Characterization of a Heat Sink with Embedded Heat Pipe with Variable Heat Dissipating Source Placement for Power Electronics Applications

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Abstract:

The present study is to investigate the heat spreading characteristics of an embedded heat pipe heat sink versus a heat sink without embedded heat pipe. Experimental and numerical studies have been conducted to investigate the placement effect of a heat dissipating source applied to horizontally orientated heat sinks. The numerical analysis was verified with experimental testing. For the experimental testing, a heater block was designed to represent a standard IGBT module size and was applied at three different placements on the base plate of the heat sink. The three different placements for the heater block were considered with respect to the inlet air velocity direction (leading, middle and trailing edge). It was concluded that the performance of the heat sink with embedded heat pipes was not significantly affected by the placement of the heater block. The thermal modeling software Qfin 6.1 was used for the numerical analysis. Modeling of the heat pipe with high conductivity solid core assumption was also compared the standard vapor core model available in Qfin6.1. The numerical simulations results for the heat sink with and without embedded heat pipe were in good agreement with the experimental results.

Key Words:

Heat pipe, embedded heat pipe heat sink, experimental testing, numerical modeling, solid core, vapor core, power electronics, IGBT

Nomenclature:

Q: Heat load, (W)

ΔT: Temperature rise (˚C)

R_{th}: Thermal resistance (˚C W^{-1})

Abbreviations:

BHS: Blank Heat Sink

CH: Cartridge Heater

EHP: Embedded Heat Pipe

EHP-HS: Embedded Heat Pipe Heat Sink

HP: Heat Pipe

HS: Heat Sink

IGBT: Insulated-Gate Bipolar Transistor

TC: Thermocouple

Introduction:

Heat pipes are widely used in different industries because of the unique capability of the heat pipe to carry heat with very high effective thermal conductivity. A heat pipe is a heat transfer device that is a sealed vessel under vacuum in which a working fluid will evaporate at a heat source into a vapor which will condense as it moves across the lower temperature section of the vessel. At this point the working fluid flows back to the hot spot through capillary forces, thereby creating a two- phase flow. In the power electronics industry, Insulated-Gate Bipolar Transistor (IGBT) modules are used in power conversion inverters to convert voltage and current from AC to DC or from DC to AC. Power loss, in the form of thermal energy, is released due to electrical resistance and frequency switching losses through the IGBT and diode chips inside the module. Heat pipes are used to improve performance of the air cooled heat sink by spreading the heat along the heat pipe which is embedded in the base plate of the comb shape air cooled heat sink. The heat pipe consists of three layers; (1) the casing which represents the shell of the heat pipe, (2) the wick which represents the structure for the liquid to move due to capillary forces and (3) the core layer which represents the two phase flow region inside a heat pipe. Finding the accurate and fast modeling method for solving heat pipe applications is the main motivation behind this study. The traditional method of heat pipe modeling is to assume a solid material with a very high thermal conductivity value to represent the core layer. Although this method is easy to use and provides reasonable results, the value of the heat pipe equivalent thermal conductivity varies from one application to another. The estimated value of heat pipe equivalent conductivity is obtained through iterations by comparing a combination of experimental results, successful designs, correlations and calculations. The thermal modeling software Qfin 6.1 that was used in this study is able to model the core of the heat pipe as high conductive solid core as well as the newly developed vapor core model.

Several studies to investigate the heat pipe behavior, modeling and characterization were undertaken. Chen, Ming-Ming, and A. Faghri. [1] presented a numerical analysis for vapor flow and the heat conduction through the liquid-wick and pipe wall in a heat pipe with single or multiple heat sources by solving a generalized energy equation with different thermal diffusion coefficients in the investigated section. In that study the numerical results were compared with four cases from previous experimental studies. It was concluded that the presented model can predict general performance of the heat pipe for the cases with single or multiple heat sources for both high and low operation temperatures. Zuo, Z. J., and A.Faghri. [2] provided the network thermodynamic of the heat pipe for transient heat pipe analysis. The results for simplified governing equations for transient heat pipe as a first-order, linear, ordinary differential equation were compared with experimental results from El-Genk and Huang, 1993. Borgmeyer, Brian V., and Ma, H.B [3] performed heat-spreading analysis of a heat sink base embedded with a heat pipe. They presented the simplified model of the embedded heat pipe heat sink with embedded heat pipe as flat plate with high conductivity. The results were compared with the experimental results that were obtained by Ma and Peterson and modeled in Fluent. They found that when effective thermal conductivity of the heat sink base is higher than 6000 W/m K, the heat sink can be modeled as a flat plate. John Thayer [4] analyzed a heat pipe assisted heat sink experimentally and numerically is using CFD commercial software Flotherm. The author implemented the high conductive solid core to model the core material. The numerical results were in good agreement with the experimental results. Analytical spreading resistance models have been studied extensively by Microelectronics Heat Transfer Laboratory (MHTL) at Waterloo University. The graphic interfaces for those analytical models are available on the MHTL website.

