

# Different Applications of Nanotechnology to Enhance Thermal Performance of Heat Pipes

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## ABSTRACT

Heat pipes are heat transfer devices which are widely used due to their higher effective thermal conductivity in comparison with conductive metals such as copper and aluminum. Several kinds of heat pipes exist such as pulsating heat pipe, rotating heat pipe, wick heat pipe, vapor chamber and thermosiphons. Heat pipes contain a fluid which evaporates by receiving heat at evaporator and then the vapor is converted into liquid by heat dissipation in the condenser. Different types of heat pipes are classified based on the mechanism of return of condensed fluid from the condenser to the evaporator. Nanotechnology is mainly used in recent years to enhance heat transfer in different mediums as well as heat pipes in the form of nano-fluids or nano-surfaces. This paper gives a comprehensive review on the most recent applications of nanotechnology to enhance the performance of these heat pipes.

**Keywords:** Nanotechnology, Nano-Fluids, Nano-Surfaces, Rotating Heat Pipes, Wick Heat Pipes, Pulsating Heat Pipes, Vapor Chambers, Thermosiphons, Micro Heat Pipes

## 1. INTRODUCTION

Heat pipes are effective cooling devices that have been widely used for various purposes and applications in recent years, such as cooling turbine blades, water heating systems, and solar stills. There are various types of heat pipes which include rotating heat pipes, wick heat pipes, pulsating heat pipes, vapor chamber and thermosiphons. Heat pipes are generally categorized based on the mechanism of fluid motion inside them.

The heat pipe is a closed passive heat transfer device that is vacuumed and charged with working fluid. The working principle of heat pipes is based on fluid vaporization at the heat source and condensation of that vapor at the heat sink. Hence, the main parts of heat pipes are the evaporator and condenser, respectively, which are in the vicinity of the heat source and heat sink. Additionally, in cases where there is a significant gap between the evaporator and the condenser, an adiabatic segment can be added.

The working fluid receives the heat from evaporator section and evaporates. It then reaches to the condenser section. The working fluid that is evaporated condenses by releasing

heat in the condenser part and the condensed liquid goes back to the evaporator part. The cycle is thus completed and repeated. In general, the condensed fluid is transferred to the evaporator section using the gravity and capillary forces. With this approach, a small amount of a certain working fluid can transfer large amount of heat using its phase change characteristics.

Heat pipes are utilized extensively in various applications due to their efficient heat transfer performance, especially in different energy systems. Therefore, heat pipe combines boiling and condensing heat transfer altogether. Because to its simple geometry and passive characteristic, it has been widely applied in various industries.

Standard heat pipes use the capillary force for fluid return. Grooves or wicks in the pipe can provide this necessary capillary force. Rotating heat pipes use the centrifugal force to bring back the condensed liquid from the condenser to the evaporator part. Generally, a bigger centrifugal force leads to improved thermal performance in these heat pipes. Pulsating heat pipes also consist of a tube with small diameter (capillary tube) with several bends. On the other hand, gravity force is the main reason for liquid motion in the thermosiphons. Consequently, compared to other types of heat pipes, thermosiphons are more sensitive to the orientation [1].

In general, there are various situations in industry where enhancing the effectiveness of heat transfer can benefit the quality, quantity, and/or cost of a product or process. In many of these cases, nanotechnology is a good candidate for the enhancement of heat transfer performance. In the heat pipe industry, nanotechnology can be utilized to replace the traditional working fluids with nanofluids or modify the surface of the heat pipe to increase the heat transfer.

## **2. DIFFERENT TYPES OF HEAT PIPES**

### **2.1. Pulsating heat pipes (PHPs)**

These are the most compact type of heat pipes. Because of its two-phase heat transfer mechanism, the efficient thermal conductivity of PHPs is much higher compared to metals. PHPs consist of a capillary tube that is bent in multiple turns and partly filled with a working fluid. If capillary tubes two endings are connected to each other, the PHP is considered closed loop PHP. On the other hand, when the ends are separated, the PHP is known as open loop PHP. The main parts of PHPs are evaporator and condenser sections. In addition, adiabatic section exists in cases there is distance between condenser and evaporator.

