Applications of Nanoporous Layered Wick and Nanofluids in Heat Pipes: a Review

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***Abstract*—This Literature review concentrates on optimization two core research investigation outputs in two phase heat and mass transfer applied recent heat pipes development; the amount of nanofluids concentration in heat pipes and thickness of nanoporous layer on wick surfaces for best performance in heat pipe applications. Research outputs of nanofluidic heat pies, nanoporous heat pipe trails, pool boiling characterization of nanofluids, pool boiling characterization of nonporous wicks, numerical studies on nanofluidic heat pipes and nanofluids has been reviewed thoroughly to generalize the requirement of optimizing nanofluids-nanoporous layered wicks for best performance of heat pipe applications. Finally the review deals with the future advantages of functionalized CNTs its application in heat pipes with proper functionalization methods.**

Keywords: nanofluids, nanoporous, wick, heat pipe, CNT functionalization.

I. Introduction

Since the last decade a lot of numerical and experimental studies on nanofluids has been investigated by several researchers around the world in the application of different types heat pipes; circular, flat evaporator and innovative design works too. Advancement in the area of heat pipe study come injunction with nanofluids and nanolayered porous media film boiling phenomenon. Researchers on nanofluids have reported that nanoparticles deposit on the surface of the evaporator area and this has been attributed as the main contribution for the performance increments in applications of nanofluids in the area of various two phase heat transfer [1-8]. The effect of density, thermal conductivity, viscosity and surface tension has been considered as a secondary effect [5]. On the other hand of the research area of film boiling on nanolayered porous wicks, a lot of research investigations has been done to increase the areas of nucleate citation to improve the boiling phenomenon by developing nanolayer wicked porous medias which are the current research area [14-26]. This review paper objective is to investigate the cross linked relation between the nanofluids, nanofluidic heat pipes and boiling on nanolayered porous media. This research review is believed to give an insight for researchers to develop the existence of an optimum level of nanofliud concentration and optimized level of nanoporous layered wicks to enhance the thermal performance of two phase heat transfer especially in the application of heat pipes which is considered in detail. CNTs are considered as the future potential area of nanofluids and nanoporous wick application due to its high thermal conductivity as well are high capillary potential in heat pipe applications [39-42].

II. Nanofluidic and Nanoporous Wick Heat Pipes

A. Nanofliudic Heat Pipes: CHF, concentration, thermal resistance, wettability and capillary pressure

R. Sureshkumar et al [1] presented a review of recent research on fluid flow and the heat transfer characteristics of nanofluids in heat pipes and identifies perspective of nanofluids that can be used in heat pipes for further research. Performance of heat pipe using nanofluids enhances due to an increase in critical heat flux and convective heat transfer of the nanofluid.

S.-W. Kang et al [2] studied the thermal performance of sintered wick circular heat pipe using silver nanofluid in DI water base fluid. In this study, two different sizes of nanoparticles of 10 and 35 nm at three different concentrations of 1, 10 and 100mg/l mixed in two step method without surfactant has been investigated. The thermal resistance (temperature distribution over the length) of the heat pipe was measured and analyzed. The results indicate that the temperature difference between evaporator and condenser section decreases with an increase in nanoparticle concentration. Using nanofluids the critical heat flux increased to 70W compared to pure water limited to 50W. The effect of nanoparticle size on heat pipe thermal performance is slight.

M. Kole et al [3] studied the performance of Cu-DI water nanofluid prepared without surfactant at concentration ratios of 0.0005%wt, 0.005%wt, 0.05%wt and 0.5%wt for different orientation of circular heat pipe with screen mesh. The results indicate that the thermal conductivity of the fluid increased by 15% at 30◦C resulting in 27% reduction in thermal resistance of the heat pipe 0.5%wt concentration. The total thermal resistance of the heat pipe decreases with the increasing Cu concentration in nanofluid and with an increase in input power. A heat dissipation of 100W were achieved at inclination angle of 90° keeping the evaporator at bottom. Deposited Cu layer were observed on the screen mesh wick of the evaporator explained as the reasons for heat pipe performance enhancement.

