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Research Paper

Evaluating the scale effects of metal nanowire coatings on the thermal performance of miniature loop heat pipe

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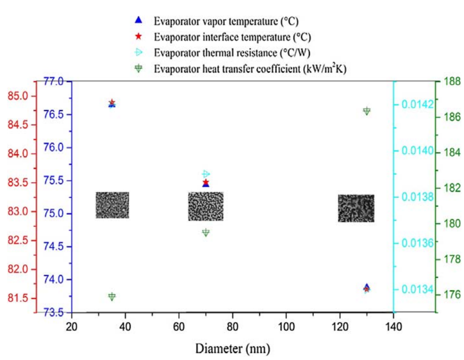
HIGHLIGHTS

- Role of metallic nanowire coating on the thermal characteristics of MLHP.
- Ability of copper nanowires to work as lone fluid transport medium in MLHP.
- Cavity density and cavity size was observed to increases with nanowire diameter.
- Thermal performance was found to improve with increase in the diameter of CuNW.
- CuNW coated surfaces are efficient in removing high heat flux due to capillarity.

GRAPHICAL ABSTRACT

Graphical abstract indicates the variation of evaporator vapor temperature, interface temperature, thermal resistance and heat transfer coefficient values with different diameter of CuNW coated samples for maximum heat load of 580 W.



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ABSTRACT

In this work, the effect of metallic nanowire coating on the evaporator surface of miniature loop heat pipe is investigated. Copper Nanowires (CuNW) of three different diameters (~35, ~70 and ~130 nm) and constant height of ~25 µm were fabricated using electrodeposition technique on the evaporator surface. A dedicated holder was designed to fabricate nanowire coating on the interior surface of the evaporator section. These CuNW coated surfaces were characterised for their morphology, dimensions and wettability. Cavity density and cavity size of the nanowire coated surfaces were analysed using image processing technique and both were found to increase with increase in the diameter of nanowires. The micron scale cavities generated plays a vital role in generating the effective nucleation sites as well as improving the capillarity in the evaporator surface. The evaporator surface coated with CuNW was found to improve the heat transfer characteristics of miniature loop heat pipe (MLHP). As compared to the evaporator surface without any CuNW coating, an increase of nearly 2.7 times in the heat transfer coefficient values and a decrease of approximately one-third in the thermal resistance values were observed in nanowire coated surfaces. This was believed due to an increase in the area of thin-film evaporation. Enhanced characteristics of CuNW coated surfaces like improved bubble nucleation, capillarity and reduced thermal resistance made it possible to transfer a maximum heat load of 580 W with the surface temperature value of 83 °C. This paved a plausible way to employ these kinds of nanostructured surfaces in miniature loop heat pipes to cool high heat dissipating modern electronic equipment.

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Nomenclature

Q	heat load
R	thermal resistance
h	heat transfer coefficient
Q_a	heat supplied to the evaporator
q	heat flux
V	voltage
I	current
T_e	evaporator temperature
T_s	surface temperature
T_v	vapor temperature
lpm	litre per minute

Abbreviations

CuNW	copper nanowires
CHF	critical heat flux
SEM	scanning electron microscope
NCG	non-condensable gases
MLHP	miniature loop heat pipe
CC	compensation chamber
O.D	outer diameter
I.D	inner diameter
MHP	micro heat pipes
HP	heat pipes
CPL	capillary pumped loops
LHP	loop heat pipes
FESEM	field emission scanning electron microscope

1. Introduction

With the advancement in modern electronics industry, reduction in size and increasing heat loads of electronic devices have led to challenges in the development of efficient cooling systems [1]. As life and performance of the electronic devices also depends on temperature, it is very important to develop a proper and efficient cooling system [2]. Two-phase capillary devices like heat pipes (HP), micro heat pipes (MHP), capillary pumped loops (CPL) and loop heat pipes (LHP) have been used for the cooling purpose, as high heat flux cannot be removed by simple conduction or air convection cooling system [3]. Among the factors influencing the performance of capillary devices, i.e., thermal characteristics, reliability, miniaturisation, operating temperature and manufacturing cost, miniaturisation of LHP is at the forefront of extensive research and development. Due to upsurge in thermal design, the demand for efficient cooling devices to dissipate heat can be proficiently met by miniaturized loop heat pipes (MLHP) [4].

