النانوية بالتوصيل الحراري العالي مقارنة بالسوائل التقليدية. ولذلك فإن استخدامها في الأنابيب الحرارية يؤدي إلى تحسن كبير جداً في الخواص الحرارية. كل هذا يعتمد على ظروف التشغيل، ونوع السائل النانوي، وحجم الجسيمات النانوية، وتركيزها. وأشير إلى أن الأنابيب الحرارية تحقق أعلى أداء حراري عند تركيز معين من السوائل النانوية. .وبالإضافة إلى ذلك، ينبغي ملاحظة التعارض بين تعزيز التوصيل الحراري الفعال وزيادة اللزوجة بسبب تشتت الجسيمات النانوية.

الكلمات الدالة: الأنابيب الحرارية، الموائع النانوية، المقاومة الحرارية، الأداء الحراري.