Z-H Liu [4] reviewed literatures on heat pipes using nanofluids as a working fluid. They explained the possible mechanisms of enhanced heat transfer of the micro-groove wick heat pipe and the mesh wick heat pipe using nanofluids by three reasons. The first reason is that the effective thermal conductivity of nanofluids increases. The second reason is that is that nanofluids decrease the solid–liquid contact angle; it makes the liquid extending in micro-grooves and mesh. Also, the reduction of solid–liquid contact angle increases the capillary force in the heat pipe. The third reason is that nano-particles deposited on the wall form a thin porous layer, which increases the solid–liquid wettability and the capillary force.

M H. Busschmann et al [5] reviewed the recent experimental and modelling studies of nanofluids in thermosyphons and heat pipes. The review indicated that the main mechanism responsible for the improved thermal performance seems to be a porous layer built from nanoparticles on the evaporator surface. Additional positive effects may follow from the changed thermo physical properties of the working fluid. He reviewed that most studies indicate that the condenser is not or only weakly affected by nanofluids; however, some experiments see also strong effects. There are no research results on investigation of the vapour phase with respect to the transport of nanoparticles directly. Nanofluidic heat pipe possible mechanisms for performance improvement has been categorized as; due to improved thermal conductivity, higher critical heat flux, increased bubble departure frequency, enlarged heat transfer area and capillary force, presence of optimum concentration ratio and change of wettability due to porous nanoparticle layer formed on the evaporator.

Z-H Liu [6] investigated the effect of aqueous CuO nanofluids on the thermal performance of a horizontal mesh heat pipe working at sub-atmospheric pressure. They found that at 1.0%wt nanoparticle concentration heat dissipation has been improved by 42%. Z.H. Liu et al [7] performed an experiment to investigate the effect of nanoparticles in the nanofluid on the thermal performance in a miniature thermosyphon. The nanofluids consisted of de-ionized water and CuO nanoparticles having an average size of 30 nm CuO-water nanofluid was used as the working fluid. Based on the experience they had, in order to prevent the occurrence of a sorption layer formed by nanoparticles on the heat transfer surface, no surfactant was added into the suspensions. The mass concentrations of the CuO nanoparticles in the present experiment were 0.1, 0.5, 1.0, and 2.0 wt %, respectively. The surface tension of the nanofluid decreased about 15% compared with that of water irrespective of the mass concentration of particles. The presence of only 1.0 wt % of nanoparticles can significantly decrease the wall temperature of the evaporator section when the input power is below about 200 W. The experimental results indicated that the mass concentration of nanofluids has great influence on the nucleate boiling heat transfer for every test pressure. At a fixed test pressure, the heat transfer coefficients of nanofluids are gradually enhanced with the increase of the mass concentration compared with that of water when the concentration is less than 1.0 wt %. The maximum enhancement effect corresponds to the mass concentration of 1.0 wt % and the heat transfer coefficient could be double at sub atmospheric pressures. The pressure has very significant influence on the boiling heat transfer and the CHF of nanofluids, the heat transfer coefficient, and the CHF of nanofluids greatly increase with the decrease of the test pressure, with unknown reasons. The heat transfer coefficient and the CHF increased, respectively, about 160% and 120% at the pressure of 7.45 kPa.

Z-H Liu et al [8] has carried out to understand the heat transfer performance of a miniature thermosyphon using water-based multiwalled carbon nanotube (CNT) suspensions as the working fluid with average diameter of 15nm and length range of 5–15µm. Effects of the CNT mass concentration and the operation pressure under three steady operation pressures of 7.4 kPa, 13.2 kPa and 20 kPa on the average evaporation and condensation heat transfer coefficients, the critical heat flux and the total heat resistance of the thermosyphon were investigated. Experimental results show that CNT suspensions improved the thermal performance of the thermosyphon at an optimal CNT mass concentration of about 2.0%. The enhanced heat transfer effect is weak at low heat fluxes while it is increased gradually with increasing the heat flux which confirms that the thermal performance of a miniature thermosyphon can be strengthened. They also found that the operation pressure has significant influence on the evaporation heat transfer coefficient enhancement while negligible impact on the CHF enhancement.

Generally experimental studies indicate that nanofluids are identified as the best working fluids in cooling applications with a concentration of o 0.5%wt to 1%wt. Limited researchers reported a use of nanofluids reduces the thermal performance of the heat pipe. Layer of nanoparticle deposition is attributed as the main reason for CHF improvement at the evaporator while the effect is negligible at the condenser.

