KMU Journal of Engineering and Natural Sciences
https://dergipark.org.tr/en/pub/kmujens
3(1), 44-73, (2021) © KMUJENS
e-ISSN: 2687-5071

# Nanoakışkanların Isı Borularının Isı Transfer Performansına Etkisinin İncelenmesi

# Investigation of The Effect of Nanofluids on Heat Transfer Performance of Heat Pipes

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***(Received: 13 April 2021; Accepted: 2 June 2021)***

**Özet.** Isı transferi birçok endüstriyel ve tüketici sisteminde önemli bir role sahiptir. Isı borusu, ısı transferi için kullanılan yüksek ısı iletkenliğine sahip bir cihazdır. Isı borusu üç bölümden oluşur; ısıyı çalışma sıvısına ileten buharlaştırıcı bölümü: ısı transferi için kullanılan adyabatik bölüm ve çalışma sıvısını soğutan yoğunlaştırıcı bölüm. Isı borusunun temel çalışma prensibi, içinde bulunan çalışma sıvısının fazını değiştirmektir. Isı borusu, evaporatörden ısıyı emer, adyabatik bölümden yoğunlaştırıcıya dönüşür ve sıcaklığını ortama iletir, yani ısıyı bir bölgeden diğerine buharlaşma ve yoğuşma fazı değişikliği kullanarak aktarır. Isı borusunda kullanılan geleneksel çalışma akışkanlarının zayıf ısıl iletkenliği, ısı transferinin etkinliğini ve uygulamasını sınırlar. Bu nedenle, geleneksel çalışma sıvısını yüksek ısı transfer performansına sahip bir çalışma sıvısı ile değiştirme fikri oluşmuştur. Bilim adamları ve mühendisler, nano boyutlu parçacıkları sıvılara dağıtarak bu temel sorunun üstesinden gelmek için büyük çaba sarf ettiler. Nanosıvılar, nanopartiküllerin geleneksel çalışma sıvısı ile karıştırılmasıyla oluşturulan kararlı katı-sıvı süspansiyonlardır. Bu çalışmada, ısı borularında kullanılan nanoakışkanlar üzerinde deneysel ve sayısal araştırmalar incelenmiştir. Isı borusunun ısıl performansı ve ısıl

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direnci birçok deneysel koşula bağlıdır. Bu koşullar, ısı borusu tipleri, nanoakışkan özellikleri, ısı borularının tasarımı ve çalışma koşulları gibi farklı parametreleri içerir.

**Anahtar Kelimeler**: Isı borusu, ısı transferi, termal performans, nanoakışkan

**Abstract.** Heat transfer has an important role in many industrial and consumer systems. The heat pipe is a device with high thermal conductivity used for heat transfer. Heat pipe consists of three parts; the evaporator section, which transmits heat to the working fluid: the adiabatic section used for heat transport and the concentrator section that cools the working fluid. The basic working principle of the heat pipe is to change the phase of the working fluid contained in it. The heat pipe absorbs heat from the evaporator, transforms from adiabatic section to concentrator and transmits its temperature to the environment, i.e. transfer heat from one region to another using evaporation and condensation phase change. The weak thermal conductivity of the traditional working fluids used in the heat pipe limits the effectiveness and application of heat transfer. Therefore, the idea of replacing the traditional working fluid with a working fluid with high heat transfer performance has been formed. Scientists and engineers have made great efforts to overcome this fundamental problem by distributing nano-sized particles into liquids. Nanofluids are stable solid-liquid suspension created by mixing nanoparticles with traditional working fluid. In this study, experimental and numerical research on nanofluids used in heat pipes are examined. The thermal performance and thermal resistance of the heat pipe depend on many experimental conditions. These conditions contain different parameters such as heat pipe types, nanofluid properties, design of heat pipes and working conditions.

**Key words:** Heat pipe, heat transfer, thermal performance, nanofluid

## 1. Introduction

Due to limited energy sources and the high costs of these resources, efforts are being carried out to enable the development of energy efficiency in the industrial area. Heat transfer is an important work issue that needs to be considered in the industry. Therefore, the improvement in heat transfer will increase energy efficiency, while reducing working times in industrial applications, increasing the life of materials. [1] Studies to improve heat transfer are often classified as "active", "passive" and "mixed" methods. Passive methods do not require the use of external power. Passive-returned flow devices, rough surfaces, healing elements put inside the pipe, etc. can be given as examples. The external power supply should be used in active methods. Methods such as fluid vibration, mechanical mixers, electrostatic areas, surface vibration can be counted from this class. Hybrid methods are methods in which two or more active and passive methods are used together. [2]

Heat transfer of water, motor oil and ethylene glycol is traditionally used as fluid in heat pipes. However, due to the low heat transfer performance of these traditional healing methods, the desired efficiency is not achieved in recovery and the heat changer is limited to small volume and geometry.

Putting solid particles into a basic fluid used in the heat exchanger is one of the passive methods of improving heat transfer. This method increases the thermal conductivity of the fluid and improves heat transfer capacity. Thin solid metals that participate as suspensions into a basic fluid increase the thermal conductivity of the base fluid, as their thermal conductivity is higher than the conductivity of the basic fluid.

It has long been known that the thermal conductivity of the fluid is enhanced by embellishment into solid particles measuring millimeters or micrometers. [3] However, these methods were not attractive due to problems such as sedimentation, wear and large pressure drops in industrial operations. In addition, suspensions prepared with particles of this size show a less stable structure in microchannels, causing blockages. In parallel with the developments in material science in recent years, these problems have been created by producing particles in nanometer sizes. Solid particles such as gold, silver, copper and aluminum with high thermal conductivity and nanometer sizes have been produced in a new heat transfer fluid type by joining traditional heat transfer fluids. These new heat transfer fluids, which are joined by solid particles of nanometer sizes, are called "nanofluids". [4]

Heat pipes are one of many heat-bearing systems using nanofluids. Heat pipes allow large amounts of heat to be transported with very small section areas, and no additional power is needed in the process. It is the most important advantage that distinguish these characteristics from other traditional heat-carrying systems. In addition, it has advantages such as easy design and production, very small temperature difference between heat transmitter and receiver, and can be operated at different temperature ranges. [5]

The idea of distributing solids into fluid was proposed by Maxwell through his theoretical work more than 120 years ago. Then, in 1975, Ahuja, Liu and others in 1988 were used by researchers at Argone National Laboratory in 1992 to distribute mm and/or µm-sized particles to fluids. All these studies are based on the fact that metals have high thermal conductivity at room temperature compared to fluids. For example, at room temperature, copper has a thermal conductivity 3000 and 700 times larger than that of an engine oil and water, respectively. Since metallic liquids have much higher thermal conductivity than non-metallics, there is the same difference in thermal conductivity groups between liquids. [6]

