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Research paper

Startup Transient Characteristics of Helical Grooved Flat Heat Pipe

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Abstract

Heat pipes are used in thermal management of electronic devices due to their efficient heat transfer capability from source to sink with a very small temperature difference. These passive heat transfer devices can employ sintered powder, screen mesh, machined grooves or its combination as wick material to exert capillary action on the working fluid. In this work, attempt was made to develop a flat heat pipe using a helical grooved cylindrical pipe. The helical groove present in the cylindrical pipe is used as wick. The developed flat heat pipe was targeted for a power range of 3 W without dedicated cooling mechanism for condenser. Experimental studies were also conducted up to 5 W to verify the extension of operating power range of the heat pipe using a fan. This paper primarily focus on the transient behavior of to understand the time constant of the heat pipe at different orientations and cooling scenarios. Later the transient thermal performance of heat pipe was also compared with dry heat pipe.

Keywords: *Flat heat pipe, transient, time constant, Grooved heat pipe*

1. Introduction

The recent trends in industries indicate the extensive usage of heat pipes in electronics cooling due to their reliable and efficient thermal management capability. It is to be noted that approximately 15 million heat pipes are produced worldwide for computer and electronic products [1]. A heat pipe consists of an hollow container lined with a wick that is saturated with a small amount of working fluid in an evacuated condition. One end of the heat pipe is exposed to higher temperature called the evaporator section and the other end to a relatively colder temperature called the condenser section. The latent energy is used to evaporate the working fluid in the evaporator and condense the vapor in the condenser. The circulation of working fluid in the heat pipe is completed by the return flow of condensate to evaporator through the wick under the driving action of capillary forces. This phenomenon continues as long as enough capillary pressure exists. It is imperative to select a proper working fluid and wick structure to transfer heat effectively from the evaporator section to condenser section. The configuration of a cylindrical heat pipe is shown in figure 1.

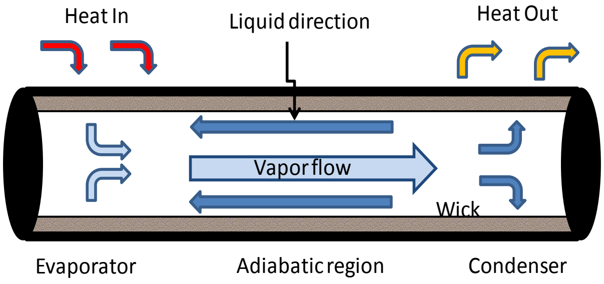

Fig. 1: Cylindrical Heat Pipe

The flat heat pipes operate similar to cylindrical heat pipes and difference between the two is geometrical. The flat heat pipe geometry allows it to have a compatible mating surface with semiconductor devices compared to cylindrical heat pipe. Hence flat heat pipes can be easily implemented in complex design. Figure 2 shows a typical flat heat pipe with electronic device mounted.

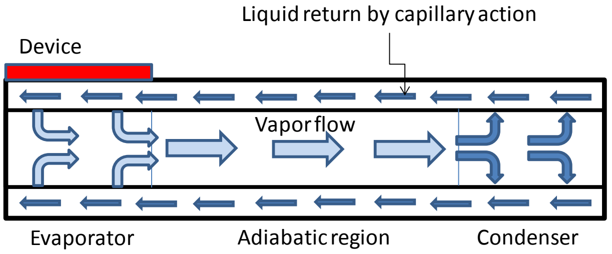

Fig. 2: Flat Heat Pipe with electronic device

The electrical power numbers encountered in smartphone processors and LED (Light Emitting Diode) display application are generally less than 10 W. Flat heat pipes can function as heat spreaders or efficiently transfer the heat to a heat dissipating mechanism like heat sink in such applications. The present work discusses about the development of a flat heat pipe in the range of 3 W to 5 W using a readily available helical grooved copper pipe. The inherent helical grooves present in raw copper pipe are being used as wick avoiding the expensive machining process for groove cutting. The cylindrical copper pipe was flattened for easily adhering to electronic device surface. Earlier the steady state functionality of the developed flat heat pipe was demonstrated under natural convection mode at 3 W power input at different mounting angles. The test results indicated that the heat pipe was functioning satisfactorily at all angles with thermal resistance of around 3 K/W [2]. It was noted that by using fan as a dedicated cooling mechanism the power range of heat pipe can be extended up to 5 W.