In the evaporator section, the received heat generates vapor and results in growth of the size of bubbles and increase in vapor pressure. This causes the movement of the fluid toward the condenser part. During the dissipation of heat in the condenser section, the pressure of bubbles decreases and condensation happens. Growth and collapse of the bubbles inside the tube results in a pulsating movement of the fluid inside the PHPs.

Aside from the more compact size relative to other types of heat pipes, PHPs have a simpler structure than regular heat pipes, as they do not need a wick structure. They also are more compact compared to thermosiphons. PHPs can also be used in a range of applications that are small in scale. In recent years, several studies have been conducted which show the increased thermal efficiency of PHPs. Some of them concentrate on the structure of the PHPs to enhance the movement of fluids to achieve better thermal behavior. For example, the fluid

movement in the tube can be improved by interconnecting the PHP channels or using non-uniform channels which leads to a more stable pulsation of the fluid in horizontal mode compared to PHPs that have uniform channels. PHPs are appropriate devices to be used as heat exchangers due to their high effective thermal conductivity.

## **2.2. Wick Heat Pipes**

Wick heat pipes are widely used because of their higher capillary limits. Wick heat pipes are widely used because of their simplicity, flexibility and also their ability to work against gravity. The working fluid inside the heat pipe can be circulated by capillary force which is generated from wick structure. This structure enables the wick heat pipe to function in any orientation. Typically, the wick heat pipe consists of a sealed container with a wick material which is filled with enough liquid to completely saturate the wick.

Several types of wick structures exist and can be utilized within the heat pipe. They are mainly categorized as mesh, grooved, powder, and composite wicks. A grooved heat pipe is a copper tube which is made of shallow grooves around the internal perimeter of the heat pipe. A mesh heat pipe is a copper tube with smooth walls and a woven copper mesh installed along the interior side of the pipe. In a powder wick heat pipe which is also known as sintered heat pipe, working fluid can efficiently pass through sintered pipes due to the small size of the pockets. These pipes can be used at all degrees between horizontal and vertical directions including even upside down. A mandrel is placed in the middle of the pipe during the fabrication process, and copper powder is poured into the pipe around the mandrel. The pieces are put inside a sintering oven after the powder is properly packed. The copper powder will stick to the pipe and to itself at a certain temperature, creating plenty of internal pockets like a sponge.

## **2.3. Rotating Heat Pipes**

Rotating machines are devices that convert electrical energy into mechanical energy or conversely, the mechanical energy into electrical energy. In such machines, heat is generated as a result of the electrical and mechanical losses inside the machine which can cause overheating and hence, reduce the machine performance as well as its lifespan. Therefore, managing the thermal dissipation for maintaining temperature in the specified range is vital for the safety and reliability in numerous engineering domains. A general solution for this problem is to insert a cylindrical heat pipe within the axis of rotation of the rotating machine as well as inside the various gaps between the axis and other parts of the machine to extract its heat and reduce its temperature. In this process, the pipe rotates or revolves at the speed of the machine. Rotating and revolving heat pipes have been successfully studied and implemented in cooling rotating machinery and generators for decades.

## **2.4. Vapor Chambers**

A vapor chamber is a capillary driven equipment with planar design with a low aspect ratio. Extra wick blocks between the condenser and evaporator assist the condensate to return, especially when the condenser is below the evaporator. If the condenser is placed above the evaporator, then there would be no need to have a wick in the condenser section. This is because the condensate on the upper plate is going to move back to the evaporator with the help of

gravity. However a wick is required in the evaporator section to disperse the liquid uniformly on the entire surface and prevent dry out parts.

The vapor chamber is a perfect candidate to be used in electronic cooling applications, particularly for applications with high heat flux, such as desktops and servers. For electronic cooling with heat fluxes higher than 50 W/cm<sup>2</sup>, vapor chambers are preferred over CHPs because in this case heat flow is two-dimensional or three-dimensional, compared to one-dimensional in CHPs. In addition, vapor chambers can be put in direct contact with CPUs by using thermal interface materials. This reduces the overall thermal resistance of heat sinks.

## 2.5. Thermosiphons

The simplest structure among the mentioned types of heat pipes belongs to thermosiphons. It consists of a tube which is evacuated and charged partially with a working fluid. The working fluid evaporates due to heat it receives at lower part of the tube (evaporator) and then it converts to the liquid state and condenses at upper section (condenser) of tube which has lower temperature compared to the evaporator. Gravity is the driving force for fluid return from condenser to the evaporator.