One of the problems caused by the use of fluids containing µm particles in size is the blockage of small channels caused by large lumping of solid particles, making it difficult to use in heat transfer equipment, which is furnished with small channels. Nanofluids exceed this barrier because they contain a small enough particle size that can pass through such channels properly. Another advantage of using nanoparticles is that they have an extremely large surface area with heat transfer mechanism between particles and its surroundings. Therefore, reducing the size of the particles from mm and µm to nm increases the surface area excessively, increasing the heat transfer. In 2000, Xuan and Li redefined the term nanofluidic to include nanoscale metallic, ametallic and polymeric particles mixed with a non-carcinogenic base liquid. [7] They also noted that effective (effective) thermal conductivity can be increased by more than 20% by adding nanoparticle concentration surged as low as 1-5% per volume to the base liquid, and the increase can be strongly affected by the shape of particles, particle sizes, volume fractions added to the base fluid and the thermophysical properties of particles. The term "effective" was used to identify the thermophysical properties of the nanofluid and separate the thermophysical properties of the base fluid itself, and distinguish between the base fluid and its new fluid, which consists of scattered nanoparticles. [8]

## 2. STUDİES WITH NANOFLUIDS IN HEAT PIPES

### 2.1. Experimental Studies

Experimental studies using nanofluid in micro grooved, mesh wick, sintered metal, thermosyphon and oscillating/pulsating heat pipes, which are widely used, have been investigated.

#### *2.1.1. Micro-Grooved Heat Pipes*

Micro grooved heat pipes are widely used in different application areas. On the inner surface of these heat pipes, there are grooves to make it easier for the condensed working fluid to return to the evaporator section through capillary force. The evaporation rate of the operating fluid varies depending on the evaporator heating. Similarly, the refrigerant controls the condensation rate of the operating fluid, such as fluid temperature, mass flow rate, specific heat, etc. Evaporation speed, condensation rate and condensation flow rate (from condensator to the evaporator section) must be in harmony for the heat pipe to operate efficiently. If the evaporation rate is higher than the condensation rate, it will be drying. A lower evaporation rate will lead to lower yielding. To avoid drying, condensate flow is required from condensator to evaporator. Therefore, grooves or suppositories should be able to produce enough capillary force to produce the necessary condensate to the evaporator part under different working parameters. The researchers found that using different nanofluids in micro grooved heat pipes, there was a significant increase in thermal performance.

Wang et al. [9] examined the thermal performance of the heat pipe loaded with aqueous CuO nanofluid heat pipe. In an unstable state, the initiation time decreased when aqueous CuO nanofluid was used as a working fluid. When nanofluid was used instead of water as a working fluid, heat transfer increased by 40%, thermal resistance decreased by 50%.

Liu and others [10] examined the effects of inclination angle and working pressure on the thermal efficiency of the sloping miniature grooved heat pipe using water-based CuO nanofluid as a working fluid. It is showed that inclination angle effected the heat transfer properties of the heat pipe. With the increase in the slope angle, both the evaporator and the condensator section HTC (Heat Transfer Coefficient) gradually increased and reached the maximum level with a slope angle of $75^0$. The evaporation of the curved heat pipes HTC and condensation HTC has increased from about 60-80% and nearly 2 times from about 2 times, respectively, compared to the horizontal heat pipe.

Do et al. [11] investigated the effect of water-based $Al_2O_3$ nanofluids on the thermal performance of a flat microgrooved heat pipe with rectangular corrugated wick. In optimum conditions, thermal performance for the nanofluid heat pipe increased significantly by about 100% when the base fluid was added to nanoparticles, which were only 1% less than 1% of the volume. The thermal resistance of the nanofluid heat pipe has shown a tendency to decrease by increasing the size of the nanoparticles.

Mehrali et al. [12] examined the thermal performance of a grooved heat pipe using aqueous nitrogen graphene (NDG) nanofluid. The results showed that the concentration of NDG nanoparticles in the inclination angle and operating fluid strongly affects the heat transfer performance of the heat pipe. The $90^0$ slope angle emphasizes the importance of gravity, providing the best total temperature performance in all cases. In case of nanofluid use of NDG, high thermal conductivity is provided as it increases nanoparticle performance at low temperature inputs. Higher input heat forces assume that the build-up of NDG nanolayers on the evaporation surface during evaporation creates a porous hydrophilic layer that can lead to an increase in heat transfer coefficient and overall performance.

Wei et al. [13] used a cylindrical micro grooved heat pipe with an internal diameter and length of 6 mm and 200 mm respectively. Therefore, the thermal resistance of the grooved heat pipe varies depending on the size of the nanoparticles.

Liu et al. [14] conducted an experimental study to understand heat transfer using water-CuO nanofluids at different operating pressures and different nanoparticles mass concentrations. The mass concentration of nanofluids has a remarkable effect on both boiling heat transfer coefficient and critical heat flux (CHF). When mass concentration is less than 1%, heat transfer coefficient and CHF increase with increased concentration. However, when the concentration is weighted above 1%, CHF is basically close to a fixed value and heat transfer gradually deteriorates. There is an optimum mass concentration for nanofluids corresponding to the maximum increase in heat transfer, and this optimum mass concentration is 1% at all test pressures.

Liu et al. [15] conducted an experimental study to examine the heat transfer performance of the cylindrical micro grooved heat pipe using aqueous nanofluids as working fluids. Five types of nanofluids were used, with an average diameter of 40 nm and 20 nm, CuO with a diameter of 50 nm and 20 nm, and SiO with an average diameter of 30 nm. Among the five types of nanofluids tested, Cu and CuO nanofluids increased the thermal performance of the heat pipe. However, the SiO nanofluid heat pipe has disrupted thermal performance. This can be caused by different surface structures of the coating layers formed by nanoparticles on the heated surface.

Aly et al. [16] investigated the thermal performance of a micro grooved heat pipe using water-based alumina nanofluids. When nanofluid is used instead of distilled water, the maximum increase in evaporation and condensation heat transfer coefficients and maximum reduction in thermal resistance were achieved as 30,4%, 11% and 18,2%, respectively. Both the inclination angle and the filling ratio have significantly affected the thermal performance of the heat pipe. Evaporation and condensation heat transfer coefficients increased by increased in the rate of filling, but decreased as the total heat resistance filling rate increased. The optimum slope angle was found to be $60^0$ and showed the best thermal performance when using distilled water and nanofluid.