In actual electronic products or modules the time taken for semiconductor devices once powered on to reach steady state is also an important factor to understand the functioning capability. Also during actual operation of these modules, device power dissipation values can fluctuate based on its intended functions. Hence in the heat pipe product level implementation it is also imperative to understand its heat transfer capability with respect to time. This paper focuses on the transient startup characteristics of the developed flat heat pipe. The time constant values for different test conditions are reported and compared with a dry heat pipe to demonstrate the heat pipe efficiency.

2. Literature Survey

Extensive literature survey has been carried out on research activities and current trends in flat heat pipes. Amir Fahgri [3] in his review paper has done a detailed overview of heat pipes covering the historical perspective, principles of operations, types of heat pipes, performance characteristics, simulations and its various applications. It has been observed that several million heat pipes are now manufactured each month since all modern laptops use heat pipes for CPU cooling. Sergii Khairnasov and Alyona Naumova [4] indicated that flat heat pipes are at an early stage of wide implementation in electronics thermal control systems. Jihad Hammoud [5] et al. implemented heat pipe in automotive radio and experimentally validated the effectiveness of the system by comparing the CD/media temperature with and without heat pipe.

A. Steady State Studies

Wang et al. [6] developed flat copper heat pipe with silicon wick for a capacity up to 10 W. The flat heat pipe had 45 mm length, 16 mm width and 1.5 mm height. The heat pipe was able to remove heat from a surface of 16 mm x 16 mm. A comparative analysis of a grooved copper wick and a silicone based wick was also included in their study. The grooved copper wick heat pipe efficiency was higher than the one on the basis of silicone by 17%. Their research demonstrated the use of flat heat pipe for LED cooling systems.

An experimental investigation of aluminum-acetone flat plate heat pipe application in heat dissipation of high power LEDs was done by Wu-Man Liu et al. [7]. The high power LEDs temperature with and without heat pipe were compared. The input power variations studied were 6.27 W, 13.32 W and 20.61 W. The maximum temperature experienced was 161^{o}C for power of 20.61 W without heat pipe, against 36^{o}C when tested with heat pipe. The heat removal efficiency of the flat heat pipe was found to be around 92-95%.

Ultra-thin heat pipe developed by Hirofumi Aoki et al. [8] can be used for thinner and lighter electronic equipment. Their study was focused on optimizing vapor and liquid flow pressure drop in the heat pipe. The heat pipe developed had 1 mm thickness with maximum heat transfer rate of 22.1 W. Copper block heater (40 mm x 10 mm) was used as heat source and a copper block (85 mm x 10 mm) cooled by water cooling system as the condenser. Thermal resistance of the heat pipe was estimated to be around 0.13 K/W. These flat heat pipes with 20 W power range were applied mainly for electronic devices and for LED cooling systems. The temperature in such application was restricted to around 100^{o}C considering the limit of electronic device temperature.

AMEC Thermasol [9] are commercially producing aluminum flat heat pipes with acetone as working fluid. These heat pipe can operate within the temperature range from -40^{o}C to +100^{o}C at different tilt angles from 0 to 90 degrees. The grooved wick allows the use of these heat pipe in horizontal position and small tilt angles. These heat pipes with a dimension of 200 mm length, 20 mm width and 1.2 mm thick are rated for maximum power range of 5 W to 18 W. They are generally used for cooling memory cards, optical communication modules and lighting systems.

Zaghdoudi et al. [10] had carried out experimental study to verify the concept of Flat Mini Heat Pipe (FMHP) for cooling high power dissipation electronics components. The FMHP prototype had capillary structure composed of parallel rectangular channels manufactured and a filling apparatus was developed to charge the heat pipe. The heat pipe performance was compared to that of copper plate having same dimension for different heat flux rates. The overall length, width and thickness of the heat pipe were 100 mm, 50 mm and 3 mm respectively. The heat pipe had 47 micro channels. The micro channels height, width and spacing were 0.5 mm, 0.5 mm and 1 mm respectively. Heat was removed from the FMHP by a water cooling mechanism. The length of the evaporator, adiabatic and condenser zones were 19 mm, 35 mm and 40 mm respectively. The experiments were conducted with different heat inputs ranging from 10 W to 60 W.

Effective conductivity based thermal model for simulating vapor chamber type heat pipe using FloTHERM^{TM} commercial software was developed by Wei and Sikka [11]. The model consists of a heated chip mounted on one side of a vapor chamber and cooled by heat sink on other side. The effective conductivity based model used in simulation predicted the temperature profile in close agreement with the detailed numerical model.

Kesav Kumar and Sridhara [12] arrived at a steady state network based approach for the above model to predict the peak temperature of the heated chip. A correction in area is suggested while calculating the wick thermal resistance as thermal contours in wick will be highly two dimensional. The network model suggested was validated with FloTHERM^{TM} results and seems to work well for varying power densities when heat sink cross section normal to the direction of heat flow matched with the vapor chamber.