In the present study, six independent experiments were conducted to investigate the effect of the placement of the heat dissipation source. During the experiments, the temperature of the heater block on the surface that is in contact with base plate was recorded for a range of air flow rates. The temperature rises calculated from the experiments were used to validate the numerical study results.

Mathematical formulation:

The temperature measurement used during the experiment is the average of five thermocouples placed on the mounting surface of heater block, Figure 1. In the experiments, steady state is considered when a maximum temperature fluctuation of thermocouple does not exceed 0.5 ◦c over a continuous five minute span. In the numerical model, five temperature measuring probes have been located as the same placement on the heater block.

$$\Delta T = \text{Average}(T_i)_{i=1 \text{ to } 5}$$

The testing power load for the heater block is 450W. The power load fluctuated ±10W over the duration of the experiment. To provide the accurate measured temperature rise across all experiment, the normalized ΔT was calculated for all experimental results as:

Q =Average power load in steady state time

R_{th} (thermal resistance of the heat sink) = $^{\Delta T}/_{Q}$

Normalized ΔT= $R_{th} *$ testing power load

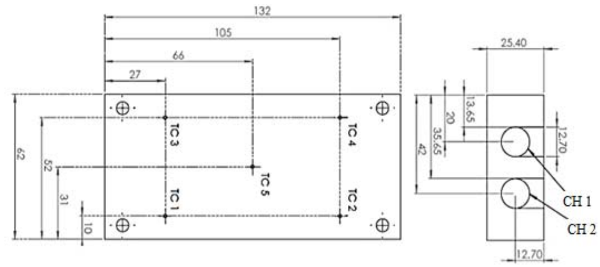

Figure 1: Bottom surface and side view of the heater block with 5 thermocouple (TC1 to TC5) and location of cartridge heaters (CH1, CH2)

Type K thermocouples were used in the experiments. Based on the data acquisition system (Keysight 34972A), that was used, the accuracy of the temperature for thermocouple type K is ±2°C. Flow rate was measured using the pressure transducer Omega model PX653 with accuracy of ±0.5%. The accuracy of the measurements of the current and the voltage are ±0.1 A and ±0.001 V respectively. Hence, the power uncertainty is ±0.1 W.

Experimental setup:

To characterize the thermal performance of the heat pipe for power electronic applications, two nearly identical heat sinks were compared as the basis of the experimental and numerical analysis. The heat sinks have the following dimensions: 189.4 mm width, 200 mm length with 18 mm baseplate thickness and 63 mm fin height. The effective fin pitch is 3.43 mm center to center with 0.9 mm fin thickness, Figure 2-A. The heat sinks were made of aluminum alloy 6063-T5 with the fins mechanically swaged into the baseplate [5, 6]. The first heat sink had no augmentations and is referred as the heat sink without embedded heat pipe or the blank heat sink (BHS) in this paper.

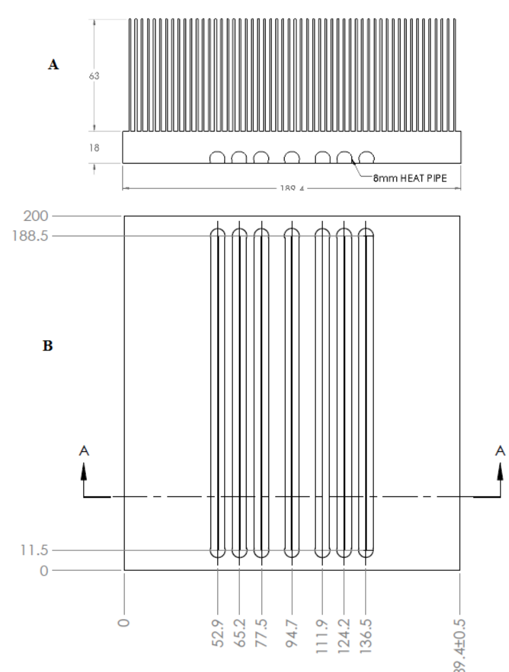

Figure 2: Cross section of the EHP-HS for experimental testing. Side view (A) Top view (B)

