Performance study of flat heat pipe with metallic copper hierarchical structure as a wick

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Abstract: Flat plate heat pipes (FHP) can transport high heat fluxes liberated by electrical and electronic equipment. Wick structure plays an essential role in the performance of the heat pipe. The wick structures are made of materials like sintered metal powder, foam, screen mesh, different shapes of grooves, or any material capable of producing capillary force. Generally, wick structures can be inserted or fixed easily inside the heat pipe enclosure. There are cases where one cannot insert or fix the wick structure, such as tubes with several bends and varying cross-sections. Therefore, this study directed to develop a wick structure inside the enclosure through an electrochemical process. As a preliminary study, a hierarchical wick structure is formed at the inner side of the flat heat pipe, and the performance is studied. This method can be applied to create dendrite copper wicks with the required porosity, pore size, and wick thickness by adjusting the electrolyzing conditions. In this study, a flat heat pipe is fabricated with copper hierarchical wick structure, and the performance analyzed over another heat pipe without wick and with screen wick

1. INTRODUCTION

Due to the increased performance and limited heat dissipation space, electronic cooling becomes a difficult task as the miniaturization of electronic components are continues. As a result, heat pipes came into existence and play a crucial role in electronic cooling industries as it is so effective in heat transfer, especially in electronic cooling. It has very high thermal conductivity, faster response in terms of heat transfer, and there is no need for any external power. Construction-wise heat pipe consists of a hollow shell lined with a porous wick like structure and partially filled with a working fluid at low pressure. At one end, termed as an evaporator, where heat is absorbed into the evaporating or boiling working fluid, and the generated vapour flows to the condenser side, where it gives up heat to a heat sink and condenses back to the liquid state. The liquid is continually replenished at the evaporator via the porous lining, which pumps fluid from the condenser by the assistance of capillary forces. The vapour flows through the adiabatic section to the condenser section due to the pressure difference. The condenser part is connected with the heat sink and losing its latent heat and condensed. The condensed liquid returns to the evaporator through the wick structure. Wick structure provides enough space for phase change of liquid to vapour state, and it develops capillary pressure needed to pump the working fluid from the condenser end to the evaporator end. Therefore, the wick structure plays a vital role in enhancing the performance of the heat pipe by increasing the liquid return.
Weibelet al. [1], investigated the capillary fed boiling of water in porous sintered powder wick applicable in high conductivity vapour chamber. The thickness of the wick is 1 mm and is composed of 100μm copper particles. There were many patterns fabricated within the sintered powder to create a multi-scale wick with regions of different pore sizes. It was concluded that the boiling in sintered-powder wick reduces the effective thermal resistance leading to performance enhancement. Deng et al. [2] evaluated the capillary performance of a sintered porous wick by estimating the capillary pressure as well as permeability and testing the same in a Nickel and Copper wick loop heat pipes. An infrared (IR) thermal imaging method was used to monitor the capillary rise processes. There were four different kinds of sintered porous wicks, i.e., two Inco type 255 and 123 nickel wicks with powder size of 2.2–2.8 μm and 3–7 μm respectively, and two spherical and irregular copper wicks of 75–110 μm, were characterized for wick design in the loop heat pipe. Ethanol and acetone were the two working liquids tested, and the results showed that the capillary performance was good for copper wicked heat pipe than the nickel wicked heat pipe. Karthik et al. [3] performed a numerical analysis by adopting the VOF model to obtain static meniscus shapes in the pore space of the sintered wick samples. The liquid–vapor phase change heat transfer was modeled using a modified Schrage equation. In this study, the best performing sample (particle size range) was identified along with the optimum contact angle. The improvement in heat transfer with a decrease in particle size may be attributed to increased meniscus area as well as to an increased number of solid-liquid contacts per unit volume. Franchi et al. [4] examined the thermal performance of a heat pipe by employing composite wicks. The wicks were fabricated from a bi-porous structure made of fine nickel metal powders sintered onto layers of coarse pore copper mesh. Horizontal, gravity-assisted, and against-gravity tests were conducted to determine whether these designs were orientation-dependent. Through composite wick design, heat pipe performance improved at all heat inputs and showed a significant improvement in heat transfer. Putra et al. [5] examined the thermal performance of bio-material wick loop heat pipes with water-based Al2O3 nanofluids. They found that the temperature differences between the evaporator and condenser sections were less than that of the one using a sintered copper powder wick. Similarly, the use of nanofluids over pure water in bio-material wick also resulted in lower temperature differences. As a result, the thermal resistance of the LHP lowered significantly. Wu et al. [6] studied the effect of Polytetrafluoroethylene (PTFE) wick structure on the performance of a loop heat pipe. The best wicking property was found when the sintered particle size ranges from 300-500μm with the effective pore radius of 1.7 μm, the porosity of 50% and permeability of 6.2 x 1012 m s-1. The performance test in the loop heat pipe showed that the heat load was reached 450W under the operating temperature of 85 °C with a low thermal resistance of 0.145 °C/W. Moreover, the critical heat capacity extended up to 600W with the use of PTFE wick structure over traditional nickel wick. Ji et al. [7] developed a heat pipe for high-flux applications by incorporating a porous network as wick structure. The wick was prepared by making a layer of sintered wick at the bottom and inserting more copper foam bars in the provided channels. Experimental results indicate that that the fin efficiency increased to 93%, and the evaporator temperature brought to 68.7 °C at the heat flux of 161.1 W/cm².