B. Transient Studies

Wang and Vafai [13] investigated the transient thermal performance of asymmetrical flat heat pipe. The flat heat pipe used in their studies was 190.5 mm in length, 139.7 mm in width and 34.93 mm in thickness. The heat pipe wall is made up of thick copper plate of 3.175 mm thick. The porous wicks were made of sintered copper powder (thickness 1.651 mm) attached to the inner surface of the heat pipe wall. The heat pipe also had vertical wicks to provide a secondary return mechanism for the condensate forming four channels for vapor region. The evaporator was located on center of one of the outside surfaces of heat pipe. Therefore the heat pipe had one evaporator and three condenser sections. In all tests the heat pipe was mounted vertically so that same average heat transfer coefficient is achieved on the three condensation surfaces. A flexible heater (139.7 mm length and 50.8 mm width) was used as the heating element and other side of heater was insulated. The tests were conducted at varying heat flux levels ranging from 426 W/m^2 to 1690 W/m^2, which translates to 3 W to 12 W. The concept of the heat pipe time constant was introduced to describe the transient characteristics of the flat heat pipe and an empirical correlation for time constant in terms of input heat flux was presented. The time constant value measured was inversely proportional to input heat flux and varied from 55 minutes to 80 minutes. Later they developed an analytical model for predicting transient performance of flat heat pipe for startup and shut down operation [14].

Zaghdoudi et al. [15] studied the effect of transient acceleration forces with constant input power on thermal performance of copper-water flat heat pipe. Transient accelerations were generated using a centrifuge table to simulate acceleration forces typifying high performance aircraft maneuvering. The heat pipe dimension was 150 mm in length, 50 mm in width and 2.4 mm in thickness, weighing around 75 grams. The evaporator and condenser dimension was 50 mm x 15 mm. The heat pipe was designed for a power of 60 W. The arterial screen meshes were used as the capillary structure. The investigation revealed decrease in the heat pipe thermal performance with increasing acceleration as a result of partial dry-out of the evaporator and pooling in the condenser.

A transient thermal model to simulate the cooling power of MOSFET by helicoidally grooved cylindrical heat pipe systems was done by Ameni Driss et al. [16]. The power variation studied was from 30 W to 150 W. The MOSFET and heat pipe were modeled using RC thermal circuit approach. The thermal resistance and capacitance values of heat pipe were determined by experimental and theoretical calculations.

A computational finite difference based model for transient analysis of flat heat pipe was developed by Sobhan et al. [17] to obtain the variations of velocity, temperature and pressure distributions. Water was chosen as the working medium. The wick and wall are made of copper. A wick porosity of 0.6 is used with a uniform heat flux of 1 W/cm^2 is applied externally at the evaporator section, while the condenser section is cooled by imposing a heat transfer coefficient of 1000W/m^2 K at a coolant temperature of 300 K, equal to the initial temperature of the heat pipe. The two dimensional model had a total length of 300 mm and thickness was 37 mm. The evaporator, adiabatic and condenser length was 100 mm each. The heat pipe wall and wick thickness was 6 mm and 1.5 mm respectively.

Literature survey indicated that most of the researchers were focusing on application of flat heat pipes for electronics cooling. The demand of several million of heat pipes per month for electronics industry indicates the thrust required in this area for the research. Most of the work done on heat pipes are on steady state conditions. There were limited literature available on understanding the transient behavior of flat heat pipes. The transient characterization is essential to understand the rate at which the heat pipe response to heat load. In actual applications the heat input can vary with time and understanding the time constant of heat pipe is critical. The flat heat pipes works carried out earlier had a dedicated cooling mechanism in the form of heat sink or a cooling jacket in condenser region. The water cooling for condenser region can lead to complications in electronics cooling design. Further dedicated cooling system adds to cost, weight and package space. Earlier a flat heat pipe was developed without a dedicated cooling mechanism for 3 W power range based on power dissipation in smartphone processors [2]. The operating temperature of heat pipe was limited to 100^{o}C based on electronic devices limit. The steady state test revealed the heat pipe can function at mounting orientations varying from 0 degree to 90 degree when evaporator is at bottom. The studies conducted using fan indicated the heat pipe range can be extended by using a dedicated cooling mechanism. In this work it is attempted to determine the time constant of developed heat pipe for different test conditions. The variation of heat pipe time constant with respect to power variation and mode of cooling mechanism is explored. Later the transient behavior of heat pipe is compared with dry heat pipe.