K.H. Do et al [27] developed one-dimensional mathematical models to study the effect of nanofluids on heat pipe performance based on thermophysical property improvement and change of heat transfer area characteristic. It is found that the change of the heat transfer surface characteristics by the formation of the thin porous coating layer plays a primary role in the heat transfer enhancement of the heat pipe compared with the change of fluid thermophysical properties. The numerical study also resulted the optimum concentration ratio of 1.0%wt and optimum nanoparticle size range of 10nm to 60nm for better thermal performance of a nanofluidic heat pipe. Heat transfer enhancement ratio defined as thermal resistance of nanofludic heat pipe to base fluid heat pipe were used to compare the results. The heat transfer enhancement ratio ranges from 1.2 to 2.2 for the different nanoparticle size, working temperature, and input heat rate.

Maryam Shafahi et al [28] analytically obtained the liquid pressure, liquid velocity profile, and temperature distribution of the heat pipe wall, temperature gradient along the heat pipe, thermal resistance and maximum heat load for the flat-shaped heat pipes utilizing a nanofluid from common types of nanoparticles of Al_2O_3, CuO and TiO_2 as the working fluid. They also studied analytically the effect of nanoparticle concentration and wick thickness in maximizing the heat removal capacity of a disc and flat shaped heat pipe using nanofluids. The potential for reducing the size of a heat pipe for a given heat load by utilizing a nanofluid has been studied. For an applied heat input of 9 kW and the evaporator temperature was kept at 90 °C and the smallest particle size results in the largest reduction in the size of the heat pipe. For CuO based nanofluid a 30% and 20% reduction in size can be realized for the disk and rectangular shaped heat pipes respectively.

K. Alizad et al [29] investigated analytically the transient behavior, performance, and operational characteristics of flat-shaped heat pipes using nanofluids of Al_2O_3, CuO and TiO_2nanopowder as the working fluid. The results demonstrate that a higher percentage of nanoparticles results in a better performance for the flat-shaped heat pipes.

H. Hassan et al [30] developed three-dimensional transient model with experimental validation for vapour chamber (flat heat pipe) and the effect of nanofluids on its performance. The effect of Cu, CuO and Al_2O_3 nanofluids on the vapour chamber performance is investigated for different wick porosities. They found that at volume fraction 9% of Cu nanoparticles, the maximum temperature gradient of vapour chamber decreases by about 19.5% for wick porosity 0.75 and 15.7% for wick porosity 0.35.

L. Asmaie et al [31] studied numerically the effect of CuO/Water nanofluid for a thermosyphon circular heat pipe based on the experimental data done by previous researcher, Z.-H Liu et al [4]. Based on the VOF simulation, they have found that the effect of nanoparticles on the reduction of the wall temperature was more significant for high inlet power and the maximum heat flux of the nanofluid was found only a performance improvement of 46% which is a huge deviation from the experimental result. However, the optimum concentration of CuO nanoparticle has been matched with experimental result.

B. Gavtash et al [32] simulated the effect of nanofluids on the heat pipe outer wall temperature distribution, thermal resistance, liquid pressure and axial velocity in presence of suspended nano-scaled solid particle (i.e. Cu, Al_2O3 and TiO_2) within the fluid (water). The effect of particle concentration and size were explored and it is concluded that the thermal performance of the heat pipe is improved when using nanofluid as the system working fluid. Additionally, it was observed that the thermal resistance of the heat pipe drops as the particle concentration level increases and particle radius decreases. They used a transient, three-dimensional model considering micro wicks developed by M. Rajan et al [33]

Even though researchers have done extensive numerical studies on nanoflidic heat pipe, it lacks testing of the expected results experimentally. Up to the current authors knowledge there are no numerical and experimental comparative studies to optimize the amount of nanoparticles concentration with determined micro-layer on the wick material. This needs further numerical as well as experimental investigation to reach on an optimum level of lanofluidic-nanolyerd heat pipe for best performance in the recent cooling technology development.

