ABSTRACT

The thermal performance of a heat spreader with Phase Change Material (PCM) is investigated experimentally under transient conditions. The transient thermal load generated by a microprocessor is obtained by running a variety of software applications commonly encountered in Personal Computer usage. The representative load cycle is used to simulate the chip with a variable heat source heater. Introducing PCM in selected pockets of the heat spreader modifies the heat spreader thermal characteristics. The heat dissipation characteristics of the air-cooling system mounted on the heat spreader are maintained constant for all of the experiments. The results indicate that modifying the thermal characteristics of the heat spreader improves the maximum heat dissipation rate under actual transient conditions encountered in PC operation.

INTRODUCTION

The thermal management of electronic devices has become an important topic in heat transfer. The power dissipation of the computer chips is rapidly increasing. The thermal management of these high power systems provides a complex challenge. Unfortunately, the heat transfer area is not increasing in line with the power dissipation. This results in an ever-increasing heat flux with higher power processors.

It becomes even more important to provide the proper cooling for these high power chips. In the most recent literature, new techniques have been developed to handle the demand for high power dissipation. New heat sink designs have new flow paths, increase in surface area, and heat transfer coefficient enhancements.

Microchannel heat sinks show a promising potential. In recent works, a microchannel has been applied to this problem. The small-scale enhancement of a microchannel gives and enhancement in the thermal performance of the heat sink. Yu et al. [1] used a microchannel heat sink for chip cooling. They found that the microchannel heat sink could provide an improvement.

Unfortunately, the majority of available literature does not take into account the transient nature of chip cooling. Most of the work has been done dissipating a steady state power load. However, the actual computer chip does not dissipate a steady state power. The highest power rating is still used as the design limit. However, the design limit is the maximum condition at 100% usage. An actual chip power will fluctuate with time. This is especially true for personal computers and small electronic devices. Therefore, the power output is directly dependent upon the percent CPU usage. This also allows the possibility of a momentarily higher than allowable surface temperatures.

The use of Phase Change Materials (PCM) is traditionally used in transient control of thermal systems. The PCM makes use of the latent heat of fusion to absorb heat. The addition of a PCM to a cooling scheme can add a better transient control.

Lu [2] modeled the transient performance of a high power electronics chip with PCM using FEM. Their results indicate the potential of a PCM in improving the transient performance. However, their results have employed very high temperatures, on the order of 5000 K, which do not have any practical significance. In another work, Weinstein [3] added a PCM to a handset mock up to provide transient control. They found that the PCM would allow for an increase in operation time. The present work explores the application of the PCM in PC chip cooling by conducting experiments with different void fraction ratios of the PCM in the heat spreader.

NOMENCLATURE

- $h_L$: Average heat transfer coefficient, W/m²K
- $P$: Power, W
- $t$: Time, s
- $\Delta t$: Time interval during transient power loading, s
- $T$: Temperature, °C
- $v$: Velocity, m/s
- $V$: Volume, m³
- $VF$: Volume Fraction, dimensionless
GREEK LETTERS

θ Excess Temperature Percentage, \( \frac{\Delta T}{(T_b - T_a)} \times 100 \)

SUBSCRIPTS

a Air
b Base
i Inlet
o Outlet
s Surface
w Wax, used as PCM

OBJECTIVES OF THE PRESENT STUDY

The present work involves the use of phase change material in a heat spreader plate. The PCM is used to control the transient effect of chip loading. A typical power cycle is used to emulate the loading of a computer chip. The effect of the PCM on the transient thermal performance of the spreader plate is experimentally evaluated.

EXPERIMENTAL SET-UP

The experimental apparatus was developed to study the effect of PCM on the transient performance of a spreader plate. An electric heater is used to emulate the computer chip. The actual heater is a 1 cm x 1 cm flexible heater. The heater size is close to the actual dimensions of a chip. The heater is secured to a spreader plate using an adhesive. The power input is controlled to impose the desired loading conditions.

The spreader plate is manufactured from a plate of aluminum. The plate has the overall dimensions of 3 inches wide by 3 inches long and ¾ inch thick (76.2mm x 76.2mm x 19mm). The spreader plate is shown in Figure 1.