3. Experiment Set up

A readily available helical grooved hollow copper pipe is used to fabricate the flat heat pipe. The working fluid is selected as water because of its high merit number in the operating temperature range. The heat pipe is wound with Nickel-Chromium wire to supply heat in evaporator section. The temperature values across the length of the heat pipe were monitored using thermocouples. The thermocouple data are recorded as a function of time at intervals of 10 seconds. Initially the experiments were conducted at different mounting angles when condenser section is cooled by pure natural convection. Later tests were conducted by blowing air by fan on the condenser section. The performance of the flat heat pipe developed was then compared with dry heat pipe (without working fluid) to ascertain its thermal performance.

A Flat Heat Pipe Development

A hollow cylindrical copper pipe of 3/8" outer diameter (9.53 mm) with 15^o helical internal grooves was selected for fabrication. The inner diameter of the pipe was found to be 8.53 mm. The cylindrical pipe used for fabrication is shown in figure 3. The pipe had a total of 34 grooves of height 0.16 mm and width 0.21 mm. The pipe used for fabrication had minimum wall thickness to ensure minimum wall thermal resistance. The cylindrical pipe was cut to a length of 150 mm and later flattened to the required thickness using a mechanical press. The pressing operation was carried out using a die to ensure no deviation in the final dimensions of the spreader. Proper cleaning of heat pipe container is essential as slightest of impurity may deteriorate its performance. The pipe was cleaned to remove macro impurities like dirt, oil and micro impurities like traces of oxides present on the surface of the pipe. Immersion of the pipe in various chemical baths removed the macro impurities. The oxide impurities were eliminated by heating the heat pipe container in a hydrogen environment furnace. After the cleaning process, it was ensured that the pipe does not come in contact with any contaminants. A 0.5 mm thick copper sheet was used to manufacture the end caps. The end caps were also cleaned following the same procedure of that of the heat pipe. The end caps were attached to the heat pipe by brazing them with a copper filler rod. A leak proof inspection was carried out after brazing as small gap in the system may cause air to leak inside the heat pipe and can lead to non-functionality. Later the heat pipe was attached to a specialized evacuation and charging rig. The pipe was evacuated to a vacuum of 0.017 mbar. Then distilled water was charged into the pipe through a degassing setup. The purpose of degassing setup was to remove the dissolved non-condensable gases (NCG) from the water. Avoiding degassing process in manufacturing will result in releasing of NCGs over a period of time causing reduction of the effective length of the heat pipe. The fabricated flat heat pipe had final dimension of 150 mm length, 13 mm width and 2.8 mm thickness. The volume of liquid charged in heat pipe was around 0.25 cc. The flat heat pipe fabricated is shown in Figure 4.

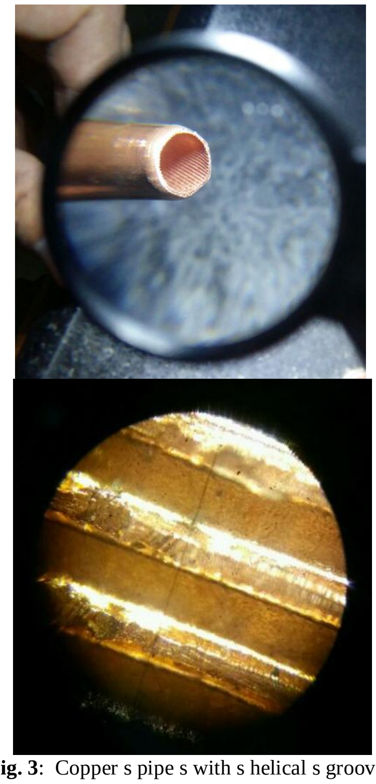

Fig. 3: Copper pipe with helical grooves

Fig. 4: Copper-Water flat heat pipe

B Thermal Instrumentation

Nickel-Chromium (Ni-Cr) wire of "K" type thermocouple was wounded up to a length of 40 mm (evaporator area) above heat pipe to act as heating element. Ni-Cr wire had insulation to avoid short circuit between windings and a paste prepared by mixing Omega 400 cement with water was applied above the windings to avoid relocation. Later the evaporator region was wound with fiber glass insulation to restrict heat loss to the ambient. Total six number of "K" type thermocouples (Nickel-Chromium/ Nickel-Alumel) were instrumented along the heat pipe at a distance of 10 mm, 20 mm, 50 mm, 80 mm, 110 mm and 130 mm respectively as shown in figure 5. The thermocouple at 10 mm and 20 mm are in the evaporator section of heat pipe. It is to be noted that as wire is used as heating element, thermocouple reading in evaporator section will read the wire temperature. The total resistance of the heating element was around 11 ohms.

