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MULTI-OBJECTIVE OPTIMIZATION OF GRAPHITE HEAT SPREADER FOR PORTABLE SYSTEMS APPLICATIONS

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ABSTRACT

The advancement made in portable electronic systems has primarily been due to miniaturization of electronic devices. This results in an increase in power density that leads to higher temperatures and formation of hot spots. There is a temperature specification of system surfaces for human comfort (such as the surface close to a keyboard on laptops). The challenge of cooling portable devices is that there is not enough room to accommodate heat sinks. It is therefore important to have heat spreaders that can transfer the heat from critical devices to regions where cooling is available. Traditionally, copper has been the best heat spreader due to its high thermal conductivity. However, copper has a relatively high density and correspondingly high weight. Graphite is a suitable alternative. Recent advances in graphite technology have resulted in fairly high conductivity in the planar directions. In spite of these advances, the cost of graphite is an issue. In this paper, a multi-objective optimization is utilized that considers weight of the graphite heat spreader as objective functions. The data is then compared to published data that utilizes graphite in a laptop.

INTRODUCTION

Various methods of spreading heat are widely used in today's electronics. Heat spreaders are used in die-level packaging to spread heat from the microprocessor chip into the packaging. Multi-chip modules have been built that incorporate a copper heat spreader. On a component level, active spreaders such as heat pipes are used to move heat from chip packages to heat sinks. Passive heat spreaders have been incorporated into plasma display panels. Spreaders are commonly used within electronic

enclosures to move heat from discrete components to the walls of the enclosure [1].

This paper deals with optimizing weight and hence, volume of a graphite heat spreaders keeping in view the high costs associated with manufacturing of graphite heat spreaders. In addition to CFD analysis a thermal stress analysis is conducted to verify whether the changes made in design are good structurally too.

FLEXIBLE NATURAL GRAPHITE MATERIALS

Natural graphite flakes are a polycrystalline form of carbon composed of layer planes containing hexagonal arrays of carbon atoms. These layer planes, referred to as graphene layers, are ordered to be substantially parallel to one another. Detail information on how the layers are fabricated can be found in [1].

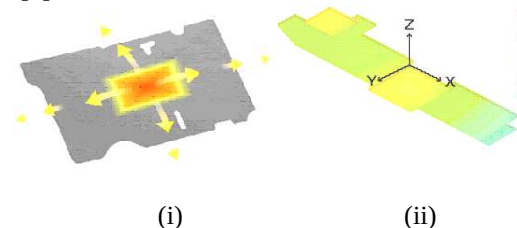


Figure 1: Orthotropic graphite heat spreader (i) a and b axes (ii) c axis

As shown in Table 1, natural graphite material is highly anisotropic, with a thermal conductivity ranging from 140-500 W/mK in and along the "a" and "b" axes (parallel to the layer planes) and from 3-10 W/mK along the "c" axis

(perpendicular to the planes). By comparison, conventional isotropic materials used for spreading heat, such as 1100 series aluminum and 11000 series copper, have a thermal conductivity of 220 and 388 W/mK, respectively. Natural graphite has a density ranging from 1.1-1.7 g/cm³ compared to 2.7 and 8.89 g/cm³ for aluminum and copper, respectively. Also, because of their excellent flexibility, natural graphite materials are able to conform well to surfaces under low contact pressures. This combination of properties makes natural graphite a potential substitute for aluminum and copper materials as heat spreaders. In particular, the highly anisotropic thermal conductivity of natural graphite implies that a natural graphite sheet can function as both a heat spreader and an insulator and can be used to eliminate localized hot spots in electronic components [1].

Table 1: Thermal properties of heat spreader materials

PROPERTY	Direction	Graphite	Al 1100	Cu 11000
Density(g/cm ³)		1.1-1.7	2.71	8.89
Thermal Conductivity (W/m ³)	A,b	140-500	220	388
Thermal Conductivity (W/m ³)	C	3-10	220	388
Specific Heat Capacity (J/Kg.K)		846	904	385

LITERATURE REVIEW: HEAT SPREADERS

There are many references to the use of passive heat spreaders in die and chip-level packaging. Spreaders for moving heat from chip-level packaging into heat sinks were described by Anschel *et al.* [3]. The use of a heat spreader embedded into a molded plastic electronic package was described by Mahulikar *et al.* [4]. Chu *et al.* describe a heat spreader for a multi-chip assembly [5].

A variety of advanced materials has been proposed for use as heat spreaders. Jagannadham [6] has examined the use of multilayer diamond heat spreader substrates bonded to silicon chips [6]. Use of polycrystalline diamond as a heat spreader between a chip and a heat sink was described by Hall *et al.* [7]. A composite heat spreader, with carbon fibers dispersed in a carbon or metal matrix, was described by Houle [8]. The performance of two-dimensional, composite heat spreaders made from carbon-carbon (C-C) and carbon-silicon carbide (C-SiC) materials were measured by Kowbel *et al.* [9]. The thermal performance of these materials was found to be superior to that of metal alloy spreader materials with similar coefficients of thermal expansion such as copper-tungsten.

Advanced materials have also been used as heat spreaders in electronic assemblies and housings. The use of conformal metallic layers applied to the inside of a molded plastic

electronics enclosure is described by Watchko *et al.* [10]. The coating provides both heat dissipation and EMI shielding. Weinstein *et al.* investigated the use of a graphite-loaded polymer (GLP) as a material for the housing of cell phone handset [11]. The thermal performance of GLP handsets was compared to those of handsets made with conventional acrylonitrile-butadiene-styrene (ABS) and incorporating aluminum or copper heat spreaders. The use of a carbon/carbon heat spreader in a laptop computer was described by Dilley *et al.* [12]. This heat spreader was used to move heat from laptop motherboard to the back of the LCD display. Carbon fibers in various orientations were used to form heat transfer conduits to move heat from an absorption plate and spread the heat uniformly across the back of the LCD display. Murthy *et al.* studied the performance of two-phase heat spreaders that incorporated microfabricated structures to enhance boiling [13].