The second heat sink, embedded heat pipe heat sink (EHP-HS), had seven 8 mm diameter heat pipes with 180 mm length. The heat pipes were embedded on the mounting surface of the base plate parallel to the 200 mm heat sink length, Figure 2-B. The heat pipes were pressed into a machined “D” shape cross section area grooves with epoxy. They were placed directly under the heat source. The heat pipes were pressed into the mounting surface of the heat sink and machined with the baseplate so that there were no flatness issues under the module. The heat load used in the experiment is provided by a heater block that was designed to represent a standard IGBT module size of 62 mm x 132 mm, Figure **1**. Two cartridge heaters were positioned in the center of the aluminum heater block provided the required power load. To achieve consistent temperature measurements, one heater block has been used for all tests. Five standard type K thermocouples are mounted through the heater block so the temperature measurement was very close to mounting surface. The thermal grease Timtronics White Ice 510™ was applied to the heater block surface using a silk screen with initial thickness of 0.08 mm. The heater block with the thermal grease was then mounted to the heat sink. The final thickness of the thermal grease between heater block and heat sink after mounting was expected to be 0.05 mm on average. The heat sink with the mounted heater blocks were placed in a horizontal wind tunnel with cross sectional dimensions that matches the overall width and the fin height of the heat sink. The wind tunnel in Figure 3 was designed to be ducted so that there is no air flow bypass around the heat sink. The air flow was provided by a 5 hp fan that flows through a series of screens, calibrated nozzles, and through the wind tunnel to the heat sink. The wind tunnel was open to the ambient temperature and atmospheric pressure inside the lab. The air flow direction was parallel to the 200 mm length of the heat sink. A pressure transducer measured the pressure differential across the nozzle section of the wind tunnel. A nearby thermocouple located closer to the nozzle section measures the air flow temperature. The measured pressure differential and air temperature were used to calculate the volumetric flow rate of the air using the wind tunnel calibrated formula of the selected nozzle. The experimental setup is shown in Figure 3. The air temperature after the nozzles section was used as the ambient temperature value. The air flow rate range between 0.8 to 4.2 m^3/min with increments of 0.8 m^3/min is repeated for all experimental tests. The Keysight 34972A data acquisition unit has been used to record the experimental data in this study.

Figure 3: Test set up, 1: wind tunnel, 2: heater block, 3: heat sink

The three different placements for the heater block were considered with respect to the inlet air velocity direction; leading, middle and trailing edge, as shown in Figure 4.

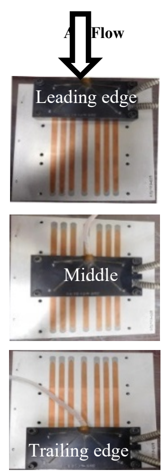

Figure 4:Heater block placement in experimental test

Repeatability of testing measurements over time period of four months are validated for power load of 450W for the embedded heat pipe heat sink with the heater block located on leading edge of the heat sink, Figure 5.

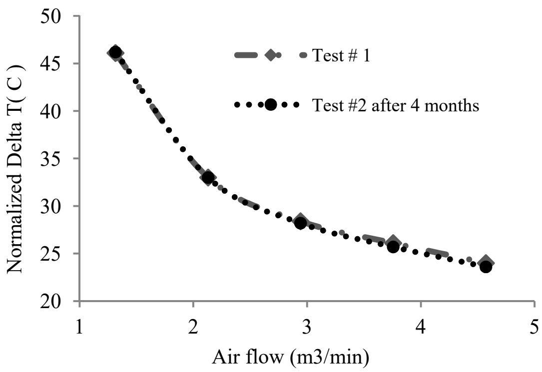

Figure 5: Repeatability testing for experimental setup, EHP-HS, heater block on leading edge

Numerical modeling:

For modeling the experimental testing, the commercial computational fluid dynamics code (CFD) Qfin version 6.1 has been used. This Finite Volume method code has the option to model the heat pipe as either high thermal conductive solid core or vapor core. Qfin vapor core model option simulates the behavior of the heat pipe for different conditions and predicts the heat pipe dry out condition. It provides the capability to predict heat pipe behavior by considering vapor phase working fluid, water, inside core. The total thermal resistance of the system with heat pipe is a combination of radial and axial resistances, Figure 6.