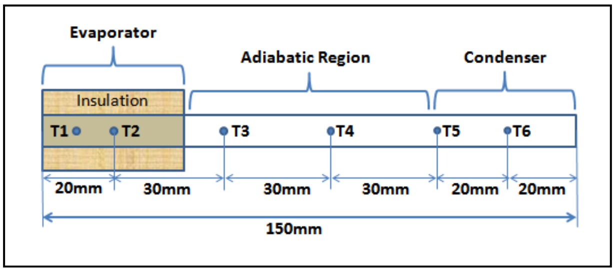

Fig. 5: Thermocouple locations

C. Test Set Up

The heat pipe was mounted vertically with evaporator at bottom and enclosed by a cardboard box (100 mm length x 100 mm breath x 200 mm height). The condenser section of 40mm length was protruding outside the cardboard box and exposed to the environment. The cardboard box restricted heat loss from evaporator and adiabatic section of heat pipe to ambient environment. A 8 channel PPI Unilog data acquisition system was used to record temperatures at intervals of 10 seconds during tests. A DC regulated power supply 0-30 V/ 2 A (Make: SIGMA) was used to supply heat input to the evaporator section. FLUKE multimeter (Model 106, 600 V CAT III) was used to reconfirm the voltage and current readings.

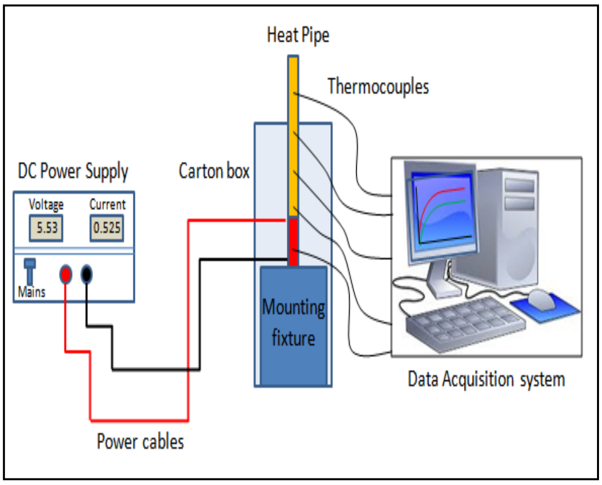

Fig. 6: Natural convection set up

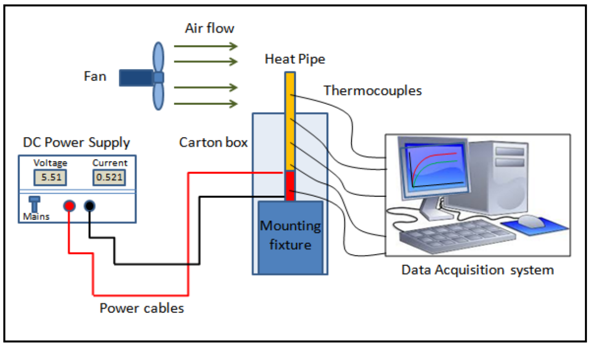

Fig. 7: Forced convection set up

The schematic of natural convection test set up is shown in figure 6. The heat pipe was also tested at different inclination angles. Later a fan was used to blow air in the condenser section at a velocity of 4 m/s and 5 m/s to verify if the capacity of heat pipe can be extended. The air velocity from the fan was measured using hot wire anemometer based sensor. The distance between fan and heat pipe was 50 mm. The test set up schematic with fan is shown in figure 7.

4. Steady State Performance

Initially the heat pipe was tested under natural convection for 3 W heat input. The tests were conducted at different mounting angles varying from 0 degree, 30 degree, 45 degree, 60 degree and 90 degree (horizontal position is 0 degree and vertical position is 90 degree) respectively. Three tests were conducted at each angle to ensure repeatability. The consolidated heat pipe experimental results at steady state for all angles are shown in a single graph in figure 8. The results indicate that the temperature distribution along the heat pipe is almost flat for all orientations indicating its functionality. The thermal resistance value is highest for vertical orientation (3.3 K/W) and lowest at horizontal orientation (3.1 K/W) [2]. The overall heat transfer coefficient was calculated to be around 255 W/m^2 K for horizontal and dropped to a value of 240 W/m^2 K in vertical test. All these calculations indicated that the heat pipe performs best in horizontal orientation. Figure 9 gives the test results of forced convection test set up conducted using a fan.