Figure 1: Aluminum Spreader Plates. The overall dimensions are 3"x 3"x ¾" thick and ¼ inch diameter holes. Four different volumes of PCM; 0.00 m³, 2.413x10⁻⁶ m³, 7.239x10⁻⁶ m³, and 1.267x10⁻⁵ m³. The volume fraction, VF, is defined here as the volume of PCM divided by the volume of material. The respective VF for the PCMs are 0.02, 0.07 and 0.11. After completion of the first round of tests, a fifth spreader plate was constructed. Figure 2 shows the fifth plate. It has a wax volume of 2.17x10⁻⁵ m³ and a VF of 0.20.

Figure 2: Modified Aluminum Spreader Plate. Overall dimensions are 3"x 3" x ¾" thick with one ¼" diameter hole and 2 ½" diameter hole. Volume of PCM = 2.17x10⁻⁵ m³ and VF = 0.20.

Thermocouples are distributed in the spreader plate to determine surface temperatures. The base temperature is known. An array of surface temperatures on the cooling side is known. The temperature of the PCM is also known.

The spreader plates are placed in an identical air-cooling setup. A small wind tunnel is constructed to provide uniform airflow over the heat spreader as shown in Fig. 3. The air velocity is fixed at 4.00 ± 0.05 m/s. Each of the spreader plates is mounted in the same manner.


The air-cooling system involves the use of a miniature wind tunnel made of Lexan as shown in Fig. 3. The Lexan is an optically clear polycarbonate. A variable speed fan controls the air velocity. The voltage is fixed to provide an air velocity of 4 m/s. The air passes through a set of flow straightener and enters the test section. The air velocity is measured using a pitot tube. The inlet and outlet air temperatures are measured using thermocouples. The thermocouples where calibrated to ±0.1°C. The inlet temperature varied slightly during the testing due to the changing ambient conditions. However, the temperature was within the range of 22.1°C to 23.1°C.
EXPERIMENTAL PROCEDURE

The spreader plates are mounted in the wind tunnel. The air velocity is held constant for each test. Four different volumes of PCM are tested. The four VF for these cases are 0, 0.02, 0.07, and 0.11. The air velocity is set at 4.00 ± 0.05 m/s. First, a steady state power load of 100 Watts is applied to the spreader plate. The temperatures are recorded for this case. The other cases involve a varying power load to emulate transient chip power usage. The thermal performance is reported for each testing condition.

RESULTS

The thermal performance of a spreader plate is found under several different power loading conditions. A spreader plate is used to distribute the heat from a small area into a larger base area. A variable electric heater is used to emulate a microprocessor. The maximum base temperature is limited to 62 °C. The reported melting temperature of the wax is 66 °C. However, the actual melting temperature was experimentally determined to be considerably lower, around 50-55 °C.

There are several different loading conditions that are presented. The thermal performance of each case is reported. The reference case for comparison is a spreader plate that has no PCM. It is the point of reference for all of the testing. This plate was tested first for each of the loading conditions. For reasons of clarity, only the spreader plate with a VF of 0.00, 0.07, and 0.11 will be presented. The spreader plate that has a VF of 0.02 has a similar performance as the plate with 0.00 VF PCM.

The first loading condition is a steady state power loading. The heater is set to deliver a constant power. The steady state temperatures are recorded.

Figure 4 shows the thermal performance for the constant load of 40 Watts. As seen in the figure, the temperatures reach a steady state value in approximately 2500 seconds. The average heat transfer coefficient, \( h_L \), on the cooling side is calculated to be 28.8 W/m²K. The spreader plate with no PCM reaches the lowest steady state temperature of 77.5 °C. The spreader plate with a VF of 0.07 reaches a steady state temperature of 76.1 °C. The spreader plate with the most PCM and a VF of 0.11 reaches the highest steady state temperature of 80.1 °C. This behavior makes sense because the increase in the PCM material results in a decrease in the thermal conduction paths. The base temperature for the plate with a VF of 0.11 shows a slight depression in the shape between 55 °C and 65 °C. This is due to the energy being consumed in the latent heat used to melt the PCM.

Figure 5: Wax Temperature for Steady State Loading of 40 Watts. The transient history of wax temperatures for each spreader plate cavity. The plate with VF=0.07 has 3 cavities. The plate with a VF=0.11 has five cavities. VF = 0.00, 0.07, and 0.11.

Figure 5 demonstrates the temperature history for the wax temperatures in the PCM under a constant load of 40 watts. The distinct temperatures are the temperatures of the wax in independent cavities. The spreader plate with a VF of 0.07 has three cavities. The spreader plate with a VF of 0.11 has five cavities. The effect of the PCM and latent heat can be seen by the flattening of the slope around the melting temperature of the PCM. This curve for each constant loading power input was useful in developing the transient loading.