Thermosiphons are gravity-assisted heat pipes which operate by using latent heat of vaporization of working fluid. The most important advantage of thermosiphons is their efficient performance without requiring any mechanical device such as pump. Thermosiphon applications include heat exchangers, cooling systems, energy storage, water heater, heat recovery, solar ponds.

Several parameters affect thermal performance of thermosiphons including geometry, working condition, heat input, material and surface roughness of the tube, filling ratio, inclination angle, and working fluid.

## 3. APPLICATION OF NANOFUIDS IN HEAT PIPES

### 3.1. Nanofluid Characterization

Initial research and development of nanofluid technology has uncovered an excellent potential for heat transfer applications and has led both industry and universities worldwide to launch research and development efforts in this area which has increased considerably over the past several years.

Nanofluid is a term to describe a fluid in which nanometer-sized particles are suspended. Nanofluids are heat transfer fluids based on nanotechnology that are derived from stably suspended particles of a nanometer size (with standard length scales of 1 to 100 nm) in common heat transfer fluids, typically liquids. It has been shown that nanofluids consisting of such particles suspended in liquids (typically traditional heat transfer liquids) improve the convective heat transfer efficiency and thermal conductivity of the base liquids. Usually, the particle thermal conductivities are higher than those of the base fluids, which are primarily water, ethylene glycol, and light oils. Therefore nanofluid application, even at low volume concentrations, results in major thermal efficiency increases.

Several methods have been evaluated in recent years in order to change properties of working fluids to obtain fluids with more desirable specifications. Adding surfactants to a fluid can significantly influence the surface tension; while adding nanoparticles augments thermal

conductivity. In addition, it would be possible to have a mixture of fluids with various boiling points by using binary fluids which may result in improved heat transfer capacity. Thermal conductivity of the working fluid and its boiling heat transfer play key role in thermal behavior of heat pipes in general. Many industrial processes involve the transfer of heat by means of a flowing fluid in either the laminar or turbulent state as well as flowing or stagnant boiling fluids. These processes cover a wide range of temperatures and pressures. Many of these processes benefit from a decrease in the thermal resistance of the heat transfer of the working fluid. This approach would lead to smaller heat transfer systems with lower capital costs and improved energy efficiencies. Nanofluids are able to reduce such thermal resistances. Nanofluids can be defined as a solid-liquid composite materials which consist of nanometer sized solid particles, fibers, rods or tubes present in different base fluids. Nanoparticles mainly are pure metals (Ag, Au, Fe, and Cu), metal oxides (SiO<sub>2</sub>, CuO, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, ZnO, and Fe<sub>3</sub>O<sub>4</sub>), Nitrides (SiN, AlN), Carbides (TiC, SiC), and various types of carbon (graphite, diamond, single/multi wall carbon nanotubes). Base fluids mainly are water, ethylene glycol and engine oil. Nanofluids have thermal properties that are very different from those of conventional heat transfer fluids. The distinctive features of nanofluids include a stronger temperature-dependent thermal conductivity than the base fluid alone, a substantial increase in thermal conductivity with low particle volume concentrations, an increase in critical heat flux (CHF) in pool boiling, and a substantial increase in the heat transfer coefficient at low particle volume concentrations. Nanofluids have many advantages such as:

- 1- High effective thermal conductivity.
- 2- Very small size, so it fluidizes easily inside the base fluids and can move faster inside porous media.
- 3- High specific surface area.
- 4- Small particle concentration which helps the fluid to sustain Newtonian behavior.
- 5- Viscosity, specific heat, density and thermal conductivity can be easily changed by changing particle concentrations to make them suitable for various engineering applications.
- 6- Low pumping power needed.
- 7- Heat transfer enhancement which is the result of increasing the heat transfer surface area between the particles and fluids.
- 8- High extinction coefficient which is a function of the particle diameter and wave length of the light compared to the conventional base fluid. This makes the nanofluid capable of absorbing the light's energy in solar energy systems such as solar collectors.
- 9- High dispersion stability.
- 10- Prevention of the erosion and clogging phenomena because of the small size of the particles.
- 11- High thermal capacity, because of the small volume of nanoparticles which helps the nanofluid to easily store a large quantity of heat. This in turn decreases the energy losses and eventually increases the efficiency of the system
- 12- Nanoparticles significantly increase the optical properties of the base fluid

Nanofluids improve the heat transfer coefficient of thermal energy systems and facilitate the reduction in size of such systems which leads to increased energy and fuel efficiencies, lower pollution, and improved reliability.