B. Nanoporous layered wick heat pipes: thermal performance, nanoporous layer thickness, permeability and capillary pressure

M. Hashimoto and J. Weibelet al [9,10] developed a model two phase heat spreader with sintered copper powder of size 50μm targeting the passive cooling of heat sources with fluxes greater than 5 W/mm^2 without requiring any active power consumption for the thermal solution. Additionally, thermal chemical vapour deposition method has been used to coat multi-walled carbon nanotubes (CNT) that were rendered hydrophilic by UV irradiation. Such nano-structured evaporators successfully showed a further reduction in thermal resistance of the vapor chamber. The evaporator with CNTs coated CNT using a sputtered catalyst exhibits a lower thermal resistance than the bare sintered sample except at the lowest heat flux. The CNT-coated sample prepared using a dendrimer catalyst, in contrast, shows degraded performance compared to the bare sample. Reductions in thermal resistance of up to 20-37% with CNT nano structuring relative to a bare sintered surface were demonstrated. The different catalyst growth methods were found to yield differing CNT lengths and densities which directly impact the observed thermal performance. They also found that based on the thermal resistance comparison for a heat spreading capacity of 5 W/mm^2, the best performing sample was with a thickness of 0.5mm CNT layer for a 100μm copper particle size. The heat spreader developed can dissipate at least 8.5 W/mm^2 when using a micro-structured sintered particle wick evaporator.

L.L. Vasiliev et al [11] analyzed experimentally the parameters of the evaporators with smooth capillary grooves and capillary grooves having porous coating of walls with a thickness of 20-100 μm. Ammonia and propane were used as the working fluid. Porous coating plays the role of additional and stable centers for the vapor generation, which do not require high superheating of the surface. For grooves of different shapes and dimensions, the increase in the heat transfer coefficients is within the range of 1.3-1.6 times.

R. Ranjan et al [20] they have developed models based on continuum analyses to predict capillarity, permeability, and thermal resistance of nanowicks (NWs). The model is based on the assumptions of vertically aligned posts in both hexagonal and square packed arrangements on the substrate, a contact angle of 15◦C and continuum approximation in determining the liquid meniscus shape in the wick pore and the liquid flow and heat transfer at the scale of CNTs and NWs. They found that use of nanowicks can lead to a decrease in the wick thermal resistance by two orders of magnitude compared to commercially available wicks however, the permeability of these wicks is very small. This numerical based study on CNT-enhanced sintered particle wick microstructure resulted in an enhancement in the permeability and showed that hydrophilic CNTs can lead to a 14% decrease in the thermal resistance relative to the corresponding wick with the same flow resistance and without nanostructures. Based on typical fabrication processes available, the CNT diameter and wick density are varied over 40–300 nm and 10^8-10^{10}per m^2 respectively, to study the effect on ΔP_{cap}.

J. A. Weibel et al [22] developed a numerical model of a wick with integrated sintered and nanostructured areas to estimate the thermal resistance of the evaporator region compared to that of a homogeneous sintered powder wick. The inputs needed for this model include the permeability and the capillary pressure in the two regions. A parametric study is conducted as a function of the ratio of conduction and evaporative resistances for the nanostructured and sintered regions. For a given heat input, the optimal liquid-feeding geometry that minimizes thermal resistance is obtained. In the best cases, the thermal resistance is reduced by a factor of thirteen through the use of the integrated nanostructured wicks compared to the resistance of a homogeneous sintered powder wick.

III. CHARACTERISTICS OF NANOFLUIDS AND NANOPOROUS LAYERED WICKS

A. Characteristics of nanofluids

1. Thermal conductivity and stability

K. M. Khanafer and K. Vafai [34, 35] et al reviewed the disagreement in the experimental data reported by many authors for the effective thermal conductivity and dynamic viscosity of nanofluids. They developed an experimental model to create a classical equations at low-volume fractions for the effective thermal conductivity and viscosity of nanofluids of Al_2O_3–water and CuO–water at room temperature.

K. M. Khanafer and K. Vafai [34, 35] developed a generalized correlation for the effective thermal conductivity of Al2O3 –water and CuO–water nanofluids at ambient temperature accounting for various volume fractions and nanoparticles diameters using various experimental data. Eastman et al [36] showed that increase in thermal conductivity of approximately 60% can be obtained for the nanofluids consisting of water and 5 vol% CuO nanoparticles. Das et al [37] reported that even though CuO–water nano-fluids have shown better thermal properties, they have not been used because CuO nano-particles have explosive characteristics at temperature more than 100◦C with moist air and they produced considerable fouling.