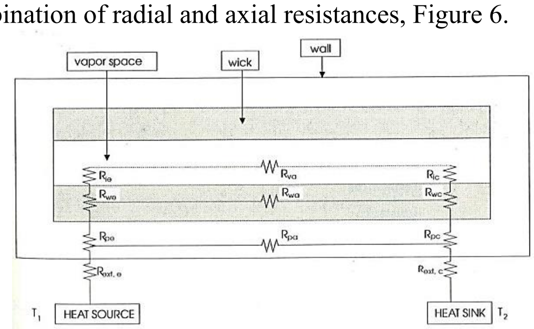

Figure 6: The thermal resistance map for a heat pipe, (Peterson, [7] - p.147)

The heat pipe resistance network consists of three groups as follows: (1) radial thermal resistance between the heat source and vapor core evaporator area, (2) axial thermal resistance along the three layers of heat pipe casing, wick and vapor core from evaporator area (heat source area) to the condenser area (heat sink area) and (3) radial thermal resistance from the vapor core condenser area to the heat sink. The flexibility of the vapor core model eliminates the iterations required for the high conductive solid core model. The heat sink was modeled with the same material properties and dimensions as the heat sink sample used in the experimental setup. Air flow ducting around the heat sink matched the overall heat sink width and height so it was assumed there is no bypass. The following assumptions have been applied for the numerical model: (1) The fin configuration was simplified as flat surfaces for the numerical model. (2) The cartridge heaters were modeled as a solid material with uniform heat distribution. (3) The five thermocouples in the heater block were modeled as probes that measure the material that it overlaps with. (4) Different interface layers were modeled as thermal resistance where defined for: a) thermal grease between heater block and base plate of the heat sink, b) thermal epoxy between casing of the heat pipe and base plate. The properties of thermal grease and thermal epoxy defined as per suppliers data sheets. (5) A standard rectangular cross sectional area of 8 mm x 8 mm was used to represent the pressed 8 mm diameter heat pipe in Qfin 6.1, Figure 7. It is Qfin 6.1 standard representation for a heat pipe which is very quick to mesh. (6) Based on the analytical analysis, the heat loss from the heater block and top surface of the base plate through radiation and convection does not exceed 1.8% for low air flow rate and 0.8% for high air flow rate. In this numerical modelling, it was assumed that convection and radiation from heater block and base plate to the environment is negligible, and all power generated in the heater block is transferred to the base plate through conduction. The estimated value of heat pipe equivalent conductivity was obtained through iterations by comparing experimental results versus numerical simulations results. To define the thermal conductivity value of the heat pipes for the modeling of EHP-HS sample, the values are chosen based on matching the performance of the leading edge results for the solid core model. The core thermal conductivity value was changed until the numerical result was in good agreement with experimental data by less than ±10% difference. The thermal conductivity value was used for the rest of the modeling with solid core method for the other heat placements. Regarding model geometry and meshing generated in Qfin 6.1, a fine mesh size with minimum four cells for the fluid (air) area between two fins was selected. Results showed that when the number of the cells is higher than 170000, the solution was independent of the mesh. In this model, the number of the cells was 180000. All results in this study are obtained using the system solver feature of Qfin 6.1. When setting up the system solver, there is no need to specify if the flow will be laminar or turbulent. The reason for this is that the system solver implicitly calculates the Reynolds (Re) number in each section of the solution domain and applies the appropriate correlations, [Qfin6.1 manual page 42]. The solid part of the model is solved with a detailed finite model using a hexagonal mesh.

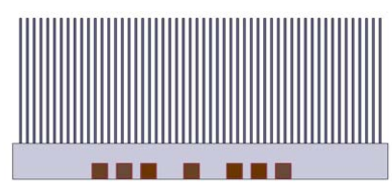

Figure 7: Configuration of the EHP HS in modeling, Qfin.