### 3.2. Nanofluid Fabrication

Modern technology allows the fabrication of materials at the nanometer scale. Nanoparticles are a class of materials that exhibit unique physical and chemical properties compared to those of larger (micron scale and larger) particles of the same material. Nanoparticles used in nanofluids are made out of various materials. The nanoparticles manufacturing process can be divided into two broad categories: physical processes, and chemical processes.

Some nanoparticle materials that have been used in nanofluids are oxide ceramics (Al<sub>2</sub>O<sub>3</sub>, CuO); nitride ceramics (AlN, SiN); carbide ceramics (SiC, TiC); metals (Ag, Au, Cu, Fe); semiconductors (TiO<sub>2</sub>); single-, double-, or multi-walled carbon nanotubes (DWCNT, SWCNT, MWCNT); and composite materials namely core-polymer nanoparticle shell composites. Additionally, new materials and structures are desirable to be used in nanofluids where the interface between particles and liquids is doped with different molecules.

Nanoparticles of various materials have been produced by physical or chemical synthesis techniques. Typical physical methods include the mechanical grinding and the inert-gas condensation techniques.

Chemical methods to create nanoparticles include chemical precipitation, deposition of chemical vapors, micro-emulsions, spray pyrolysis, and thermal spray. A sonochemical method for making suspensions of iron nanoparticles stabilized by oleic acid has also been developed. Mechanical milling, inert gas condensation procedure, chemical precipitation, spray pyrolysis, and thermal spraying are the latest methods for producing metal nanoparticles.

Nanoparticles of most materials are commonly produced in the form of powders. In powder form, nanoparticles can be dispersed in aqueous or organic host liquids to form nanofluids for specific applications. Many types of host liquids have been used with the nanoparticles mentioned.

Nanofluids have been produced by two techniques: a two-step technique and a one-step technique. The two-step technique starts with producing nanoparticles by one of the physical or chemical synthesis techniques, and then to disperse them into a base fluid. The one-step technique simultaneously makes and disperses the nanoparticles directly into a base fluid. Most of the nanofluids containing oxide nanoparticles and carbon nanotubes are created by the two-step process.

Nusselt number most often represents the heat transfer resistance of a flowing fluid. It takes into account the fluid thermal conductivity through the Prandtl number. Therefore, obtaining thermal conductivity is the first evaluation of a nanofluid's heat transfer potential.

In order to prepare nanofluids by dispersing nanoparticles in a base fluid, a proper mixing and stabilization of the particles is required. The nanoparticles are very small in size and within the range of 1–100 nm. Due to the following key issues, it is strongly recommended to not use large solid particles (more than 100 nm) in the base fluids:

- 1-The standard millimeter or micrometer-sized particles sink quickly in the fluid and create a layer on the surface. This fouling layer reduces the heat transfer of the fluid.
- 2-Large solid particles need a high pumping power which increases the cost.
- 3-Due to the high viscosity, the pressure drop in the fluid increases considerably.

4-The large particles in the suspension make it inapplicable with the emerging miniaturized devices. It is because these large particles can block the small channels of these devices.

### **3.3. Application of Nanofluids in Pulsating Heat Pipes**

The most pragmatic approach to improve the thermal performance of PHPs is to use surfactants or nanofluids. Thermal performance of PHPs is improved using nanofluids which is related to higher thermal conductivity of the nanofluids compared to the pure fluids and also the increase in nucleation sites caused by the presence of nanoparticles.