K. Han et al [38] conducted an experimental study and invalidated the previous research findings on temperature dependence of thermal conductivity of nanofluids. K. Han et al studied the thermal conductivities of water and ethyl glycol as well as nanofluids using Transient Hot Wire Method (THWM) excluding the impact of natural convection for the temperature range 293–338 K. Using this method, the thermal conductivity enhancements of the water-based Ag nanofluid with 0.7% volume fraction and the EG-based ZnO nanofluid with 1.3% volume fraction were measured to be 6.3% and 8.2%, respectively. Based on statistical analysis, they have found that the thermal conductivity values were independent of the fluid temperature.

A. Nasiri et al [39] studied experimentally the heat transfer mechanism and stability for five different CNT structures functionalized by using a one-step chemical functionalization method. They found that the CNT structures with smaller diameter show greater enhancement in thermal conductivity and as the number of nano-tube wall increase, both stability and thermal conductivity decrease. The increase of temperature in all suspensions led to thermal conductivity enhancement and a linear relationship were obtained in the range of 15–40°C.

L. Chen et al [40] compared that CNTs have the higher thermal conductivity than metal or metal oxide materials based on the chemical surface effects of CNTs in improving the thermal conductivity enhancement with the increase of temperature. For the nanofluid containing sphere metal or metal oxide nanoparticles the strong temperature dependence of thermal conductivity was due to the Brownian motion of nanoparticles. However, for the water-based nanofluids containing CNTs with chemical functionalization, in addition to the Brownian motion of CNTs, the chemical surface effects of CNTs should come into the main play in determining the extent of energy transfer in nanofluids with changes of temperature. Thermal conductivity values for single-walled carbon nanotube (SWNT), double-walled carbon nanotube (DWNT) and multi-walled carbon nanotube (MWNT) are 6000 W/mK, 3986 W/mK, and 3000 W/mK, respectively. At about 55◦C and the same CNT volume fraction of 0.002, the thermal conductivity enhancements are 15.6%, 14.2%, and 12.1% for SWNT, DWNT, and MWNT nanofluids in water, respectively.

Finally, effective thermal conductivity of the nanofluids has a positive improvement on the heat pipe but still the effect of thermal conductivity improvement contribution on the overall heat pipe performance needs to be quantified by further researches compared to the effect of the particles settled on the evaporator forming layers of coating.

2. Nanoparticle deposition, critical heat flux, concentration, and wettability

The nanolayer deposition occurred during the pool boiling experiment has been studied at different concentrations of nanofluids by H. D Kim et al [12] and B. Stutz et al [13]. This research team investigated that there exists an optimum thickness of nano layer deposition on the heating element for enhancement in the CHF.

H. D Kim et al [12] investigated the CHF characteristics of nanofluids, pool boiling experiments of nanofluids with various concentrations of TiO_2 or Al_2O_3nanoparticles using a 0.2 mm diameter cylindrical Ni–Cr wire under atmospheric pressure. The nanofluid's volumetric particle concentrations has been varied from 10^{-5}% to 10^{-1}%. They have performed two experimental works; pool boiling CHF experiment and characterization of the heating surface modification. They have used SEM images to characterise the nanoparticle deposition on NiCr heating element during tests on the nanofluids. They reported that the same heating element, in which nanoparticles has been deposited during nanofluid performance test, has been used to study the pool boiling characteristics of pure water. The results indicated that the same CHF has been obtained and concluded that the improvement in CHF of nanofluids is clearly due to the heating element modification by nano particle deposition. They also observed that the contact angle in case of pure water on a coated heating element were much smaller compared to the bare heating element which is a result of significant enhancement in surface wettability.

B. Stutz et al [13] performed a similar experiment as H. D Kim et al [12] with a different heating element of a 100µm diameter platinum wire immersed in saturated water or pentane at 1 bar. Nanostructured surface coating has been obtained by deposition of charged γ-Fe_2O_3 nanoparticles (average diameter of 10 nm) on the platinum wire by vigorous boiling process or electrophoresis process in nanofluid of 1g/l. A significant decrease (from 88◦ down to 33◦) of the static contact angle was observed between the clean surface and the nanoparticle-coated surface. This enhancement in wettability has been attributed to the increase of the liquid–solid interfacial tension of water from non-oxidized metal to metal oxide, and the roughness of the surface. For the poorly wetting fluid (water), the CHF initially increases rapidly with the surface contamination, until it reaches an asymptotic value when the heater is entirely covered with nanoparticles with maximum the relative CHF improvement of about 90%. On the contrary for the highly wetting fluid (pentane), the increase in heat transfer area induced by the coating, the CHF increase does not appear to be appreciable. The CHF enhancement depends on the covering rate of the heated surface by nanoparticles also it evolves with the coating duration. It reaches a maximum when the heater is entirely covered with nanoparticles and then decreases slowly when the thickness of the coating increases. The CHF increase is more noticeable with a poorly than with a highly wetting fluid.