Results and discussion:

The present study is to investigate the heat spreading characteristics of an embedded heat pipe heat sink versus a heat sink without embedded heat pipe experimentally and numerically.

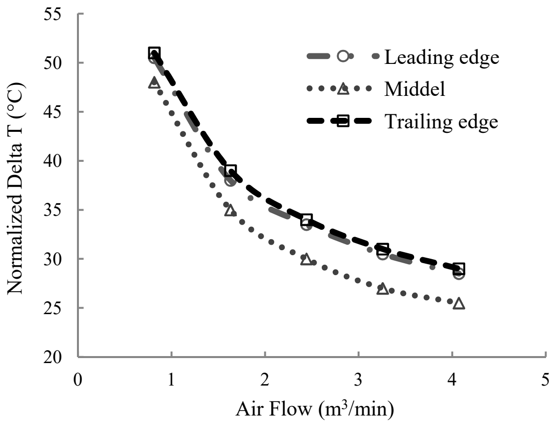

Figure 8: Effect of the heat spreading in the base plate due to the heater block placement for the BHS, Experimental results

The experimental results for normalized temperature rise of the blank heat sink, BHS, for three different heater block placements are shown in Figure 8. Comparing the experimental results for the blank heat sink for the three heater block placements show that the heat sink with the heater block on the middle position performs on average 10% better than the other two. It is due to better spreading the heat along the base plate on both sides of the heater block.

Effect of the heater block placement on performance of the embedded heat pipe heat sink was experimentally investigated. The normalized temperature rise for embedded heat pipe heat sink for the flow rate 0.8 to 4.2 m3/min is shown in Figure 9. The results show that the heater block placement has no effect on the performance of the heater block which is a direct effect of the embedded heat pipes.

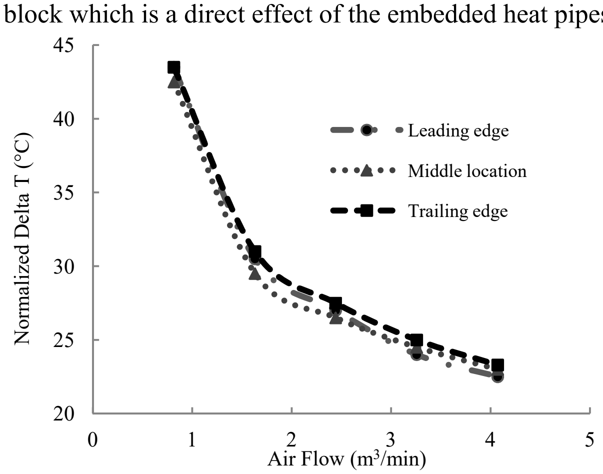

Figure 9: Effect of the heat spreading in the base plate due to the heater block placement for the EHP-HS, Experimental results

The performance of the embedded heat pipe heat sink was compared with the blank heat sink as shown in Figure 10. Results show that using embedded heat pipe improved the thermal performance of the heat sink by transferring the heat along the heat pipe and spreading thermal energy away from the heater block. The average improvement of thermal performance for the embedded heat pipe heat sink comparing to the blank heat sink is around 18%, 11% and 18% for the case when heater block is located on leading edge, middle and trailing edge placement of the heat sink respectively.

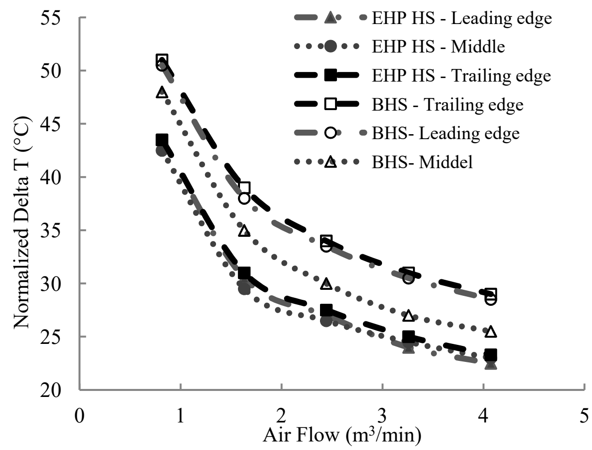

Figure 10: Comparing EHP-HS versus BHS for the leading edge and middle and trailing edge