Mohammad Alhuyi Nazari et al. studied the effect of using graphene oxide nanofluid in thermal performance enhancement of a PHP. Graphene oxide nanofluid with 0.25 g/lit, 0.5 g/lit, 1 g/lit, and 1.5 g/lit concentrations were utilized as working fluid in the PHP. In all tests the filling ratio was 50% of the PHP's total volume. Enhancement in fluid dynamic viscosity and thermal conductivity was made by adding graphene oxide to the base fluid. Their results showed that adding graphene oxide nano-sheets to the base fluid at 10W heat input and 0.25 g/lit concentration can reduce PHP's thermal resistance to more than 40%. Moreover, they found out that increasing concentration worsens thermal performance of the PHP which is attributed to increase in dynamic viscosity of working fluid. A regression model was also proposed to compare the effects of nanosheets concentration and heat input on thermal performance of the PHP. The R-square and root mean square deviation of this regression model were obtained to be 0.9562 and 0.080, respectively which showed validity of correlation [1].

Meibo Xing et al investigated the thermal performance of a vertical closed PHP filled with hydroxylated MWNTs based aqueous nanofluids in 0.1 to 1 wt% concentration range. They found out that adding nanoparticles to the working fluid could significantly improve the heat transfer characteristics and increase the PHP's heat removal capacity. However, nanofluid PHP would generate larger motion obstruction of the liquid slugs in higher viscosities. Results showed that the nanoparticles concentration influences the start-up procedure of PHP. The heat transfer also happens due to frequent variations in temperature and a higher frequency of temperature fluctuation results in higher heat transfer of the PHP. Meibo Xing et al. concluded that the application of MWNTs-OH in the PHP depending on the concentration and input power can significantly improve the heat transfer performance of PHP. Their experimental results indicated that when input power is increased to 100 W, the thermal resistance of PHP with 0.1 wt% nanofluid content is decreased by 34% compared to pure water PHP [2].

### **3.4. Application of Nanofluids in Wick Heat Pipes**

Due to the larger application domain, researchers have used nanofluids as working fluid in mesh wick HPs and have found some positive results. In the last years, many research articles on effects of the application of different nanofluids on mesh wick HPs thermal characteristics have been published. The majority of research articles claimed that nanofluids improved the thermal performance and operating limits of HPs.

Naveen Kumar Gupta et al. investigated the improvement in mesh wick heat pipe (HP) thermal performance by using TiO<sub>2</sub>/H<sub>2</sub>O nanofluid as working fluid with different concentrations of 0.5, 1.0, and 1.5 vol % and for different power inputs of 50, 100, and 150W. HP's wick surface was then coated with TiO<sub>2</sub> nanoparticles using physical vapor deposition

method. The experimental investigation had been also carried out on coated wick HP using water as working fluid.

Naveen Kumar Gupta et al. concluded that heat pipe with TiO<sub>2</sub>/H<sub>2</sub>O nanofluid as working fluid shows higher thermal performance compared to water alone. Nanoparticle coating might be used to enhance the thermal performance of heat pipes. In their study, thermal performance of heat pipe with coated wick using water as working fluid was very close to that of the heat pipe with uncoated wick using nanofluid. Thus, nanoparticle coating might be a good substitute for nanofluid in similar cases. Temporal deterioration study also supports the use of nanoparticle coating [3].

M. Vijayakumar et al conducted an experimental investigation on the characteristics of heat transfer for inclined copper sintered wick heat pipes with surfactant free Al<sub>2</sub>O<sub>3</sub> and CuO nanofluids as their working fluid. The minimal difference between the surface and vapour temperature of evaporator section viz. 1.8 °C and 2.6 °C, for the optimum concentration of 1.0 wt.% and 1.5 wt.% were compared with the DI water. The obtained results for the same conditions in the condenser section were -1.3 °C and -2.1 °C for Al<sub>2</sub>O<sub>3</sub> and CuO nanofluids. The optimum reduction in vapor temperature difference for Al<sub>2</sub>O<sub>3</sub> and CuO nanofluids viz. 9.6 °C and 8.5 °C at 1.0 wt.% and 1.5 wt.% respectively. The inclination angle was kept constant at 45° for both the cases.

M. Vijayakumar et al. found out that the heat pipe thermal efficiency increases around 30.42% by adding nanoparticles at low operating conditions. Their experiments showed that the copper sintered wick heat pipe is ideal for operations with high and low heat flux. They found out that sintered wick heat pipe that is filled with CuO/DI water nanofluids reaches the maximum thermal conductivity of 48.88, 63.52 and 52.85% compared with Al<sub>2</sub>O<sub>3</sub>/DI water nanofluids of 40.84, 48.97 and 59.23% of the concentration of 0.5 wt.%, 1.0 wt.% and 1.5 wt.% respectively [4].