Table 1: Summary of experimental studies using nanofluids in micro heat pipes

| **Author** | **Size of heat pipe** | **Nanoparticle** | **Nanoparticle size** | **Main fluid** | **Concentration (Weight)** | **Effect** | **Results Obtained** |
|---|---|---|---|---|---|---|---|
| Wang *et al.* [9] | Length:350 mm<br>Outer diameter:8 mm<br>Wall thickness: 0.6 mm | CuO | 50 nm. | Water | 0.5–2.0 | a | 1, 2, 3, 4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Liu *et al.* [10] | Length:350 mm<br>Outer diameter:8 mm<br>Wall thickness: 0.6 mm | CuO | 50 nm | Water | 0.5, 1.0 and 2.0 | a | 1 |
| Do *et al.* [11] | W (mm) 13.41 T (mm) 0.1<br>D (mm) 8.92 N (ea.) 62<br>$W_0$ (mm) 4.875 T (mm) 15.6<br>$D_0$ (mm) 0.61 T (mm) 70.0<br>H (mm) 0.42 Lc (mm) 34.4<br>S (mm) 0.2 Lb (mm) 0 | $Al_2O_3$ | 38,4 nm | Water | 0.0-1.2 | a | 1&4 |
| Mehrali *et al.* [12] | Outer diameter:10 mm<br>Wall thickness:0.5 mm<br>It has a groove with a long edge of 75 mm and a long edge of 300 mm. | Graphene | - | Water | 0.01, 0.02, 0.04 and 0.06 | a | 1&4 |
| Wei *et al.* [13] | Length:180 mm<br>Outer diameter:6 mm | Ag (Silver) | 10 nm | Water | 5 mg/l, 10 mg/l and 15 mg/l | a | 1 |
| Liu *et al.* [14] | It has a 40x40 mm groove with a short edge of 0.5 mm long edge of 0.8 mm. | Cu (New Year's Eve) | 30 nm | Water | %0.5, %1 | a | 1&9 |
| Liu *et al.* [15] | Length:350 mm<br>Outer diameter:8 mm<br>Wall thickness: 0.6 mm | Cu, CuO, Sio | 40&20 nm<br>50&20 nm<br>30 nm | Water | 0.5, 1, 1.2 | a, b | 1, 9, 12 |
| Aly *et al.* [16] | Length:550 mm<br>Outer diameter:15.87 mm | $Al_2O_3$ | 20 nm | Water | 3 | a | 1, 4, 9, 10 |

a: Heat performance increased
b: Heat performance decreased
-: The researchers did not specify the desired value

### *2.1.2.* Mesh Wick *Heat Pipes*

Mesh wick heat pipes are widely used in different applications. So the researchers tried to find some important results, using nanofluids in mesh wick heat pipes.

Kole et al. [17] examined how the thermal performance of the mesh wick heat pipe changed when using Cu-water nanofluid as a working fluid. The heat resistance of both water and nanofluid heat pipes is high in low heat input forces, but as the heat load increases, it is rapidly minimized. This feature of thermal resistance as a function of evaporator input power is a typical feature of the heat pipe. High thermal resistance observed for low heat loads is due to the formation of a solid liquid film in the evaporator section. On the other hand, core decoction, which is more important in high heat loads, causes a rapid drop in heat resistance. Total thermal resistance can be noted to decrease both with increased Cu concentration in the nanofluid and by increasing input power. Vertically positioned heat pipes are also seen to perform superiorly compared to the sloped positions.

Do et al. [18] examined the effects of nanofluids on heat transfer performance of mesh wick heat pipes using water-based $Al_2O_3$ nanofluid in 1.0% and 3.0% volume flow. The thermal resistance of heat pipes using water-based $Al_2O_3$ nanofluid is decreased compared to the heat pipe that uses DI water.

Putra et al. [19] conducted an experimental study to determine the concentrations and types of nanofluids that can best improve the thermal performance of mesh wick heat pipes, and to determine the effect of coatings on the formal suppository structure after using nanofluid as a working fluid. The evaporation heat transfer coefficient of nanofluids much higher than that of the base liquid. The vaporizing heat transfer coefficient increases with the increase of volume concentration, and this increase is quite obvious when the volume increase ranges from 0% to 5%.

Wang et al. [20] conducted an experimental study to investigate the thermal performance of a sloping miniature mesh wick heat pipe using water-based CuO nanofluid as a working fluid. When the mass concentration shifts from 0% to 1% the total heat resistance increased with increased concentration of nanoparticles. Then, the mass concentration began to decrease after the weight exceeded 1.0%. Therefore, it has an optimal mass concentration corresponding to the minimum heat resistance, and this optimal value is equal to 1.0% weight for both horizontal and vertical pipes.

Solomon et al. [21] conducted an experimental study to examine the thermal performance of a heat pipe operated by nanoparticle-coated suppository. The decrease in thermal resistance in the evaporator and heat pipe clearly shows the increase in the heat transfer coefficient in the evaporator, which is the effect of the thermal performance of the heat pipe in the suppository.

Asirvatham et al. [22] using Ag/water nanofluid, they noticed an increase in the thermal performance of the mesh wick heat pipe. With the increase in the concentration of silver nanoparticles, evaporation and condensation heat transfer coefficients are observed increasing. The difference between evaporating wall temperature and steam temperature at 60 W heat load is observed to be 5.8, 5.4, 4.7 and 4.2 for heat pipes with volume concentrations of 0.003%, 0.006%, 0.009% respectively.

Saleh et al. [23] investigated ZnO nanoparticle-based nanofluids prepared using a two-stage method. For all measurements, the wall temperatures of the heat pipes decreased from the evaporator to the concentrator section throughout the test section, increasing with an increase in input power. As shown, the temperature distributions of the heat pipe containing ethylene glycol as base liquid are 88.6, respectively, when EG is 84.6, 70.8, 67.9 and 28.7$^0$C. EG, when replaced by volume 0% to 5% ZnO / EG, the temperature in the evaporator has dropped from 86.6 to 80.7 $^0$C for ZnO nanofluids with an average crystalline size of 18 or 23, respectively, from 86.6 to 80.7 $^0$C and from 86.5 to 82.6 $^0$C.

Liu et al. [24] conducted an experimental study to investigate the effects of water-based CuO nanofluids on thermal performance of the horizontal mesh heat pipe, which operates under constant atmospheric pressure. The heat transfer coefficients of the evaporator and concentrator increased with increased mass concentration when the concentration of mass was less than 1% and less than 0%. Subsequently, the mass concentration began to decrease after increasing to over 1.0% by weight. The 1.0% mass concentration by weight corresponds to the best heat transfer coefficient (HTC) equipment.