Figure 6 shows the resulting base temperatures for the constant loading case. The steady state base temperatures are reported for the various spreader plates. Based upon this data, the variable loading case was developed.

The variable loading case uses two power inputs. The higher power input is the maximum power input. The lower power input is a percentage of the maximum or higher power input, typically 25% of the maximum value. The load is varied between these two power inputs with different time intervals. This loading scenario simulates the processor being loaded at 100% capacity and then at 25% capacity.

Figure 6: Base Temperature for Steady State Load of 40 Watts. The transient history of the Base Temperature for a steady state 40 watt loading of a spreader with varying PCM. VF = 0.00, 0.07, and 0.11.
Figure 6: Base Temperature verses Power Input. The Base Temperature for a steady state loading verses the power input. VF = 0.00, 0.07, and 0.11.

The first variable loading case is shown in Figure 7. The first loading condition is using 40 watts as the maximum and 15 watts as the minimum. The time duration is 240 seconds at each power rating, starting at the maximum power.

Figure 7: Power Curve for the First Variable Load. $P_{\text{max}} = 40 \text{ W}, P_{\text{min}} = 15 \text{ W}, \Delta t = 240 \text{ s}$.

Figure 8: Base temperature versus time under variable loading – First Case. $P_{\text{max}} = 40 \text{ W}, P_{\text{min}} = 15 \text{ W}, \Delta t = 240 \text{ s}$.

The first loading was applied to the spreader plates with a VF of 0.00 and 0.11. Figure 8 shows the results of the first transient load. The base temperature for the plate with VF = 0.00 varied between a maximum of 63.1 °C and a minimum of 56.9 °C. The plate with a VF of 0.11 varied between a maximum of 63.0 °C and a minimum of 57.5 °C. The two plates transient thermal performance is very close to each other. It is interesting to see that the only difference between these plates occurs in the early transients. Although, there is no discernable difference when the plates reach a steady state pattern.

The second variable loading case is shown in Figure 9. The second loading condition is using 30 Watts as the maximum and 7.5 Watts as the minimum. The time duration is 240 seconds at each power rating, starting at the maximum power.

Figure 9: Power Curve for the Second Variable Load. $P_{\text{max}} = 30 \text{ W}, P_{\text{min}} = 7.5 \text{ W}, \Delta t = 240 \text{ s}$.

Figure 10: Base temperature versus time under variable loading – Second Case. $P_{\text{max}} = 30 \text{ W}, P_{\text{min}} = 7.5 \text{ W}, \Delta t = 240 \text{ s}$.

The second loading was applied to the spreader plates with VFs of 0.00, 0.11, and 0.20. Figure 10 shows the results of the second transient loading case. The base temperature for the plate with VF = 0.00 varied between a maximum of 52.5 °C and
a minimum of 46.7 °C. The plate with a VF of 0.11 varied between a maximum of 50.1 °C and a minimum of 44.5 °C. The plate with a VF of 0.20 varied between a maximum of 47.5 °C and a minimum of 42.0 °C. When the plates reach their steady state pattern, the spreader plate with PCM has a lower maximum surface temperature. The percent temperature excess, $\theta$, for the VF of 0.11 is 8.0%. It seems that the VF of 0.11 is not absorbing enough energy to depress the base temperature for this loading. The plate with a VF of 0.20 begins to show a considerable improvement. The excess temperature for the VF of 0.20 is 16.7%.

The third variable loading case is shown in Figure 11. The third loading condition is using 30 Watts as the maximum and 7.5 Watts as the minimum. The time duration is now 120 seconds at each power rating, starting at the maximum power.

![Figure 11: Power Curve for the Third Variable Load. $P_{\text{max}} = 30 \text{ W}, P_{\text{min}} = 7.5 \text{ W}, \Delta t = 120 \text{ s.}$.](image1)

![Figure 12: Base temperature versus time under variable loading – Third Case. $P_{\text{max}} = 30 \text{ W}, P_{\text{min}} = 7.5 \text{ W}, \Delta t = 120 \text{ s.}$](image2)

The forth variable loading case is shown in Figure 13. The forth loading condition is using 35 watts as the maximum and 8.75 watts as the minimum. The time duration is now 120 seconds at each power rating, starting at the maximum power.