Their results showed that any addition of high conductive particles tremendously increases the sintered wick heat pipe's thermal performance at an optimum tilt angle of 45°.

### **3.5. Application of Nanofluids in Rotating Heat Pipes**

Ziya Uddin et al. numerically studied the heat transfer through the rotating heat pipe containing nanofluids using PSO. They found out that, the heat transfer through the heat pipe depends on various factors. viz., the input nanofluid mass, rotation speed of the heat pipe, nanoparticle size and nanoparticle concentration etc. They concluded that for maximum heat transfer there is a particular value of working fluid mass. For fixed values of nanoparticle size and nanoparticle concentration, heat transfer was Maximum for lower mass of nanofluid and high rotation speed of heat pipe. For fixed value of nanofluid mass and rotation speed, the heat transfer was maximum for high concentration of nanoparticles in the base fluid. For fixed values of nanoparticle size and fixed rotation speed of heat pipe, heat transfer was Maximum for lower mass of nanofluid containing high concentration on nanoparticles. For fixed values of nanofluid mass containing a particular size of nanoparticles, the heat transfer was Maximum for high rotation speed of the pipe and higher value of nanoparticle concentration. For fixed value of nanofluid mass containing a particular concentration of nanoparticles, the heat transfer



was maximum for high rotation speeds of the heat pipe containing nanofluid with small sized nanoparticles [5].

### **3.6. Application of Nanofluids in Thermosyphons**

One amongst the most important factors in thermal performance of thermosyphons is working fluid and its thermo-physical properties. Selection of working fluid is highly dependent on its application. For instance, at low temperature, fluids with lower boiling temperature which evaporate easier are more appropriate, while high temperature devices require fluids which have high boiling temperatures to prevent dry-out phenomenon. Due to their thermophysical properties such as higher thermal conductivity compared to the pure fluids, nanofluids have the potential to boost thermal efficiency of thermosyphons.

Ramezanizadeh et al. reviewed the applications of nanofluids in thermosyphons and presented their important obtained results. Based on their reviewed researches, different nanoparticles including carbon, carbon oxide, metal and metal oxide can be used in thermosyphons to improve heat transfer. They concluded that using nanofluids which contain different types of particles, improves thermal performance of thermosyphons. This is mainly attributed to nanofluids thermal conductivity and the nanoparticles impact on boiling heat transfer.

Based on the reviews they concluded that Nano sized solid phase in the base fluid enhance thermal conductivity which results in better heat transfer. Moreover, due to more nucleation points, these particles are able to increase the boiling point of operating fluids within the thermosyphone, contributing to higher heat transfer efficiency.

Based on the researches reviewed, they concluded that an optimum concentration exists for nanoparticles in the fluid. It is true that any increase in concentration of nanoparticles increases thermal conductivity, but on the other hand, resulting particles agglomeration reduces thermal performance. Agglomeration of particles prevents the motion of fluid and decreases boiling heat transfer. Moreover, another effect of increase in concentration is higher dynamic viscosity of the fluid which in turn negatively affects thermosyphon's operating fluid.

Finally, different applications of nanofluidic thermosyphons were represented and reviewed by Ramezanizadeh et al. They found out that using nanofluids in thermosyphons, results in higher efficiency of these systems. This improvement in the system efficiency is due to the heat transfer medium's improved thermal performance which is the result of using nanofluids as working fluid.

Ramezanizadeh et al. proposed that in future, the studies should be directed on using hybrid nanofluids which have suitable thermophysical properties in two-phase heat transfer. Using binary fluids as the base fluid, can also expand the operation range of thermosyphons. Furthermore, new types of metallic nanoparticles could be suitable alternatives for the conventional working fluids but needs more investigation [6].

## **4. APPLICATION OF NANO-SURFACES IN HEAT PIPES**

For a heat pipe, the phase distribution and parameters such as vapor pressure and temperature are not only dependent on evaporator, but also dependent on condenser. The phase distribution refers to the distribution of vapor and liquid in an empty space which is not

occupied by any solid material. In case of two-phase flow, a specific part of the void space is either occupied by liquid or vapor. The information about phase distribution indicates where the liquid and vapor phases are.