B. Characteristics of nanoporous wicks: effect of Porosity, pore size, permeability, capillary, and thin film evaporation

Small sized and high performance electronic devices are the current and future expectation from the customer side. Hence, heat and mass transfer studies on Nanoporous media for the application of heat transporting in the area of high density electronic cooling has become an active area of research. Compared to the every fast growing electronic devices, micro wicked heat pipes reached a limitation of lower heat transfer capacity at the evaporator component. More research works are required to meet the immense amount heat rejected, in terms of heat generated per unit area (heat flux) from these small high performance gadgets.

K.C. Leong et al [14] studied comparison between copper powder sintered at 800^{o}C and 1000^{o}C at different sintering time duration. The specimen sintered at 800^{o}C has more pores smaller than 6µm while sintered at 1000^{o}C has more pores in the 30-100µm range. The resulting porosity is 45% and most pores are in the range of 30-40µm. The porosity and the pore size distribution are similar to wicks fabricated using injection molding technique.

M. A. Hanlon et al [15] developed a two dimensional model to predict the overall heat transfer performance of a sintered wick and found that thin film evaporation occurring only at the top surface of a wick plays an important role in the enhancement of evaporating heat transfer and depends on the thin film evaporation, the particle size, the porosity, and the wick structure thickness. Thin film evaporation can provide significantly higher overall heat transfer coefficients, but it is limited by the capillary force and by the onset of bubble nucleation.

R. Rajan. et al [16] studied the evaporative performance for steady state and static liquid-vapour interface using a numerical model for the evaporating liquid meniscus in wick microstructures under saturated vapor conditions for different common wick geometries used in heat pipes; wire mesh, rectangular grooves, sintered wicks and vertical microwires. More than 80% of the evaporation heat transfer is noted to occur from the thin-film region of the liquid meniscus, on the order of 10µm.

R. Rajan et al [17] they have coupled a micro-scale wick-level model from results of [16] with a macro-scale device-level model in order to capture the interface curvature effects in different microstructures. Suitable user-defined functions (UDFs) have been developed to compute the evaporation/ condensation mass flow rates, temperature and pressure at the wick–vapor interface, as well as the liquid and vapor densities at every time step with static liquid menisci shape. Mass transport due to evaporation at the liquid–vapor interface is implemented by imposing mass sink terms in the liquid cells adjacent to the interface. Non-uniformity in the meniscus thickness leads to two counter-rotating Marangoni vortices in the liquid domain. The simulations are performed for two different values of the accommodation coefficient of the working fluid, viz., 0.03 and 1. From the results obtained using the coupled and non-coupled model, they found that the thermal resistance offered by the liquid–vapor interface inside the vapor chamber may become significant and affects the performance of the vapor chamber as the device is miniaturized, and as novel high-conductivity thin wicks become available.

K. K. Bodla et al [18] developed a modified VOF model with a modified Schrage equation and computed the capillary pressure, characteristic pore radius, percentage thin film area and evaporative mass and heat fluxes for sintered copper wicks. They employed X-ray microtomography to generate geometrically faithful, feature preserving meshes. They used three types of commercially sintered wicks with particle sizes in the range of 45–60 µm, 106–150µm and 250–355µm with approximately 61% porosity have been considered. It was observed that all the three samples exhibit a similar heat transfer coefficient, thereby establishing that the overall heat transfer may be improved by simply increasing the meniscus surface area per unit volume. They recommended that one such way is to reduce the particle (pore) size.

S.C. Wong et al [19] studied the combined evaporation resistance measurement and visualization for sintered copper powder wick for flat plate heat pipes. They found that quiescent surface evaporation prevailed for sintered wick working with water with no nucleation boiling observed up to heat flux larger than $100 W/cm^2$ inspite of the abundant nucleation sites. The minimum evaporation resistances were about 0.08–0.09 Wcm^2/K for wicks containing fine powders similar with those for multi-layer-mesh wicks having a fine bottom screen.