Senthilkumar et al. [25] used copper nanofluids as working fluid to examine the increase in thermal efficiency of the heat pipe. The experimental procedure made with different heat inputs (30, 40, 50, 60 and 70 W) and different pipe angles (0$^o$,15$^0$, 30$^o$,45$^o$, 60$^0$, 75$^o$ and 90$^o$) and observations were recorded. The thermal efficiency of the heat pipe is seen to increase with the increasing values of the slope angle up to 30$^0$ DI water and 45$^0$ copper nanofluid, depending on the horizontal position of the heat pipe. Conversely, when the tilt angle of the heat pipe exceeds 30° for DI water and 45° for copper nanofluid, the heat pipe heat efficiency begins to decrease. In this study, when used as copper nanofluid working fluid, it was found that the thermal efficiency of heat pipe increased by approximately 10%, compared to deiyonized water use.

Hajian et al. [26] conducted an experimental study on the effects of nanofluids on the thermal performance of a medium-sized cylindrical braided heat pipe in both temporary and fixed cases. The experiments were conducted below temperature rates of less than 500 W. Nanofluids were used in concentrations of 50, 200 and 600 ppm. Using 50 ppm nanofluid, the heat resistance and response time of the heat pipe decreased by 30% and about 20% respectively compared to DI-water

Ghanbarpour et al. [27] reveals the effect of the mesh wick heat pipe on heat performance in the cooling applications of the $Al_2O_3$ nanofluid. The results showed that the effective thermal conductivity of the heat pipe increases from 30% to 130% at different heat inlets for increased and reduced heat with 5% $Al_2O_3$ nanofluids, while 10% $Al_2O_3$ nanofluid slumps from 67% to 63%.

Tsai et al. [28] conducted an experiment with the cylindrical mesh wick heat pipe. As a result, higher thermal performance of the nanofluids proven the potential to replace the traditional DI water in the vertical circular mesh heat pipe.

Senthil et al. [29] conducted an experimental study on thermal efficiency and thermal resistance based on the sloping angle using a heat pipe. In the heat pipe, the value of thermal efficiency using $Al_2O_3$ nanofluids is higher than the value obtained using DI water. The suspension of nanoparticles in low-b liquid reduces thermal resistance, causing a tremendous improvement in heat transfer rate.

Kumaresan et al. [30] conducted an experimental study to compare the increase in thermal performance of sintered wick and mesh wick heat pipes; by changing the working fluid, inclination angle and heat input. The experiments are conducted using 0.5 %, 1 %, and 1.5 % CuO/DI water nanofluids in three different concentrations in DI water and weight. The heat carrying capacity of the sintered roving heat pipe was found to be 14.3% higher in the same working conditions compared to the mesh wick heat pipe. Similarly, 27.08% higher reduction in surface temperature is observed for the sintered suppository heat pipe, which is weighted by 1% CuO/DI water nanofluids compared to the mesh suppository heat pipe. The slope angle and weight percentage of CuO nanoparticles significantly affect the thermal performance of both heat pipes.

Kim et al. [31] conducted an experimental study comparing the heat performance of the SiC nanofluid mesh heat pipes with heat pipes filled with water and 0.01 % and 0.1% SiC/water nanofluid mesh wick heat pipes and SiC nanoparticle-coated mesh wick heat pipes to examine the nanoparticle effect on the inner surfaces of the heat pipes. Evaporator thermal resistance increased as nanofluid concentration increased due to thicker nanoparticle accumulation layer, large viscosity and interruption of phase change.

Ghanbarpour et al. [32], investigated the effect of the sloping mesh wick heat pipe on thermal performance using silver nanofluids ın cooling applications at 0.25 %, 0.5 % and 0.75% concentrations. The experiments were conducted at four slope angles of 0°, 30°, 60° and 90°. Due to the gravitational force effects of the heat pipes, it has been observed that they have a lower thermal resistance than the vertical one. In addition, under 0 °, 30 °, 60° and 90° different slope angles, the results showed that the lowest thermal resistance belongs to a slope angle of 60° at all concentrations. At this angle of inclination (60 °), the average effective thermal conductivity of the heat pipe increased by about 11% compared to the horizontal heat pipe.

Table 2. Summary of experimental studies using nanofluids in mesh wick heat pipes

| Author | Size of heat pipe | Nanoparticle | Nanoparticle size | Main fluid | Concentration (% W) | Effect | Results obtained |
|---|---|---|---|---|---|---|---|
| Kole *et al.* [17] | Length:300 mm<br>Outer diameter:10 mm<br>Wall thickness:0.6 mm | Cu | 40 nm | Water | 0.0005, 0.005, 0.05, 0.5 | a | 4 |
| Do *et al.* [18] | Length:300 mm<br>Outer diameter:4 mm<br>Wall thickness:1 mm | $Al_2O_3$ | 30 ± 5 nm | Water | %1.0 and %3.0 | a | 4 |
| Putra *et al.* [19] | Length:200 mm<br>Outer diameter:8 mm<br>Internal diameter:7.44 mm | $Al_2O_3$, $TiO_2$, ZnO, | - | Water, Etilen glycol $C_2H_6O_2$ | %5 and %1 | a | 4 |
| Wang *et al.* [20] | Length:350 mm<br>Outer diameter:8 mm<br>Wall thickness:0.6 mm | CuO | 50 nm | Water | %0.5, %1, %2 | a | 1 and 2 |
| Solomon *et al.* [21] | Length:400 mm<br>Outer diameter:19.5 mm | Cu | 80-90 nm | Water | %0.003, %0.006, %0.009 | a | 4 |
| Asirvatham *et al.* [22] | Length:180 mm<br>Outer diameter:10 mm | Ag | 58 nm | Water | 0.003-0.009 | a | 4 |
| Saleh *et al.* [23] | Length: 200 mm<br>Outer diameter: 8 mm<br>Wall thickness:0.56 mm | ZnO | 18-23 nm | Ethylene glycol (EG) | %0.025, %0.5 | a | 1&4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Liu ve Zhu [24] | Length:350 mm<br>Outer diameter:8 mm<br>Wall thickness:0.6 mm | CuO | 50 nm | Water | %0.5, %1, %2 | a | 1, 2, 3 and 4 |
| Senthilkumar *et al.* [25] | Length:600 mm<br>Outer diameter:20 mm | Cu | 40 nm | Water | 100 mg/L | a | 1 and 4 |
| Hajian *et al.* [26] | Length:1000 mm<br>Outer diameter:33.5 mm<br>Wall thickness:4.07 mm | Ag | - | Water | 50, 200, 600 ppm | a | 1, 2, 3 and 4 |
| Ghanbarpour *et al.* [27] | Length:200 mm<br>Outer diameter:<br>Wall thickness:0.71mm | $Al_2O_3$ | 100 nm-200 nm | Water | 5.0, 10.0 | A for 5%<br>B for 10% | 4 and 7% for 5%; 11 and 12% for 10% |
| Tsai *et al.* [28] | Length:170 mm<br>Outer diameter:6 | Gold | 24, 40, 8, 12 nm | Water | - | a | 1, 4 and 6 |
| Senthil *et al.* [29] | Length:1100 mm<br>External diameter:210 | $Al_2O_3$ | 50 nm | Water | %1.0 | a | - |
| Kumaresan *et al.* [30] | Length:330 mm<br>Outer diameter:12<br>Wall thickness:1 | CuO | 59 nm | Water | %1.0 | a | 4 |
| Kim *et al.* [31] | Length:1000 mm<br>External diameter:17.4 | SiC | - | Water | %0.01, %0.1 | b | 4 |
| Ghanbarpour *et al.* [32] | Length:2000<br>External diameter:6.35<br>Wall thickness:0.71 | Ag | 165 nm | Water | %0.25,<br>%0.5 and<br>%0.75 | a | 1, 4, 7 and 10 |