Firstly, the evaporator and condenser coupling, influences the vapor pressure and temperature in heat pipes. Secondly, coupling of the evaporator and condenser influences the phase distribution in the area not occupied by solid material.

If hydrophobic evaporator and hydrophilic condenser is used, the circulation of liquid phase becomes difficult and the heater is easily dried out and also the condensed liquid film deteriorates the performance of condenser. Thus, phase distribution is an important factor that influences the phase change heat transfer in heat pipes. Therefore, control of wettability and liquid in heat pipes are the key factors to manage the phase distribution. The purpose of this strategy is to retain mechanism of nucleation and to suppress mechanism of convection.

Xianbing Ji et al. demonstrated the benefit of micro/nano structure for heat pipe and the water return path. They proposed a novel strategy to enhance vapor chamber heat pipe performance. The mastoid process array, control of heat pipe wettability and liquid charged into it were comprehensively used to manage the phase distribution by nanosurface modification on sintered particle surface and/or condenser surface.

By holding the nucleation mechanism, their heat pipe behaved excellent thermal sensitivity with respect to heating loads. They thoroughly verified their idea by experimenting on three heat pipe samples: first, equal wettability sample, second, moderate wettability difference sample and third, opposite wettability sample. Nanostructured surface were used to generate the wettability difference. The first sample demonstrated the convection mechanism with constant heat transfer coefficients (HTCs) versus heat fluxes. This was due to evaporator porous wick being filled with more vapor and also condensation of liquid forming a film on condenser surface. The super-hydrophobic condenser and super-hydrophilic evaporator (third sample) showed the significant increase of the mechanism of nucleation with HTCs with increases in heat fluxes. This was due to large driving force flooding the evaporator porous wick with water and exposing condenser to vapor. They found out that heat pipe with opposite wettability match had overall thermal resistances of only 1/3 of those of heat pipe with equal wettability.

Xianbing Ji et al. concluded that using mastoid process array and control of wettability and the amount of water charged into heat pipe decreases heater temperatures by 30–40°C at high heat fluxes such as 100 W/cm<sup>2</sup> on a large heater area of 1.4 cm<sup>2</sup> which is considered a novel approach for the improvement of heat pipe performance [7].

## 5. MICRO HEAT PIPES

Many studies have been made to develop innovative micro-cooling technologies with the capability to remove a significant amount of heat from chips or improve uniformity of temperature and provide efficient and compact thermal control solutions for next generation electronics and optoelectronics. Among these technologies, micro heat pipes (MHPs) have shown to be one of the most promising solutions and have gained considerable attention.

A normal MHP consists of a single noncircular channel to accommodate both liquid and vapor phases. There are no additional wicks on the inside wall which are used by conventional

heat pipes to facilitate the condensate return to the evaporator section. Instead, large capillary forces are generated in sharp edged cross sections of the noncircular channel.

The hydraulic radius of an MHP can be compared in magnitude to the capillary radius of vapor-liquid interface. This relationship give a clearer definition of MHP and differentiates between MHPs and small sized conventional heat pipes [8].

Recently, polymer-based heat pipes made by polymer casing materials have also gained growing interest since they offer high performance, flexibility and low-cost thermal management solutions for future heat generation systems. MEMS-compatible fabrication processes also make polymer heat pipes applicable in electronics packaging especially in flexible organic display devices. Therefore, this emerging heat pipe is also included in the MEMS-based MHP category.

MEMS-based MHPs work as micro coolers and provide the following advantages Compared to conventional heat pipes [9]:

1. Accurate control of temperature at the chip level.
2. Efficient overall cooling since different heat sources inside the electronic package may be modified to decrease the contact thermal resistance.
3. Compatibility of materials to electronic systems.
4. Replication on a large scale and mass production.

In certain types of MHPs Wicks are important components. Consequently, nanostructured and micro/nano-hierarchical wick structures namely silicon or metal nanowires (NW) and carbon nanotubes (CNTs) are provided and analyzed to be used as novel wicks to suit these micro devices' small size due to their high capillarity and extended thin-film evaporation area.