Li et al. [8] experimentally investigated the thermal performance of a thin copper-water flat heat pipe consist of a novel wick structure. The wick structure was made up of hybrid copper powder with a size range of 50 to 100 μm diameter by a sintering process. It was found that the flat heat pipe could effectively dissipate a maximum of 120 W (100 W/cm²) with a minimum resistance of 0.196 °C/W. Lee et al. [9] studied the performance of sub millimeter thick flexible flat heat pipe with the nanostructured super hydrophilic surface as wick structure. A single-layered copper woven mesh with nanostructured superhydrophilic surface for liquid transport and triple-layered coarse mesh with bare copper surface for vapour transport was used. It was found that the nanostructured super hydrophilic surface significantly enhanced the thermal performance of heat pipe compared with that with the conventional base copper surface. Jiang et al. [10] analyzed the performance of a flattened heat pipe with a novel porous crack composite as a wick structure. In this wick type, microcrack was formed by phase change flattening process, and later, the crack was filled with copper powder and sintered. It
was found that the heat transfer limit of heat pipe with the composite wick was higher than 50 W compared with grooved wick flattened heat pipe and sintered wick flattened heat pipe at cooling water temperature of 50°C. Li et al. [11] studied the thermal performance of ultra-thin flattened heat pipes with three different composite wick structures namely single arch-shaped sintered–grooved wick (SSGW), bilateral arch-shaped sintered–grooved wick (BSGW), and mesh–grooved wick (MGW), to improve the thermal performance. It was found that the maximum heat transport capacities are 12, 13, and 14 W, under the corresponding optimum filling ratios of 70%, 70%, and 80% for the SSGW, BSWG, and MGW UTHPs, respectively. Ji et al.[12], experimentally studied of heat transfer and start-up characteristics of loop heat pipe with multiscale porous wick structure. The wick structure consists of three layers, the first layer and the second layer are sintered with different size of copper particles, and the third layer is absorbent wool. Compared to the conventional nanoporous wicks, the composite multiscale porous wicks shortened the start-up time, decreased the wall temperature and suppressed the temperature instability of the loop heat pipe. Vijayakumar et al. [13] studied the thermal characteristics of the cylindrical heat pipe with sintered wick and two different nanofluids CuO and Al₂O₃, respectively. The maximum performance obtained at the inclination angle of 45° and this position, the evaporation, and condensation heat transfer coefficient were enhanced by about 32.99% and 24.59%, respectively. Yang et al. [14] developed a novel braided wire wick structure with superhydrophilic treatment for ultra-thin heat pipes. The heat pipe was tested with oxidized mono and composite wick structures. The composite braided wire consists of two layers of the wick with different diameters of cables. It was found that the braided cables can primarily enhance the surface roughness due to oxidizing the surface and result in a much higher capillary force as compared to the un-oxidized one. Therefore the oxidization enhanced the maximum heat transfer capability of composite design, which outperforms mono one. Li et al. [15] developed and tested an anti-gravity loop-shaped heat pipe with a particular type of sintered wick structures. The wick structures were generated with single-powder as well as continuous step-graded structures with different copper powder sizes (<25, 25–50, 50–75, 75–100, 100–125, and >125 µm). It was found that the heat transfer performance of loop heat pipes changes with powder size, and also found that the size of 75–100 µm was the optimal particle size for single-powder and 25–50 µm was the optimal particle size for the continuous step-graded sintered wick. Moreover, permanent step graded sintered wick possesses better overall performance than the single powdered sintered wick which suggests that there was an optimal size value for the capillary force and permeability of the copper powder. Zhou et al. [16] developed an ultra-thin miniature loop heat pipe cooler for mobile electronics application with sintered fine copper mesh wick. The improved heat pipe evaporator and vapour line thickness are 1.2mm respectively and the condenser thickness is 1mm. The developed heat pipe showed a much lower resistance at the maximum heat input of 12W.