a: Heat performance increased
b: Heat performance decreased
-: The researchers did not specify the desired value

### *2.1.3. Sintered Metal Heat Pipes*

Sintered metal heat pipes are used in different applications due to its effective performance. Metallic powder made of sintered fuse in such heat pipes is used to produce capillary effect.

Kang et al. [33] investigated the thermal performance of the heat pipe using silver nanoparticles 10-35 nm in size with water. In this study, the heat pipe's thermal performance increase demonstrates the nanofluid potential instead of traditional pure water in corrugated heat pipes and sintered heat pipes. This finding makes nanofluids more attractive as a coolant.

Keshavarz Moraveji and Razvarz [34] examined the increase in heat performance of heat pipe (sintered roving) with 90° curves between evaporator and condensator parts using aluminum oxide nanofluid. The more $Al_2O_3$ nanoparticles dissipated in the operating fluid, the more performance of the heat pipe increased. For a constant temperature difference, it is observed that the use of a nanofluid as a working fluid allows the heat pipe to operate under a larger heat load.

Kumaresan et al. [35] experimentally examined the increase in heat transfer properties of the copper sintered metal heat pipe with CuO nanoparticles that do not contain surface activating substances scattered in deionized water. The experiments were conducted in four different situations, one with DI water and the other three with CuO/DI water nanofluid blood at different concentrations. The heat entry was initially increased by 10W and increased to 160 W with an increase of 10 W. Compared with DI water, a 63.5% increase was recorded in the heat conductivity of the heat pipe for 1.0% CuO/DI water nanofluid. At the same time, the 0.5% and 1.5% increase in weight was 46.6% and 55.9% respectively. Thermal conductivity decreased weight for 1.5% concentration due to the physical properties of nanofluids.

Sadeghinezhad et al. [36] conducted an experimental study to examine the thermal performance of the sintered metal heat pipe using graphene nanofluid. The study focused on changes in the effects of graphene concentration, heat pipe inclination angle and input power. Graphene nanofluid thermal conductivity increased by nanoparticle concentration and operating temperature. The increase for the nanofluid concentrations used varies between 12% and 28%.

Vijayakumar et al. [37] conducted an experimental study on the heat transfer properties of sloping copper sintered wick heat pipes using surface-activated CuO and $AI_2O_3$ nanofluids. With the addition of nanoparticles in low operating conditions, the thermal efficiency of the heat pipe increases by approximately 30.42% and the copper sintered wick heat pipe has been shown to be suitable for high and low heat flux operations.

Table 3. Summary of experimental studies using nanofluids in sintered wick heat pipes

| Author | Size of heat pipe | Nanoparticle | Nanoparticle size | Main fluid | Concentration (% W) | Effect | Results obtained |
|---|---|---|---|---|---|---|---|

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Kang *et al.* [33] | Outer diameter:6 mm<br>Length:200 mm | Ag | 10-35nm | Water | 1.0, 10.0 & 100 mg/L | a | 1,3,4 and 10 |
| Keshavarz Moraveji and Razvarz [34] | Outer diameter:6 mm<br>Length:190 mm | $Al_2O_3$ | 35 nm | Water | 0.0, 1.0 & 3.0 | a | 1, 9 |
| Kumaresan *et al.* [35] | Outer diameter:12 mm<br>Length:330 mm | CuO | 39.1 nm | Water | 1.0 | a | 1, 3, 4 and 10 |
| Sadeghinezhad *et al. [36]* | Outer diameter:12 mm<br>Length:300 mm | Graphene | Thickness= 2<br>Çap= 2 µm | Water | 0.025, 0.050, 0.075 & 0.1 | a | 1, 2, 4, 10 and 11 |
| Vijayakumar *et al.* [37] | Outer diameter:12 mm<br>Length:330 mm | CuO,<br>$Al_2O_3$ | 39.1nm<br>37.5 nm | Water | 0.5, 1.0, 1.5 | a | 1, 4, 9, 11 |

a: Heat performance increased

b: Heat performance decreased

-: The researchers did not specify the desired value

### *2.1.4. Thermosyphon Heat Pipes*

The heat pipe consists of the evaporator section where the heat is absorbed by the working fluid and the condenser section where the heat is given. The condenser condenses the intensive heat of steam giving to the cooler section, and the condensed liquid in the capillary force vaporizer with the help of the corded heat pipes heat pipe water heater with the effect of the force of gravity in the back on returns. Therefore, in thermosyphon heat pipes, the condenser is positioned at the top and the evaporator at the bottom. On the other hand, there is no limitation in vaporizing and condensing positions in roving heat pipes. Due to their simple structure and low costs, there is great interest in thermosyphon heat pipes.

Noie et al. [38], investigated the thermal performance of a closed thermosyphon when $Al_2O_3$/water nanofluid is used at a volume concentration of 1-3% as working fluid. When the thermosyphon heat pipe is loaded with nanofluid, the efficiency i.e. heat transfer capacity increases significantly. For example, at 97.1 W input power, nanofluid heat pipe with a concentration of 1% increased its yield from 75.1% to 81.56%.

Huminic et al. [39] has conducted research on the application of $Fe_2O_3$/ water nanofluid in thermosyphon heat pipe. The test was obtained by distributing nanofluids in pure water of iron oxide nanoparticles. The average size of nanoparticles is 4-5 nm. Experiments were performed at angles of $45^0$ and $90^0$ (vertical) respectively. The presence of 2% iron oxide nanoparticles, 19% increase in heat transfer rate and 5% in water, 3% iron oxide nanoparticles increased by 22%.