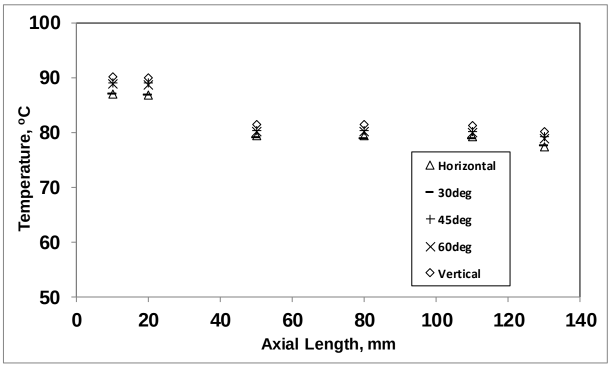

Fig. 8: Natural convection set up results – steady state

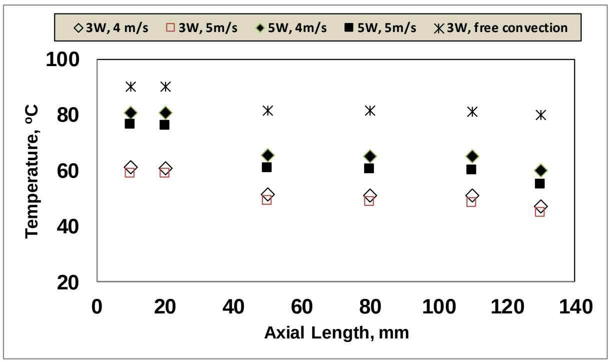

Fig. 9: Forced convection set up results – steady state

The steady state performance of water filled heat pipe developed was compared with dry heat pipe of same external dimensions in figure 10. Dry heat pipe is an empty heat pipe with no fluid filled inside it. This empty heat pipe represents a simple conductor. All the tests were done in vertical orientation to compare the heat pipe performance. The maximum evaporator temperature for dry heat pipe was around 110.8^{o}C compared to 90.2^{o}C for the water filled heat pipe.. Hence the temperatures and thermal drop across empty heat pipe is higher compared to heat pipe. It is evident from the linear curve fit of temperature across axial length which indicated that slope of empty heat pipe is higher (0.297) than that of water filled heat pipe (0.084).

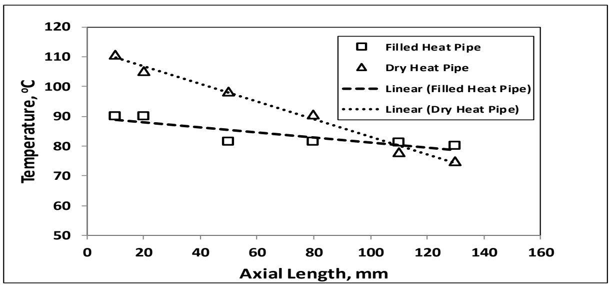

Fig. 10: Steady s state s perfroamce s comaparison s with s simple s conductor

5. Transient Performance

The data logger was capable of measuring temperature in intervals of every 10 seconds. All the experiments were carried out for nearly 2500 seconds to ensure steady state is reached. The time constant of the heat pipe is defined as the time it takes for the outside surface temperature in the evaporator section to reach its 63.2% of the maximum temperature rise [12]. A small time constant indicates the heat pipe can quickly reach its work capacity.

A Natural Convection Tests

The temperature rise history from initial ambient condition of heat pipe at evaporator section (20 mm location) for 3 W tests conducted at different orientations under natural convection is given in figure 11. The temperature rise values from ambient is also tabulated in Table 1. At horizontal orientation the total temperature rise was 58.6^{o}C and for vertical orientation it was 65.2^{o}C. The time constant for the above tests are given in figure 12. The time response varied from 249 seconds to 266 seconds. The graphical trends shows the mounting angle has no significant impact on time constant value.

Table 1: Temperature s Rise s at s 3 s W s (s NAtural s Convection)

Test s Angle	Temperature s Rise s , s ^{o}C	63% s Temperature s Rise s , s ^{o}C
0 s degree	58.6	36.9
30 s degree	61.9	39.0
45 s degree	63.3	39.9
60 s degree	63.2	39.8
90 s degree	65.2	41.1