![Figure 13: Power Curve for the Forth Variable Load. $P_{\text{max}} = 35 \text{ W}, P_{\text{min}} = 8.75 \text{ W}, \Delta t = 120 \text{ s.}$](image3)

![Figure 14: Base temperature versus time under variable loading – Forth Case. $P_{\text{max}} = 35 \text{ W}, P_{\text{min}} = 8.7, \Delta t = 120 \text{ s.}$](image4)

The forth loading was applied to the spreader plates with a VF of 0.00, 0.11, and 0.20. Figure 14 shows the results of this transient load. The base temperature for the plate with VF = 0.00 varied between a maximum of 50.74 °C and a minimum of 48.1 °C. The plate with a VF of 0.11 varied between a maximum of 48.5 °C and a minimum of 45.9 °C. The plate with a VF of 0.20 varied between 45.72 °C and 43.25 °C. When the plates reach their steady state behavior, the spreader plate with PCM has a lower maximum surface temperature. The percent temperature excess for a VF of 0.11 is 9.35%. The excess temperature for a VF of 0.20 is 17.2%.

The fourth loading was applied to the spreader plates with a VF of 0.00, 0.11, and 0.20. Figure 14 shows the results of this transient load. The base temperature for the plate with VF = 0.00 varied between a maximum of 50.74 °C and a minimum of 48.1 °C. The plate with a VF of 0.11 varied between a maximum of 48.5 °C and a minimum of 45.9 °C. The plate with a VF of 0.20 varied between 45.72 °C and 43.25 °C. When the plates reach their steady state behavior, the spreader plate with PCM has a lower maximum surface temperature. The percent temperature excess for a VF of 0.11 is 9.35%. The excess temperature for a VF of 0.20 is 17.2%.

The forth loading condition is using 35 watts as the maximum and 8.75 watts as the minimum. The time duration is now 120 seconds at each power rating, starting at the maximum power.
the plates reach their steady state behavior, the spreader plate with PCM has a lower maximum surface temperature. The percent temperature excess for a VF of 0.11 is 10.1%. The excess temperature for a VF of 0.20 is 14.1%.

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Table 1: Excess Temperature, θ, Percentage for transient loading cases. VF = 0.00, 0.11, and 0.20.

Table 1 shows the results of the transient load testing for the five different spreader plates. The VF for each plate is 0.00, 0.11, and 0.20, respectfully. Case 1 is the first loading case of Pmax = 40 watts, Pmin = 15 watts, and Δt = 240 seconds. Case 2 is the second loading case of Pmax = 30 watts, Pmin = 7.5 watts, and Δt = 240 seconds. Case 3 is the third loading case of Pmax = 30 watts, Pmin = 7.5 watts, and Δt = 120 seconds. Case 4 is the forth loading case of Pmax = 35 watts, Pmin = 8.75 watts, and Δt = 120 seconds. As seen in the table, the largest q reached was 17.2 for Case 3 and a VF of 0.20. It can be seen that the increase in VF results in improved performance. However, an optimization for specific application is required.

CONCLUSIONS

The use of a phase change material in electronics cooling can provide an improvement in handling transient thermal management. The PCM has already proven useful in such applications as high heat fluxes [2] for high heat fluxes and in hand sets [3] to extend operation time. The use of PCMs in this application could possibly extend air-cooling of microprocessors. Some conclusions from this study are:

1. The PCM provides a lag in the very early transients as compared to the spreader plate without any PCM. The early stages of the loading have shown that the plates with PCM provide a more even ramp up in temperature. This would be valuable if the steady state behavior is not of concern.

2. The PCM does make a difference in the constant loading of the spreader plate. The PCM has the effect of augmenting the typical base temperature curve. The region of change denotes the operating region of the PCM. The transient design of the spreader plate should fall within this region. If the transient loading falls outside of this region, the PCM will be ineffective in producing the desired effect, as in Figure 7.

3. The PCM does provide a reduction in the maximum base temperature of the spreader plate as compared to the plate without any PCM. This behavior is seen in Figures 9, 11, and 13.

4. The volume of the PCM has a significant effect upon the transient performance. The volume for a specific loading must be optimized for the best performance. Table 1 also demonstrates this behavior. On the other hand, too much volume of PCM will cause a limiting effect in the conduction paths of the spreader plate. This will also cause a detrimental effect upon the base temperature and cause an increase in base temperature, as seen in Figure 3.

The use of a PCM in electronics could provide a much need extension of air-cooling. Unfortunately, the application of the PCM is very dependent upon the loading conditions. Further optimization is required to determine the proper PCM material type, PCM volume, and orientation. Further experiments are being planned with significantly higher volumes of PCM embedded in the heat spreader plate.

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