Liu et al. [40], used a newly drained tubular solar air collector integrated with simplified CPC (compound parabolic intensifier) and a special open thermosyphon using a water-based CuO nanofluid as the working fluid. The results showed that the application of nanofluid improves the collection efficiency of the solar air collector system, and that the output temperature of the water is higher than that of the water user. Although the experimental assembly consists of only two collection panels, the maximum output air temperature exceeds 170°C at 7.6 $m^3$/s air flow in winter.

Kamyar et al. [41] examined the thermal performance of closed thermosyphon of different volumetric concentrations (0.01%, 0.02%, 0.05% and 0.075%) $Al_2O_3$ and $TiSiO_4$ nanofluids (water-based). In thermal resistance, $Al_2O_3$ for 0.05% volume value decreased up to 65%. However, the best performance for $TiSiO_4$ was achieved by a 57% reduction in thermal resistance at 0.075% volume.

Yang et al. [42] under constant atmospheric pressure, they conducted an experimental study to understand the flow-decoction heat transfer of the water-based CuO nanofluid in the evaporator of a thermosyphon cycle. The pressure has a significant effect on the heat transfer coefficient and a negligible effect on the critical heat flux. Heat transfer coefficient development rate increases with increased pressure.

Sarafraz et al. [43] performed an experimental study with alumina global nanoparticles with an average size of 42-48 nm, ultrasonic homogenizing, magnetic mixer, pH control at constant temperature, well distributed, prepared and stabilized in water-EG and water-

DEB base fluids at different pH concentrations using pH control. Results have shown that water/EG based nanofluids can be stabilized for more than 45 days. By increasing the volumetric concentration of nanofluid, the total temperature has dropped from evaporator to concentrator along the heat pipe for all operating fluids. The maximum reduction was 5% $Al_2O_3$–22.63% with water/EG nanofluid.

Chen et al. [44], examined the evaporation heat transfer properties of the water-based SiO2 functionalized nanofluid. The functionalized nanofluid has good dispersal and stability. The conventional nanofluid (consisting of non-functionalized nanoparticles) forms a slush-shaped layer on the heated surface following evaporation experiment in the thermosyphon. This layer reduces contact angle and surface roughness. The conventional nanofluid also distorts the evaporation heat transfer coefficient more than that of the functionalized nanofluid, but increases the maximum heat transfer of the thermosyphon compared to the functionalized nanofluid.

Heris et al. [45] examined the application of $Al_2O_3$/water and CuO/water nanofluids in the thermosyphon heat pipe electrical space and the effects of nanoparticles on thermal performance, reduced by increased input power of two-phase closed thermosyphon. Increased input power has a significant direct effect on the thermal performance of thermosyphon and causes the decreasing effects of the electric field and nanoparticle decrease.

Menlik et al. [46] examined the effect of MgO/water nanofluid on the thermal performance of a thermosyphon in different operating conditions. The maximum increase is set at 26% at a heat load of 200 W and a cooler flow rate of 7.5 g/s

Sarfraz et al. [47] investigated the thermal performance of the heat pipe (with aqueous $AgNO_3$ and Ag nanoparticles produced from the leaf extract of fresh tea) filled with nanofluids. Studies on temperature change and time response of the heat pipe have shown that with increased Ag/water nanofluid concentration, the time required for the heat pipe to reach constant temperature has decreased significantly, which means that better thermal performance is expected at higher concentrations.

Ciftci et al. [48] are aimed to improve the thermal performance of a closed thermosyphon (heat pipe) with a double phase using nanofluid, which contains nano-sized $TiO_2$ (Titanium dioxide) particles. With the use nanofluid evaporation temperature has been lower on average than 10°C. It was observed that metal oxide particles in nanofluid increased the conductivity of the operating fluid, resulting in an increase in the efficiency of the heat pipe. This increase is approximately 11.76%.

Cakir [49] aimed to increase thermal performance by using nanofluid with 2% $Al_2O_3$ (Alumina) nanoparticles in volumetric as working fluid in thermosyphon (non-roving) type heat pipe. The thermal resistance of the heat pipe with the use of nanofluid is 0.07 levels for the $45^0$ inclined heat pipe, while the use of pure water is around 0.13. On average, the use of nanoparticle has resulted in a 46% reduction in thermal resistance.

Table 4. Summary of experimental studies using nanofluids in thermosyphon heat pipes

| Author | Size of heat pipe | Nanoparticle | Nanoparticle size | Main fluid | Concentration (% W) | Effect | Results Obtained |
|---|---|---|---|---|---|---|---|
| Noie *et al.* [38] | Inner diameter:20 mm Thickness:1 mm Length:1000 mm | $Al_2O_3$ | 20 nm | Water | 1.0–3.0 % | a | - |
| Huminic *et al.* [39] | Inner diameter:15 mm Thickness:- Length:2000 mm | $Fe_2OR_3$ | 4-5 nm | Water | 0%, 2%, ve 5.3 | a | 4 |
| Liu *et al.* [40] | Inner diameter:36 mm Thickness:- Length:6500 mm | CuO | 50 nm | Water | %0.8–%1.5 | - | 1, 2, 3, 4 |
| Kamyar *et al.* [41] | Inner diameter:19 mm Thickness:1.7 mm Length:300 mm | $Al_2O_3$ and $TiSiO_4$ | <100 nm | Water | %0.01, 0.02, 0.05 ve 0.075 | a | 1 and 4 |
| Yang *et al.* [42] | - | CuO | 50 nm | Water | %>0.1 ve <1.5 | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sarfraz *et al.* [43] | Inner diameter:12 mm Thickness: - Length:220 mm | $Al_2O_3$ | 42-48 nm | Water | %1.0–5.0 | a | 1 and 4 |
| Chen *et al.* [44] | - | $SiO_2$ | 30 nm | Water | %0.5–2.5 | b | - |
| Heris *et al.* [45] | - | $Al_2O_3$ & CuO | 25&50 | Water | %1.5, 2.0 & 2.5 | a | 1 and 4 |
| Menlik *et al.* [46] | Inner diameter:13 mm Thickness:2 mm Length:1000 mm | MgO | 40 nm | Water | %5 | a | - |
| Sarafraz *et al.* [47] | | Ag | 40-50 nm | Water | %0.1-0.4 | a | 1 and 4 |
| Ciftci et al. [48] | Inner diameter:13 mm Thickness:2 mm Length:1000 mm | $TiO_2$ | <100 nm | Water | %2 | a | 1 and 4 |
| Cakir [49] | | $Al_2O_3$ | 10 nm | Water | %0.2 | a | 1 and 4 |

a: Heat performance increased
b: Heat performance decreased
-: The researchers did not specify the desired value

### *2.1.5. Oscillating/Pulsating Heat Pipes*

Su et al. [50] researched the thermal performance of the oscillating heat pipe using a nanofluid, self-wet liquid and a self-wet nanofluid. In this experiment, the maximum heat transfer performance of the heat pipe achieved at the optimum component concentration of 0.07% graphene oxide concentration and 0.7% n-butanol concentration in weight. The maximum value of the increase rate in this optimum component concentration is approximately 16% compared to the self-wet liquid and about 12% compared to nanofluid.