To verify the simulation model, the numerical results of the blank heat sink were compared with the experimental testing results for the different heater block placements, Figure 11, Figure 12 and Figure 13. The simulation curves match very well with the experimental results for the cases when heater block on leading edge and middle placement with average percentage difference +2% and +3%, respectively. The average percentage difference is +6% when heater block was on trailing edge placement. As results are shown in Figure 12 and Figure 13 there is a noticeable difference starting at 2.5 m3/min when the air flow region enters the transitional zone. The simulation results for all three considered layouts are in very good agreement with the experimental results with less than average 5% difference.

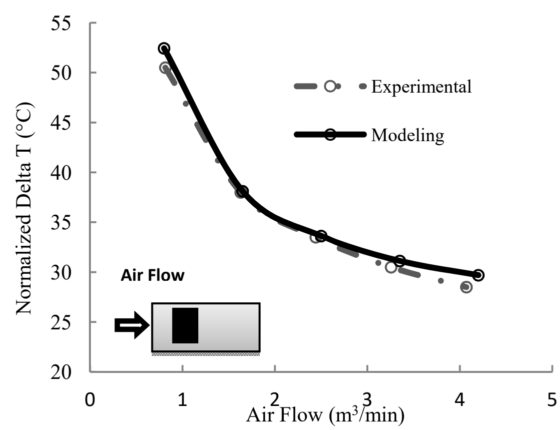

Figure 11: Numerical results versus experimental results for the BHS when heater block is on leading edge

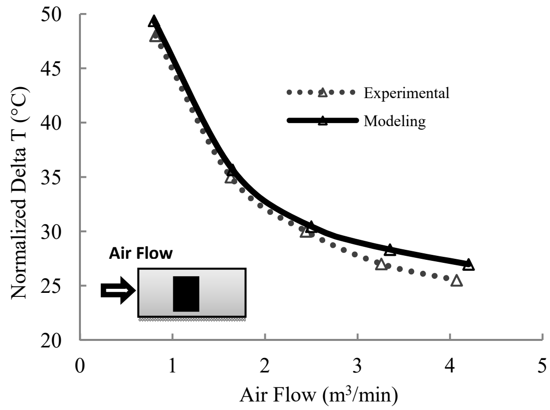

Figure 12: Numerical results versus experimental results for the BHS when heater block is on middle

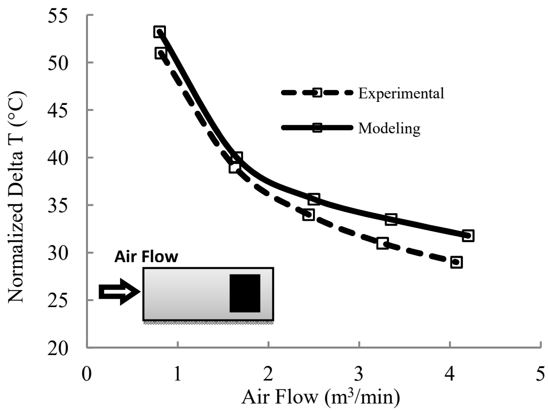

Figure 13: Numerical results versus experimental results for the BHS when heater block is on trailing edge

Numerical results for the embedded heat pipe heat sinks are compared with the experimental results in in Figure 14, Figure 15 and Figure 16 for the different heater block placements using both modeling techniques for the core heat pipe. For the case when the heater block is on the leading edge, the average numerical difference with experimental results for high conductive core modeling is +5% and for the vapor core modeling is +3%. These values for the case with heater block on the middle placement are +4% for high conductive core modeling and +3% for vapor core modeling. When heater block is in the trailing edge placement numerical difference results with experiment is +5% and +1% for high conductive core and vapor core modeling respectively.

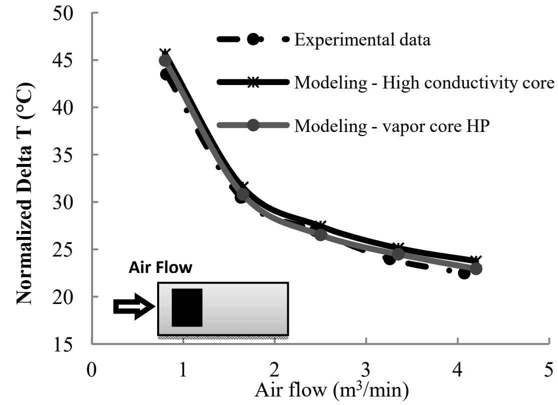

Figure 14: Numerical results versus experimental results for the EHP-HS when heater block located on leading edge.