Nowadays, advances in nanotechnology and technologies related to surface treatment have made it applicable to create micro/nanostructured surface cost-effective, and therefore particularly expanding design possibilities and produce nano-sized wicking structures available for MHPs. Compared with simple surfaces, nano-structured materials improve different aspects of the boiling and evaporation process (e.g., nucleation boiling, incipience, thin-film evaporation, and CHF) via copper nanowire (NW) and silicon NW surface coatings, nanoporous surface coatings, carbon nanotube (CNT) coatings on silicon wafers and metal substrates, and titania (Ti) nanostructure coated on Ti pillar.

In order to increase the heat pipe efficiency and avoid dry-out at higher power levels or improve the heat flux, a great deal of effort has been directed to development and optimization of wick structure to provide maximal capillary pumping while increasing the thin film area of meniscus evaporation. Consequently, nano-sized wick structures such as metal or silicon NWs and CNT have also been developed and tested to be used as capillary wicks because of their suitable characteristics and artificial micro wicks (such as micro-pillars or micro-fins).

While pores of the CNT and NW arrays can generate greater capillary pressures in order of magnitude than standard microwicks, the low permeability of these arrays also prevents the supply of fluid to the entire surface, resulting in a wick with poor performance even at normal heat inputs. In order to overcome the difficulties caused by low nano-wick permeability, a nature-inspired hierarchical nano-and micro-structured capillary wick design has recently been proposed to attain high permeability and capillary action at the same time and to greatly improve effective evaporation characteristics as a result. Such a wicking structure design is

inspired by biporous wicking systems and integrated nano-structured wick surfaces that improve the permeability of wicks and reduce their thermal resistance. Liquid return mechanism enhanced by capillary forces, evaporation of thin film on the vapor-liquid interfaces, along with rapid vapor ventilation still are key issues to be investigated further in these new wicks [10].

## 6. CONCLUSION

Different forms of nanoparticles are applicable in heat pipes, including copper, copper oxide, steel and steel oxide, to achieve improved heat transfer. The use of nanofluids, which contain different types of particles, leads to an increase in heat pipe thermal efficiency, primarily due to nanofluid thermal conductivity and the effects of nanoparticles on boiling heat transfer. Nano-sized solid phase in the base fluid improves thermal conductivity leading to improved heat transfer. In addition, due to more nucleation sites inside the heat pipes, these particles can increase the boiling point of operating fluids which leads to higher heat transfer capability.

It can be inferred that there is an optimal concentration for nanoparticles based on the researches reviewed here. Though any rise in nanoparticles concentration results in higher thermal conductivity, agglomeration of particles causes thermal efficiency degradation. Agglomeration of particles can prevent fluid movement and reduce boiling heat transfer. Furthermore, concentration increase results in higher dynamic viscosity which is not suitable for heat pipe's operating fluid.

Studies have shown that the application of nanofluid in heat pipes contributes to higher system performance. Improved system efficiency is due to enhanced heat transfer medium's thermal performance by using nanofluids as working fluid. Future research will concentrate on the use of hybrid nanofluids which have suitable heat transfer thermophysical properties. In addition, binary fluids can be used as the base fluid to expand the operating range of heat pipes. Additionally, new types of nanoparticles may be implemented as a viable alternative to standard working fluids which needs further investigation.

Researchers' findings also revealed that due to the different phase distributions using nano-surface, two heat transfer mechanisms (nucleation and convection) can be switched by variation in the wettability of evaporator and condenser surfaces. The results revealed major advantage in using super-hydrophilic evaporator and super-hydrophobic condenser to control the distribution of water and to eliminate the effect of convection in heat pipes.

With the development of nanotechnology, the hope is that hierarchical hybrid micro/nanotextured surfaces inspired by nature will serve as novel capillary wicks for emerging MEMS based MHPs. With regard to the ongoing trend of miniaturizing electronic/optoelectronic devices and circuits, and the rapid development of MEMS products, MEMS-based MHPs will play ongoing and future roles in advanced thermal engineering and biomedical applications.

Further studies on both fundamental and industrial levels are still required. Developing easy and practical charging processes and packaging standards is critical to enabling MEMS-based MHP to compete with other micro-cooling systems. For practical applications it is important to improve the robustness and durability of MEMS-based MHPs. Full understanding

of the behavior of phase change in micro-scale and micro/nano hierarchical structured surfaces, wetting and rewetting cycle, thin film evaporation, capillary pumping action, and limitation of heat transport affected by related factors are also important.

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