Ji et al. [51] conducted a study on a transparent oscillating heat pipe made of five rounds of polydimethylsiloxsandan (PDMS). When PDMS OHP ethanol/$AI_20_3$ is filled with nanofluid, particulate sediment and numerous small bubbles were observed on the inner surface. In addition, there is no significant difference between PDMS OHP and ethanol/$AI_20_3$ nanofluids installed with ethanol. For the electric field effect, no different phenomenon was observed when the 30 V DC electric area was applied to PDMS OHP. In this study, it was observed that the electrical field and Al $_2O_3$ nanoparticles did not affect the heat transfer performance of PDMS OHP.

Ji et al. [52] investigated the effect of $Al_2O_3$ nanoparticles on OHP's thermal performance. Water is used as base liquid for OHP. The particulate sits in four sizes with an average diameter of 50 nm, 80 nm, 2.2 lm and 20 lm. Among the 20 lm, 2.2 lm, 80 nm and 50 nm particles tested here, 80 nm particles could result in the best heat carrying capacity for OHP.

Qu et al. [53] examined $SiO_2$/water and $AI_2O_3$/water nanofluids on the thermal performance of the same two OHP. Unlike added, after using $SiO_2$ /water nanofluids instead of pure water, both evaporation wall temperature and total thermal resistance increased. In addition, this increase has become more pronounced as $SiO_2$ nanoparticle concentrations, rise weight from 0.1% to 0.6%. Weighted 0.6% concentration, vaporizing wall temperature and total thermal resistance increased by 3.5 $^0$C (or 5.5%) and 0.075 $^0$C /W (or 23.7%) respectively, compared with pure water. Thus, the addition of silika nanoparticles into base water disrupted the heat performance of the SIB.

Qu et al. [54] examined the application of $Al_2O_3$/water nanofluid in the oscillating heat pipe. During the experiments, the percentage of nanofluid filling, mass fractions of $Al_2O_3$ nanoparticles, power inputs, the maximum thermal performance of the heat pipe has been modified to achieve. OHP's heat transfer performance increased after the addition of alumina nanoparticles to the working fluid. Compared to pure water, the maximum reduction of thermal resistance was recorded as 58.8 W, the occupancy rate was 70%, and the mass fraction was 0.14°C/W (or 32.5%)..

Tanshen et al. [55] investigated heat transfer and pressure distribution in OHP using multi-wall carbon nanotube (MWCNT) water-based nanofluidic. The inclusion of functionalized MWCNTs increases thermal transport from evaporator section to the concentrator section. The lowest thermal resistance was achieved by aqueous nanofluids based on 0.2% MWCNT.

Goshayeshi et al. [56] performed an experimental study under the magnetic field using $Fe_2O$ 3/Paraffin nanofluid in heat pipe from copper to moon. The temperature difference between the surface and steam core in the evaporator section was achieved in the copper heat pipe (after the addition of $Fe_2O_3$ without magnetic field and with the magnetic field, respectively, 3.1$^0$C and 2$^0$C.

Riehl et al. [57] concluded that copper nanoparticles developed evaporation and blistering boiling at low heat loads and higher heat loads respectively. The vibrating heat pipe has been tested with deionized water and 5% copper nanoparticles nanofluid to compare the results. Because the thermal conductivity of the copper nanofluid on offer is approximately 15% larger than pure water, an increase is expected in thermal conductivity compared to pure water for PHP, which works with nanofluidity, and the observed experimental data has confirmed this situation.

Gunnasegar et al. [58] investigated the thermal performance of the cycled heat pipe using nanofluid for the temperature inlet range from 20 W to 100 W. $SiO_2$-$H_2O$ give LHP lower temperature using nanofluid and becomes stable in less time than LHP using pure water. As the use of nanofluid in the heat pipe gains attraction in the development of technology in this area, and with an ever-increasing amount of heat emitted by functional components such as desktop PC CPUs, this work will certainly lead to further research.

Taslimifar et al. [59] reported that ferrofluidic application at open LHP improves thermal performance in a stable situation and can be further improved by applying a magnetic field.

Table 5. Summary of experimental studies using nanofluidic in Oscillating/Vibrating heat pipes

| Author | Size of heat pipe | Nanoparticle | Nanoparticle size | Main Fluid | Concentration (% W) | Effect | Results obtained |
|---|---|---|---|---|---|---|---|
| Su *et al.* [50] | Inner Diameter:2 mm Outer Diameter:4 mm Total Length:2.2 m | Graphene oxide | 50-200 nm | n-butanol | 0.3, 0.7, 1.2 & 1.8 | a | 1 and 2 |
| Ji *et al.* [51] | - | $AI_2O_3$ | 50,80 | Ethanol | - | c | - |
| Ji *et al.* [52] | - | $AI_2O_3$ | 50, 80, 2.2 µm and 20 µm | Water | 0.5 | a | - |
| Qu *et al.* [53] | Inner Diameter:2 mm Outer Diameter:3 mm Total Length:3 m | $SiO_2$& $AI_2O_3$ | 30 & 56 | Water | 0–0.6 and 0–1.2 | a | 4 |
| Qu *et al.* [54] | Inner Diameter:2 mm Outer Diameter:3 mm Total Length:6 m | $AI_2O_3$ | 56 | Water | 0.1, 0.3, 0.6, 0.9 & 1.2 | a | 4 |
| Tanshen *et al.* [55] | Inner Diameter:3 mm Outer Diameter:4 mm Total Length:6 m | MWCNT | 56 | Water | 0.05, 0.1, 0.2 and 0.3 | a | 5 |
| Goshayeshi *et al.* [56] | Internal Diameter:1.75 mm Outer Diameter:3 mm Total Length:4.4 m | $Fe_2OR_3$ | 20 | Kerosene (Paraffin) | 2 | a | 1 |
| Riehl *et al.* [57] | Inner Diameter:1 mm | Cu | 29 | Water | 5 | a | 5 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Outer Diameter: mm Total Length:4 m | | | | | | |
| Gunnasegaran *et al.* [58] | Internal Diameter:13.5 mm Outer Diameter:15 mm Total Length: m | $SiO_2$ | 12 | Water | 3 | a | 1 and 2 |
| Taslimifar *et al.* [59] | Internal Diameter:1.75 mm Outer Diameter:3 mm Total Length: m | $Fe_3Or_4$ | 25 | - | 2.5g/l | a | 1, 3 and 4 |

a: Heat performance increased
b: Heat performance decreased
-: The researchers did not specify the desired value