The above literature review presents the recent advancements in wick structures and the performance enhancement in various heat transfer devices. It was noticed that there was several promising types of wick structures that offer better capillarity thereby enhancing the performance of heat transfer devices. Further, these wick structures are formed or coated over the simple geometric designs such as flat evaporators. The forming of wick structure in complex geometry such as with fins, bends, and grooves is challenging, and in some cases, one may not be able to use the wick structure at all. In such cases, to form a capillary structure, an electrochemical method may be a suitable option. Therefore, a simple electrochemical process is adopted to create a copper hierarchical structure in the copper base and tested in the heat pipe.

2. EXPERIMENTAL STUDY

2.1 Preparation of metal copper structures
In the first step, the copper plate polished by using a buffing operation to obtain a smooth surface. Then the chemical cleaning process is carried out to remove the grease contents and oxides on the surface to be coated. Secondly, the copper plate is immersed in a 5wt% NaOH solution for 10
minutes, and then the plate is cleaned with distilled water. Further, the copper plate is submerged in a 5wt% HCL solution for about 10 minutes. Again the surface is washed with distilled water. Then the copper plate is dried at ambient temperature and used for the electrodeposition process.

The electrodeposition cell setup consists of DC supply, two copper electrodes (anode and cathode), and electrolyte solution. The electrolyte solution used in the present study is 0.8CuSO4+1.5H2SO4. The anode and cathode are immersed vertically in the electrolyte solution at a distance of 2 cm to obtain a uniform coating. Both anode and cathode are placed in order to facing each other. The positive terminal of the DC supply is connected with a cathode (copper plate to be coated) and the other terminal is connected with copper plate (anode). For the uniform and thick coating a two-step coating procedure is followed. In the first step, the current is set at 7Amps for 3 minutes and during this process, a thick layer without much strength is prepared. To strengthen this coating, 0.5Amps is set for 360 minutes. After this process, a thick and robust layer is obtained. After this coating, the coated cathode is carefully taken out from the electrolyte and rinsed with distilled water for 5 minutes then allowed to dry before characterization.