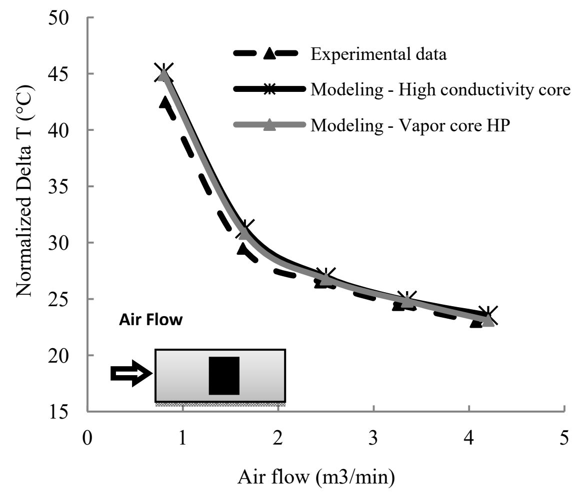

Figure 15: Numerical results versus experimental results for the EHP HS when heater block located on middle

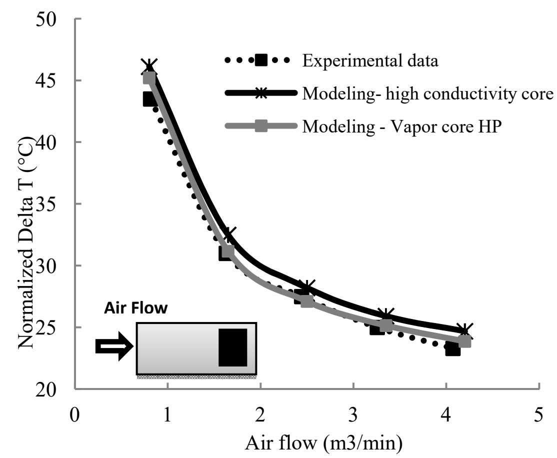

Figure 16: Numerical results versus experimental results for the EHP-HS when heater block located on trailing edge

By considering the differences between numerical results and experimental results for the modeling of the blank heat sink, it can be concluded that the numerical results from the heat pipe modeling with both vapor core and solid core are in good agreement with experimental results. It is worth mentioning that the vapor model results are in excellent agreement with the experimental measurements. This agreement has been achieved by using Qfin vapor core model without the need to iterate to reach an equivalent thermal conductivity for the high conductive model.

Conclusion:

The purpose of this study was to investigate the heat spreading characteristics of an embedded heat pipe heat sink versus a heat sink without embedded heat pip for power electronic applications with high power experimentally and numerically. The experimental results, obtained at thermal laboratory of Mersen Canada, showed that the performance of the embedded heat pipe heat sink compared with the blank heat sink improve 18%, 11% and 18% for the heater block placement on trailing edge, middle and leading edge placement respectively. It was also found that the device placement shows minimal effect on embedded heat pipe performance. The numerical results are in good agreement with the experimental results (4% difference in average). The numerical results for the embedded heat pipe heat sink with high conductive solid core with enough iteration can be used to match the thermal performance of the heat sink with less than +5% on average with the experimental results for all three heater block placement. Modeling heat pipe as a vapor core in Qfin 6.1 software can predict the heat pipe behaviour with a high accuracy for all three layouts (less than +2% on average with the experimental results). Numerical modelling of the embedded heat pipe heat sink conservatively predicted the performance of those heat pipes, so it can be used in design of embedded heat pipes. The vapor core is able to predict the behavior of the heat pipe more effectively comparing to traditional high conductive solid core by simplifying the vapor flow movement and pressure distribution. To normalize the findings of this study, more experimental and numerical studies on different configurations of the embedded heat pipe heat sink for single and multiple heater blocks would be considered for further study.

Acknowledgments:

Jan Visser at Qfinsoft for the support and help of modeling heat pipes in Qfin software using the two different approaches

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