R. Ranjan et al [20] they have developed models based on continuum analyses to predict capillarity, permeability, and thermal resistance of nanowicks (NWs). The model is based on the assumptions of vertically aligned posts in both hexagonal and square packed arrangements on the substrate, a contact angle of 15◦C and continuum approximation in determining the liquid meniscus shape in the wick pore and the liquid flow and heat transfer at the scale of CNTs and NWs. They found that use of nanowicks can lead to a decrease in the wick thermal resistance by two orders of magnitude compared to commercially available wicks however, the permeability of these wicks is very small. This numerical based study on CNT-enhanced sintered particle wick microstructure resulted in an enhancement in the permeability and showed that hydrophilic CNTs can lead to a 14% decrease in the thermal resistance relative to the corresponding wick with the same flow resistance and without nanostructures. Based on typical fabrication processes available, the CNT diameter and wick density are varied over 40–300 nm and 10^8-10^{10}per m^2 respectively, to study the effect on ΔP_{cap}.

A.S. Kousalya et al [21] developed an experimental facility that simulates the capillary fluid feeding conditions of a vapor chamber for pool boiling. Carbon nanotubes (CNTs) are fabricated on a 200 µm thick sintered copper powder wick layer using microwave plasma enhanced chemical vapor deposition technique. They compared thermal performance of the bare sintered copper powder sample (without CNTs) and the copper functionalized CNT-coated sintered copper powder wick samples. They found that a notably reduction in boiling incipient superheat for the nanostructured samples and CNT coated with thicker copper increased the dry out heat input up to $457 W/cm^2$ from a 5 mm x 5 mm heat input area. The performance improvement were attributed as due to improved surface wettability of which is found to increase with an increase in copper coating thickness.

J. A. Weibel et al [22] developed a numerical model of a wick with integrated sintered and nanostructured areas to estimate the thermal resistance of the evaporator region compared to that of a homogeneous sintered powder wick. The inputs needed for this model include the permeability and the capillary pressure in the two regions. A parametric study is conducted as a function of the ratio of conduction and evaporative resistances for the nanostructured and sintered regions. For a given heat input, the optimal liquid-feeding geometry that minimizes thermal resistance is obtained. In the best cases, the thermal resistance is reduced by a factor of thirteen through the use of the integrated nanostructured wicks compared to the resistance of a homogeneous sintered powder wick

Y. Nam et al [23] developed pool boiling 3D model for copper oxide nanostructures formed on the micropost surfaces. They have done characterization study on the effect of the interpost spacing and solid fraction for a fixed post diameter on the effective heat transfer coefficient and critical heat flux. In agreement with their experimental pool boiling test, they found a significantly enhance in the critical heat flux of, $>500 W/cm^2$, without compromising the effective heat transfer coefficient, $>10 W/cm^2K$.

Y. Nam et al [24] fabricated and characterized hydrophilic nanostructured Cu microposts using electrochemical deposition combined with a controlled chemical oxidation scheme. The effect of post diameter and pitch on the capillary performance has been tested for two cases. The micropost model has a size 50µ m diameter, 100 µm pitch, 110 µm height resulted a capillary rise of 4mm for water and 2.5mm for methanol in agreement with the predicted values, neglecting gravity effects.

J. Weibel et al [25,26] worked on implementation of controlled CNT growth techniques and functionalization methods to enhance boiling heat transfer from the porous capillary wicking surfaces with porosity of 50% sintered from 100µm particle diameter. The sintered layers in both geometries were 1 mm thick and covered the central 20.3 × 20.3 mm of the 25.4 × 25.4 mm substrate CNT hydrophilic property has been achieved by physical vapor deposition of copper micro powder on a permeable CNT, synthesized by a microwave plasma-enhanced chemical vapor deposition (MPCVD). Under an experimental facility, they obtained up to 72% reduction in surface temperature for both CNT coating and mico patterning of the porous surface under two-phase heat transfer conditions with water as the working fluid.