2.2 Characterization of wick
For the characterization, the surface morphology of the coating is viewed using Scanning Electron Microscope (SEM-JEOL). Coating thickness also measured using SEM. Figure 1 (a) shows the surface morphology of the wick structure and it clearly shows the formed hierarchical structure. Figure 1 (b) shows the thickness of the wick and it is found to be 0.7 mm. Porosity of the coating is estimated by a simple immersion method, in which, a small portion of the copper plate with wick structure is cut and the size and weight are measured. Then this sample is immersed in a pool of water and boiled for 30 minutes and the weight measured. Since the weight of the wick and pores filled with water are known, the porosity can be estimated. A flame test is carried out to find the stability of the coating. The coated plate is heated till the plate turned red hot and then cooled. Later the coating was analyzed and found that the coating is strong. This test was performed to ensure the coating stability during the fabrication process of heat pipe.

![Figure 1 Morphology of (a) Wick surface and (b) cross sectional view of wick](image)

2.3 Fabrication of heat pipe
Flat heat pipe is fabricated using the coated copper plate with the following dimensions. The length, width and thickness of the heat pipe is 150, 30 and 8 mm, respectively. Initially a square rod with the above dimension was taken and a depth of 5 mm is removed by machining process while maintain a wall thickness of 1.5 mm. After that the coating process was performed to coat the bottom part of the heat pipe enclosure and other sides are covered in order avoid unnecessary deposition on the wall surface. Heat pipe with coated surface which acts as a wick structure is shown in Figure 2. After the coating process, necessary cleaning process was done and then a top plate is fixed over the enclosure.
by brazing. A small capillary tube was also fixed at one end of heat pipe enclosure to charge the working fluid. The remaining fabrication procedure is as same as the traditional fabrication procedure cited in literatures [17–20]. The photograph of the final fabricated heat pipe is presented in Figure 3.

2.4 Experimental procedure

Figure 4 shows the experimental setup for the testing of heat pipe. It consists of a chilling unit, flow meter, dimmer stat, wattmeter, data logger, and data acquisition system connected with computer. A copper block with two cartridge heater, each with 200W heating capacity is used as a heat source. Heat is supplied from the heating block to the bottom of the evaporator of FHP. A copper condenser section is attached with the FHP. The chilled water is supplied through the condenser section at a constant flow rate of 160 ml/min. The cooling water is maintained at a temperature of 21±0.5°C. The flow rate of the cooling water is monitored by a flow meter. Heat to the evaporator section is given by adjusting the dimmer-stat and the change in FHP wall temperature is measured using the T-type thermocouples. The measured temperatures are monitored and recorded by a data logger. In this work FHP is tested under the inclination angle of 90°. Heat input is varied from 40-160 watts with the interval of 40 watts.

Heat transferred by the FHP is calculated using Newton's law of cooling as in equation (1) and the heat supplied to the evaporator is calculated by multiplying the voltage(V) and current(I) supplied to the cartridge heater as given in equation (2)

\[ Q_{out} = \dot{m}C_p(T_{out} - T_{in}), \]  
(1)

Where \( \dot{m} \) mass flow rate of cooling water, \( C_p \) is the specific heat of water. \( T_{out} \) and \( T_{in} \) is the outlet and inlet temperature of cooling water.

\[ Q_{in} = V \times I, \]  
(2)

The total thermal resistance \( R_t \) calculated by:
\[ RT = \frac{\Delta T}{Q_{\text{out}}} \]  

(3)

where \[ \Delta T = \bar{T}_e - \bar{T}_c \]. The thermal resistance at the evaporator is calculated using the average evaporator temperature (\( \bar{T}_e \)) and average condenser temperature (\( \bar{T}_c \)) as presented in Equation (4) and (5) as:

\[ R_e = \frac{\Delta T_e}{Q_{\text{in}}} \]  

(4)

\[ R_c = \frac{\Delta T_c}{Q_{\text{out}}} \]  

(5)

where \[ \Delta T_e = \bar{T}_e - \bar{T}_v \], \[ \Delta T_c = \bar{T}_v - \bar{T}_c \].