MLHP is a self-circulating device in which heat is removed by phase change technique and the working fluid is circulated using capillary force developed by the wicks. One of the advantages of using MLHP is its ability to transfer large heat load over a long distance with small temperature difference and negligible pressure drop. When long heat pipes are employed, as done by Wits et al. [5], the vertical orientation of the miniature loop heat pipe produced better results than the other orientations. This phenomenon is due to gravity acting along with the capillary effects provided by the wicks, which brings the condensed liquid from the condenser to the evaporator. Generally, in heat pipes, the NCG is generated during the first few thermal runs and is accumulated in the compensation chamber. The overall effect of NCG is to elevate the steady-state operating temperature of the loop and increase the start-up time required by the evaporator to achieve stable conditions for the given heat load. However, the results revealed that the loop heat pipes are more tolerable towards the non-condensable gases than conventional heat pipes.

The performance of LHPs is greatly influenced by the properties of working fluid used in the heat pipe. High specific heat and abundant availability in nature have made water as mostly used working fluid in loop heat pipes, but due to the enormous heat produced by the modern electronic equipment's the idea of using working fluid with increased thermal properties has been implemented to tackle the heat dissipation problems. Extensive works have been carried out to use concoction of nanoparticles and water as the working fluid in the miniature loop heat pipe. Many researchers have used Nano fluids in LHPs to enhance the heat transfer characteristics as mentioned in the review articles [6–8]. The general trend of nanofluids is to increase the thermal conductivity of heat pipes due to higher conductivity of nanoparticle as reported by most of the review articles. Liu et al. [9], have studied the effect of nanofluids on various kind of heat pipes and went on to conclude that the incorporation of nanoparticles in working fluid decreases the heat resistance, increases the heat transfer coefficient and consequently increasing the heat removing capacity for majority of micro-grooved heat pipes, mesh wick heat pipes, oscillating heat pipes and closed two-phase thermosyphon.

Incorporation of nanofluids in pulsating heat pipe unveiled that the lower concentration of nanoparticles yielded better results that the higher concentrations [10]. Concentration of 0.1–1.0 wt% nanofluid was taken into consideration for the experiments. It was found that the MWNT's nanofluids at 0.1 wt% had better start-up behavior and thermal resistance when compared to pure water and other nanofluid concentration. Similar to pulsating heat pipe the effects of nanofluids were also studied on miniature loop heat pipe. A different concentration of Graphene-water [11] and graphene oxide-water [12] nanofluids were employed for testing their effects on MLHP. Both these nanofluids reduced the evaporator wall temperature and the evaporator thermal resistance was reduced by nearly 25% when compared to water and hence the idea of using nanofluids in MLHP for cooling purpose was justified. The thermal performance was found to be increasing with the increase in nanofluid concentration. But as the concentration of the nanofluids employed was increased after a certain level it was found to affect the thermal properties as the nanofluids got attached to the wick surface affecting the permeability of the wicks. In addition to this, small diameter of transport lines and increase in density and viscosity of working fluid due to the presence of nanoparticles have resulted in poor performance of MLHP. Hence, this limits the usage of nanofluids in MLHP with respect to the concentration employed. But it should also be noted that working fluid alone is not responsible for the heat transfer properties.

Filling ratio, ratio of volume of working fluid filled to the total volume of heat pipe, can also affect the performance of MLHP as low filling ratio can lead to quicker dry out of condensate, whereas high filling ratio leads to increase in start-up time due to the need of larger superheat to drive the vapor [13]. The performance of loop heat pipe was tested for filling ratio varying as 20%, 30%, 40%, 50% and 70% [14]. The author concluded that 30% charging ratio produced superior results by comparing the evaporator wall temperature. Similarly Zhu et al. tested the LHP with 40–70% charging ratio and concluded that the filling ratio of 50% produced better results than the others [15]. Increase in percentage of filling ratio from conventional value of 30% was observed as the wick was placed above the evaporator surface which resulted in additional need of working fluid to wet the evaporator surface. Evaporator dry out and start-up failure due to limited phase change space were attributed for poor performance at 40% and 70%