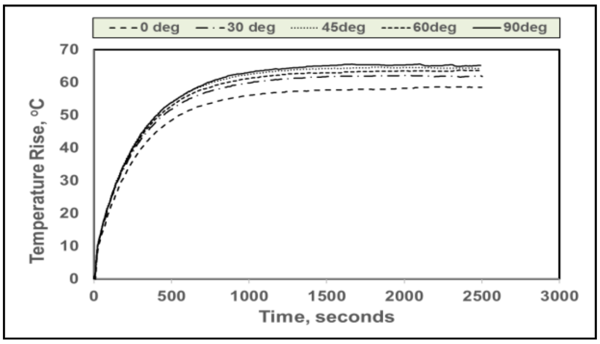

Fig. 11: Temperature s history s at s evaporator s location

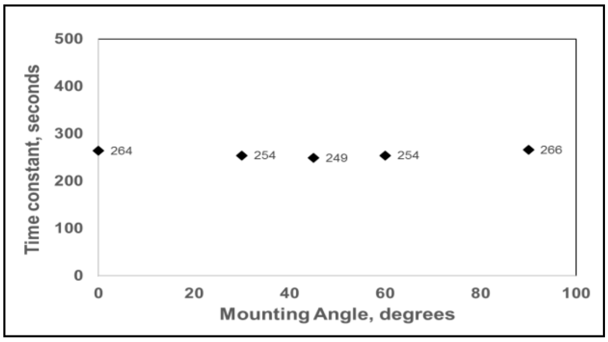

Fig. 12: Time s constant s at s different s orientations s for s 3 s W s (natural s convection)

To study the effect of power variation under natural convection the tests were conducted at 2 W in vertical orientation. The tests were not conducted above 3 W heat input, as the maximum temperature of heat pipe may exceed the allowable temperature limit of 100^{o}C. The graph shown in figure 13 compares the temperature rise of 3 W and 2 W. At 2 W power input, the temperature rise of the heat pipe at evaporator was 45.5^{o}C against 65.2^{o}C for 3 W power. The experimental results indicate the time constant for 3W was 266 seconds and 275 seconds for 2W. This is in line with the trend observed by Wang and Vafai [13] that as power number increases time constant value decreases.

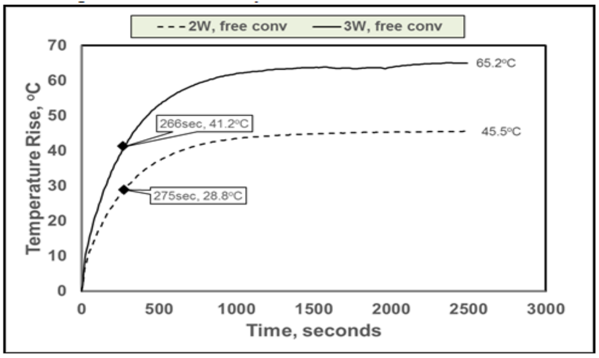

Fig 13: Power s variation s study s under s natural s convection

B Forced Convection Tests

The forced convection tests were conducted at two different air velocities of 4 m/s and 5 m/s. Tests were conducted at three different input powers viz. 2 W, 3 W and 5 W. The temperature rise and time constant values for the above tests are shown in figure 14 and figure 15. The time constant value was 132 seconds for 2 W power against 108 seconds for 5 W tests for air velocity of 4 m/s. The time constant value for input power of 5 W with 5 m/s is 98 seconds. This indicates that the time constant value for heat pipe decreases with increase in air velocity experienced by the condenser section. Also the time constant decreases with increase in heat input.