Table 6. Summary of mechanisms/causes responsible for changes in thermal performance of heat pipes in studies conducted using nanofluids by researchers

| Number | Mechanisms/Causes Of Change in Heat Generation Performance of the Heat Pipe |
|---|---|
| 1 | Advanced thermophysical properties of nanofluid (especially thermal conductivity) increase heat transfer |
| 2 | Decrease in contact angle between the inner surface of the nanofluid and heat pipe has increased capillary strength and surface wettability |
| 3 | Brownian movement of nanoparticles in base fluid increases heat transfer |
| 4 | The build-up of nanoparticles on the surface creates an artificial layer that bombards vapour bubbles during bubble formation on the solid-liquid interface, reducing thermal resistance. |
| 5 | The build-up of nanoparticles increased the number of core regions that increased bubble formation, vibration movement and, finally, thermal efficiency. |
| 6 | Improved conveyor heat transfer coefficient and critical heat flux have increased the operating range of the heat input of the heat pipe |
| 7 | Increased heat transfer area in the evaporator by creating a thin porous layer |
| 8 | Higher mix fluctuations that improve thermal performance of oscillating/ vibrating heat pipes |
| 9 | Presence of optimum nanofluid concentration |
| 10 | Effect of tilt angles (gravity effect) on heat performance of the heat pipe |
| 11 | Thermal performance of the heat pipe decreased due to increased viscosity |

| | |
|---|---|
| 12 | Thermal performance of the heat pipe has decreased due to the formation of a cover of lumped particles with weak adhesion forces between particles and heated surface |

### 2.2. Numerical Studies

Huminic and Huminic [60] performed a numerical study on the thermal performance of the thermosyphon heat pipe using water and nanofluid (Water-hanging Fe-$Fe_2O_3$ nanoparticles) as working fluids.

*Tahery et al.* [61] analytically investigated water-based nanofluids containing $Al_2O_3$ nanoparticles. As a result of numerical research, nanofluid vertical spaces are better than horizontal spaces. In addition, the gaps used in nanofluid have been shown to have better efficiency in numerical modelling of natural convection for both horizontal and vertical liquid layer.

Vasu *et al.* [62] As the car refrigerant on a flat-wing compact heat exchanger with flat pipe, the $Al_2O_3$+$H_2$ performed a theoretical analysis using that nanofluid NTU evaluation method.

Murugesan and Sivan [63] developed lower/upper limits for the thermal conductivity of nanofluids and compared theoretical data with the published experimental result.

Shafahi et al. [64] examined the thermal performance of the cylindrical heat pipe using two-dimensional analyses with $Al_2O_3$, CuO and $TiO_2$ nanofluids.

Table 7. Summary of numerical studies on heat pipes using nanofluids

| Author | Nanofluid | Comments |
|---|---|---|
| Huminic *et al.* [60] | $Fe_2O_3$ | Numerical and experimental data are in good harmony in increasing the thermal performance of the heat pipe using nanofluid. |
| Tahery *et al.* [61] | $Al_2O_3$ | Vertical cavities in nanofluids have better efficiency in numerical modelling of natural convection for both horizontal and vertical liquid layer. |

| | | |
|---|---|---|
| Vasu *et al.* [62] | $Al_2O_3$ | The cooling capacity of the $Al_2O_3$ nanofluid is very high. |
| Murugesan *et al.* [63] | $Al_2O_3$,CuO and $TiO_2$ | Particle shape, Brownian movement and nanolayer are important in increasing the thermal conductivity of nanofluids. |
| Shafahi *et al.* [64] | $Al_2O_3$, CuO and $TiO_2$ | The researchers noticed a change in maximum heat transfer, thermal resistance and wall temperature distribution of the heat pipes, which uses nanofluids. |

## 3. CONCLUSIONS

In this study, the results of various experimental/numerical studies on heat pipes using nanofluids were discussed. The study results of the current literature show that application of fluids increases the thermal performance of heat pipes. The reasons for the increase in thermal performance of the heat pipe can be explained as follows:

- The thermal conductivity of the nanoparticles is higher than that of the base liquid, so the dispersion of the base fluid increases the thermal conductivity of the working fluid. Therefore, the replacement of the base liquid with nanofluid increases the heat transfer performance of the heat pipe.
- The nanoparticles found in the base liquid form a coating layer on the suppository structure of the heat pipe. This increases the capillary movement of the working fluid, thus increasing thermal performance.
- Brownian movement of nanoparticles improves heat transfer performance.

All experimental/numerical studies can classify parameters that change the thermal performance of heat pipes as follows:

- Effects related to nanofluids parameters; main fluid, nanofluid preparation technique (single step or two step method), shape of nanoparticles, size, materials, stability of the nanofluid, concentration, surface tension, thermal conductivity, viscosity, specific heat, density, etc.

- Effects of operating parameters of heat pipes; Filling ratio, tilt angle, power input, suction pressure, etc.
- Effects on design parameters; Heat pipe type, material, evaporator length, adiabatic and concentrator section, knitting/groove properties, surface roughness, braid wall roughness, etc.
- Effects on nanofluid; Heat pipe interactions, particles and adhesion forces between heated surface, changes in wet properties, such as surface roughness and particulate size ratio

The temperature resistance and efficiency of the parameters can be summarized as follows:

- Nanofluid concentration: As the concentration of nanofluids increases, the thermal efficiency of the heat pipe increases and thermal resistance decreases.
- Nanoparticle size: As the nanoparticle size decreases, the thermal efficiency of the heat pipe increases and thermal resistance decreases.
- Input power: As the input power increases, the thermal efficiency of the heat pipe increases and thermal resistance decreases.
- Cooling water mass flow: As the cooling water mass flow increases, the thermal efficiency decreases, thermal resistance increases.
- Heat pipe inclination angle: The inclination angle of the heat pipe is also effective on heat pipe performance. As the angle of the heat pipe slope increases, it encourages the condensation of the liquid in the concentrator section and can take more fluid flow to evaporate. However, larger tilt angles, i.e. closer to the vertical position, cause performance to decrease. This is because of faster condense rotations that affect the function of the evaporator section. Therefore, there is an optimum angle value where the yield reaches the highest value.

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