The heat transfer coefficient at the evaporator (he) and condenser (hc) are calculated by using equations (6) and (7) as:

\[ h_e = \frac{q_e}{\bar{T}_e - \bar{T}_{\text{sat}}} \]  

(6)

\[ h_c = \frac{q_c}{\bar{T}_{\text{sat}} - \bar{T}_c} \]  

(7)

where \( q_e \) and \( q_c \) are heat influx at evaporator and condenser section. \( T_{\text{sat}} \) is considered as the vapour temperature.

At last, the uncertainty present in heat flux, heat transfer coefficient and thermal resistance are calculated using the equation (8), (9) and (10) respectively.

\[ \frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta (\Delta T)}{\Delta T}\right)^2} \]  

(8)

\[ \frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta (\Delta T)}{\Delta T}\right)^2} \]  

(9)

\[ \frac{\Delta R}{R} = \sqrt{\left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta (\Delta T \cdot h_p)}{\Delta T \cdot h_p}\right)^2} \]  

(10)

The calculated uncertainties in the measurements of heat flux, heat transfer coefficient and the total resistance are found to be less than 6.5% which is within an acceptable limit.
3. RESULTS AND DISCUSSION

The evaporator resistance of FHP with and without the copper hierarchical structure as well as with screen mesh was calculated using Equation 4 is presented in the Figure 5. It was found that the evaporator resistance of the wickless FHP decreases with increasing in heat input up to 120W. After 120W, the evaporator resistance gradually increases with heat input suggesting that the heat transfer capacity of the wickless FHP is limited to 120W. However, the evaporator resistance of FHP with hierarchical wick structure and screen wick structure were decreased up to a heat input of 160W and the trend shows that the resistance will decrease further with increasing heat input. This indicates that the heat transfer ability of the FHP enhanced with the application of wick structure by dissipating the heat to the fluid effectively. Moreover, the thermal resistance of FHP with hierarchical wick structure was lower than that of the screen wicked FHP with the maximum reduction of 20%. This reduction in resistance is mainly due to the increase in surface area, improved capillarity, enhancement in nucleation process, bubble frequency etc. To understand evaporation of wicked and wickless FHP, the boiling phenomenon in the evaporator is captured using camera for different heat inputs and presented in Figure 6. It was found that there are very few bubbles with large size is formed in the wickless WHP at a heat input of 40 W. As the heat input increases, the intensity of bubble formation was increased though the size of the bubble was not changed. However, in the case of hierarchical wicked
FHP, even at low heat input, bubbles are created in smaller size and large in numbers which continuously rewet the evaporator and dissipate the heat effectively to the fluid. As the heat input increases the bubble frequency was found to be increased which is clearly seen in the Figure 6. Also the formed wick increases the capillarity as well as nucleation sites which dissipate the heat effectively from the evaporator wall.

![Figure 5 Variation of evaporator resistance with increasing heat input](image_url)

WICKLESS (40W)  WICKED (40W)  WICKLESS (80W)  WICKED (80W)  WICKLESS (120W)  WICKED (120W)  WICKLESS (160W)  WICKED (160W)
The condenser resistance also calculated for various heat input for all above proposed heat pipes using Equation 5 and presented in Figure 7. It was observed that the thermal resistance was decreased as the heat input was increased for all cases. Also noticed that the variation in resistance is higher at lower heat puts and less at high heat inputs. Moreover, the resistance of the FHP with hierarchical wick structure is almost 18% lower than the wickless one indicating that the hierarchical wick structure improve or supports the condensation process in the condenser.