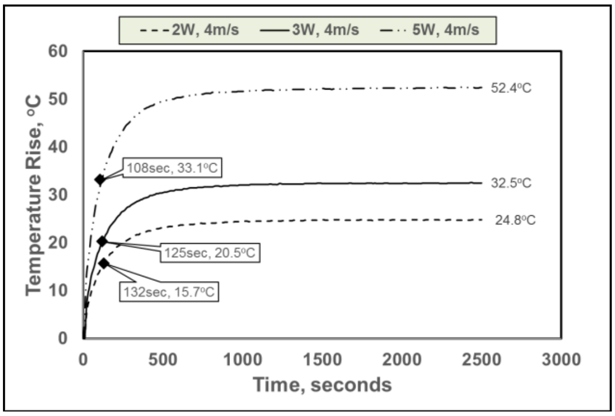

Fig.14: Forced s convection s results s at s 4 s m/s

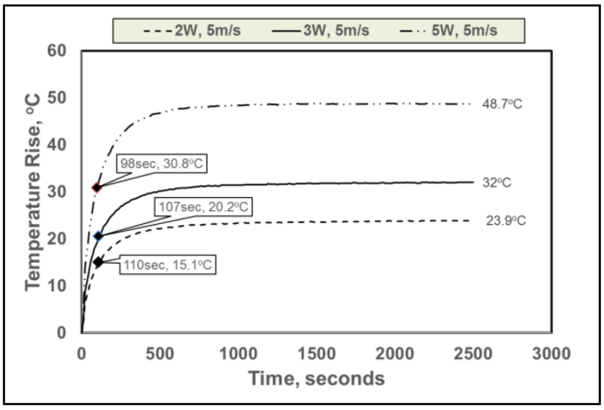

Fig. 15: Forced s convection s results s at s 5 s m/s

C Comparison with Simple Conductor

The tests results comparing the temperature rise in evaporator region and condenser region of filled heat pipe and dry heat pipe is shown in figure 16 and figure 17. The time constant of dry heat pipe was 247 seconds which is less than 266 seconds for filled heat pipe. But in condenser section the response time of dry heat pipe was 306 seconds against filled heat pipe of 303 seconds. The initial response of temperature for dry heat pipe was higher at the evaporator end as the cross sectional area of copper available for heat transfer is less for dry heat pipe as air inside the empty pipe provides more resistance to heat flow because of its poor conductivity. In filled heat pipe during the initial stage the phase change phenomenon of water provides thermal inertia for temperature rise. In the condenser section the response time of filled heat pipe is better than the dry heat pipe. This indicates the filled heat pipe has a better heat transfer capability compared to dry heat pipe.

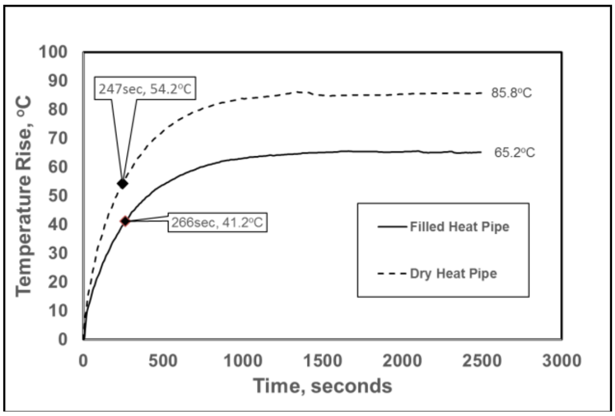

Fig. 16: Evaportor s region s temperature s rise

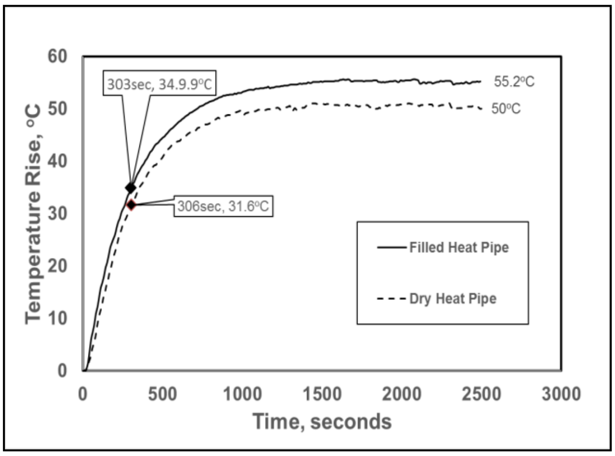

Fig. 17: Condensor s region s temperature s rise

6. Conclusion

The flat heat pipe finds wide range of applications in electronics cooling. Their thermal management application include LED display systems, automotive multimedia systems, smartphone processors etc. In Smartphone processors and LED display application the power numbers can be less than 10 W. Hence the current work was focused on developing a flat heat pipe using helical grooved copper pipe to meet the lower power applications in the range of 3 W to 5 W. Readily available helical grooved copper pipe was flattened to be used as the heat pipe container avoiding the expensive machining process for groove cutting. The developed flat heat pipe was tested under natural convection mode at 3 W power input at different mounting angles. Further tests were done at 5 W to prove that the heat pipe range can be extended by using a dedicated cooling mechanism. The performance of heat pipe was also evaluated by comparing with empty heat pipe i.e. without fluid, representing a simple heat conductor. The earlier steady state studies indicated that the flat heat pipe was functioning satisfactorily. But it is also imperative to understand the transient behavior of heat pipe to understand the startup transient characteristics. The time constant of heat pipe was calculated for different test conditions and was found to be varying between 249 seconds to 266 seconds for 3W power under natural cooling mode. This time constant showed a decreasing trend with increasing power under forced convection cooling mechanism. The time constant value was higher for filled heat pipe compared to dry heat pipe in evaporator region due to phase change phenomenon happening in heat pipe. The temperature response time and rise pattern at condenser section indicated that the filled heat pipe had better heat transfer capability than dry heat pipe.

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