As a conclusion nonporous layers leads to a higher boiling performance through and increased nucleation sites at the evaporator surface though film boiling resulting up to $>500 W/cm^2$ [23] and 72% reduction in surface temperature for both CNT coating and mico patterning of the porous surface under two-phase heat transfer conditions with water as the working fluid [25,26]. This potential of increase in heat transfer performance needs to be coupled with nanofluids for an ultimate performance achievement and reduction in size of cooling devices.

IV. CNT FUNCTIONALIZATION

Due to the hydrophobic nature of CNTs, a uniform and sustained solution of nanofluid cannot be achieved and the nano porous made from pane CNTs will be hydrophobic increasing the contact area resulting in diminished evaporation rate. Therefore CNT Functionalization is necessary to convert its characteristics to hydrophilic nature before using it for thermal application; both as a nanofluid particle as well as a nanoporous structure. L. Chen et al [41] remarked that the introduction of oxygen-containing groups on the surface of CNTs enhances their solubility in aqueous or organic solvents and reduces the van der Waals interactions between different CNTs, promoting the separation of nanotube bundles into individual tubes.

Kim et al., 2006 have chemically treated carbon nanotubes using a mixture of H_2SO_4 and HNO_3. The effects of acid treatment methods on the diameter dependent length separation of single walled carbon nanotubes were investigated. They found that smaller diameter nanotubes were preferentially shortened by the acid treatment process and migrated farther from the original sample well during the gel electrophoresis [41]. They also summarized the methods of CNT functionalization. Morphology of CNTs can be characterized by transmission electron microscopy (TEM) or scanning electron microscopy (SEM). The former one can give the structures of CNT walls, and the latter can exhibit the CNT outside sketch. UV-vis scanning spectra can be used to examine the functionalized CNTs to check the stability of the complex covalently attached to the CNTs and possible leaching of the complex. FT-IR spectroscopy can show that which kinds of groups are introduced on the CNT surfaces.

L. Chen el al [41] also summarized chemical surface effects of CNTs play the main roles in improving the thermal conductivity enhancement with the increase of temperature. CNTs with smaller diameters offer more contribution to the thermal conductivity enhancement of CNT water-based nanofluids compared with the CNTs with larger diameters. A.S. Kousalya et al [42] group have done functionalization of CNT by coating CNTs with copper powder using sintering leading an increase in dry out heat flux to 457W/cm^2. K. Balasubramanian et al [43] studies about seeking for the effect of chemical oxidation on SWNT structure, show that functionalization by means of HNO_3 causes the tube caps open but basically retain their pristine electronic and mechanical properties. No significant defects are additionally produced, thus the chemical modification mostly occurs at the opened caps and at the already existing defects along the sidewall of SWNTs.

In conclusion, CNTs need to be functionalized either by coating by sintering or chemical treatment by acid mixture solution of H_2SO_4 and HN_3 (3:1) ratio with 30 minutes ultrasonication followed by 1 hour refluxing in a magnetic stirrer followed by acid dilution and filtration process.

V. CONCLUSIONS

Generally nanofluids are identified as the best working fluids in cooling applications with a concentration of o 0.5%wt to 1%wt. Limited researchers reported a use of nanofluids reduces the thermal performance of the heat pipe.

The effect of nanofluids thermal conductivity improvement contribution on the overall heat pipe performance needs to quantified by further researches compared to the effect of the particles settled on the evaporator forming layers of coating.

Deposition of nanoporous layers leads to a higher boiling performance through and increased nucleation sites at the evaporator surface though film boiling and reduction in surface temperature under two-phase heat transfer conditions.

The heat flux rejection capability of a nanoporous wicks is limited by its low permeability. The limitation of early dry out due to low permeability of nanolayered wick could be further minimized by optimizing the nanolayer wick thickness in combination with optimum concentration nanofluids.

Even though researchers have done extensive numerical studies on nanoflidic heat pipe, it needs rigorous experimental works to characterize the nanofluid properties. In this review the author’s insights the following two core research gaps; first, up to the current author’s knowledge there are no numerical and experimental comparative studies that compare the performance of the amount of nanoparticles concentration with a predetermined nanoporous wick thickness in heat pipes. Second, there are also no works on combined optimized testing of performance using nanofluid-nanoporous wick layered heat pipes for better thermal performance.

CNTs are taken as the potential nanofluids and nanoporous layer wick material in the future with proper functionalization mechanism.

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