Figure 6 Visualization of the evaporation section of wicked and wickless heat pipes at a various heat input

Figure 7. Variation of resistance at condenser with increasing heat input

Figure 8 Variation of evaporator heat transfer coefficient with increasing heat flux

Figure 9 Variation of condenser heat transfer coefficient with increasing heat flux

Figure 10 Total thermal resistance variation with increasing heat input
The variations of evaporator heat transfer coefficient of FHP with and without hierarchical wick and with screen wick are calculated using Equation 6 and presented in Figure 8 which shows that the heat transfer coefficient of FHP with hierarchical wick is higher than that of all other FHPs studied. Also seen that the heat transfer coefficient is increasing as the heat flux increases up to 100 kW/m² and after that it starts to decrease. However, the heat transfer coefficient of wicked FHP is increasing even after 100 kW/m². Also found that the heat transfer coefficient is 16% higher than the wick less heat pipe suggesting that transferring the heat efficiently from the wall to the working fluid by reducing the incipient resistance. Moreover, FHP with hierarchical wick structure outperformed the screen wicked FHP in terms of heat transfer coefficient.

The heat transfer coefficient in the condenser section of heat pipe with respect to the heat flux is also calculated using Equation (7) and presented in Figure 9. As similar to the evaporator heat transfer coefficient, the same in the condenser also increases for all cases. However, after the heat flux of 70 kW/m² the heat transfer coefficient decreases for the case of wickless FHP. Further noticed that the condenser heat transfer coefficient of hierarchical wick is increased 23% over wickless FHP and 11% over screen wicked FHP. This suggests that the hierarchical wick structure is performing better than the screen wick.

The total thermal resistance of the FHPs are also calculated using the Equation 3 and presented in Figure 10. It was found that the total thermal resistance decreases with increasing heat input up to 120W after that the thermal resistance gradually increases for the case of wickless FHP. In the case of screen wicked and hierarchical wicked FHP, the total resistance seems to be decreasing until it reaches 160 W. When comparing wickless FHP, the one with hierarchical wick showed a better performance as the thermal resistance is decreased by almost 15%. This resistance variation is due to the presence of wick structure in the heat pipe. The wick structure generates a sufficient capillary pressure to return the condensed working fluid to the evaporator. The capillary pressure head can be calculated as \( \Delta P_c = 2 \sigma \cos \theta / r_c \), where \( \sigma \) is the surface tension of the working fluid and \( r_c \) is pore size of the wick structure and \( \theta \) is the contact angle. From the above equation it is understood that the capillary pressure is depends on the surface tension, contact angle and the pore size of the wick structure. In the present study the surface tension of the working fluid is same for both heat pipes. The pore size is estimated from the SEM image and is found to be 50 µm. Hence the corresponding capillary pressure generated by the wick structures is 2880 Pa. Similarly, the pore size of the screen wick is about 80 µm and it generates the capillary pressure of 1500 Pa which less than the capillary pressure of hierarchical wick leading to the lower heat transfer ability. Thus the lower resistance is obtained. Also compared to the traditional wick structures the proposed wick structure is prepared over the wall of the heat pipe leading to a reduction in interface resistance and improve the heat transfer between the wall and working fluid. From these results, it is clear that there is an advantage of using hierarchical wick structure. The method of preparation of hierarchical wick demonstrates that the similar wick can be formed over the complicated geometries where the traditional wicks are not usable due to complex shapes such as with bends.

4. CONCLUSION

A copper hierarchical wick structure is formed in the FHP using an electrochemical process and the performance of FHP is studied. The heat transfer results are compared with the FHP with and without commercial screen wick. The following conclusions were arrived from the present study.

- The evaporator thermal resistance of FHP with hierarchical wick structure was found to be lower than that of the screen wicked FHP with the maximum reduction of 20%.
- The condenser resistance of the FHP with hierarchical wick is almost 18% lower than the wickless one indicating that the hierarchical wick helps to improve the condensation process in the condenser.
- A much lower thermal resistance is observed in the wicked FHP as compared to that of
wickless heat pipe. This resistance variation is due to the presence of wick structure in the heat pipe. The wick structure generates a sufficient capillary pressure to return the condensed working fluid to the evaporator.

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