The use of natural graphite material as a heat spreader was examined in CFD models by Tzeng *et al.* [14]. In a simplified model, Tzeng showed that an anisotropic heat spreader, with properties similar to those of natural graphite, could lower the maximum temperature of a localized heat source. A heat spreader made from highly ordered pyrolytic graphite was described by Ritchey [15]. The pyrolytic graphite had a thermal conductivity in the a and b planes of 1500 W/mK. The use of a similar pyrolytic graphite heat spreader was described by Messenger *et al.* [16]. In this application, the pyrolytic graphite was encapsulated in aluminum, bent into an L shape, and used to transfer heat from an electronics enclosure to an external mounting rack.

Spreading heat and cooling components in laptop computers poses unique problems. Because of the high density of components packed in a laptop, very little room is available for a thermal solution. The design of thermal management system for an ultra-thin laptop was described by Kobayashi *et al.* [17]. Two aluminum heat spreaders, one coupled to a lower case made of die-cast magnesium alloy, the other to an upper case of ABS plastic, were used to cool a 3.9W Pentium processor by natural convection only. Thermally conductive silicon gap pads were used to conduct heat from the microprocessor and motherboard to the rigid aluminum heat spreaders. One disadvantage of this design is that the case temperature immediately below the heat source can be high. In later work, Kobayashi *et al.* described the replacement of the rigid aluminum spreaders with flexible graphite heat spreaders [2]. Thermally insulating elastomeric materials were placed between the graphite and the case and used to press the graphite against the heat source. The anisotropy of the graphite, combined with the insulation of the elastomer, eliminated the hot on the case.

TEMPERATURE DISTRIBUTION IN A TYPICAL LAPTOP COMPUTER

Figure 2 shows the internal layout of components directly below the keyboard and case. Major components include the heat sink, the heat pipe above the CPU chip, the fan, the slot for the PCMCIA card, the hard drive, the battery, and the

bay for the DVD drive. There is a well-designed thermal solution cooling the CPU, but there is no explicit thermal solution employed to cool the hard drive. Because of economic factors, standardization is widespread and the layout of this unit is typical of many laptops. A particular feature of this design is the placement of the hard drive under the left palm rest and the battery under the right. High hard drive operating temperatures can result in uncomfortable palm rest touch temperatures [1].

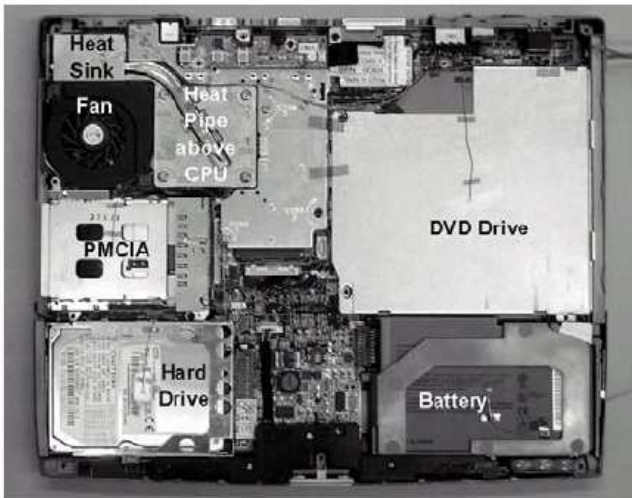


Figure 2: Typical layout of components in a laptop computer.

Researchers in [1] did experiments using temperature sensors and developed a thermal image of laptop, shown in Figure 3. Smalc *et.al*[1] reports that the hard drive reached a temperature of 30°C above ambient. This is similar to data obtained by Vichare *et al.* [20]. This increase in hard drive temperature caused the average temperature of left palm rest to increase to 14.1°C above ambient while that of the right palm rest has increased only 3°C. This results in uncomfortable surface temperatures above the palm rest. Two references, [18] and [19], report similar results.

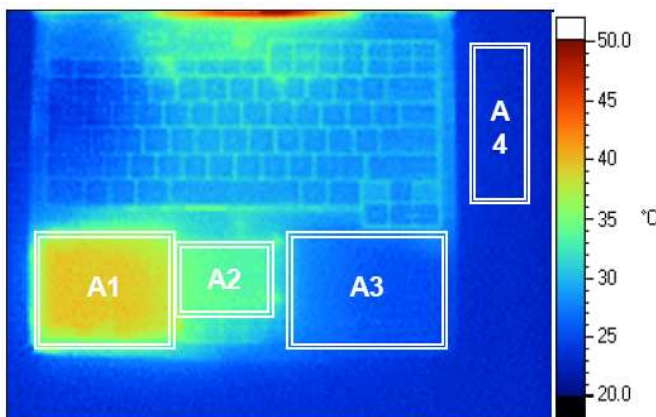


Figure 3: Thermal image of the laptop cover and keyboard.

Preceding references and observations suggest a non-uniform temperature gradient in the interior of laptop, increasing the importance of a heat spreader. In this paper, a heat spreader was considered and parameterized using Icepak™, a commercial CFD tool provided by ANSYS Inc.

ICEPAK MODELING

The Icepak model was developed considering the graphite thickness of 0.51 mm-thick natural graphite spreader that had an in-plane thermal conductivity of 369 W/mK. Installed in a laptop, the natural graphite spreader was able to conform easily to the height differences of the components it contacted. This spreader reduced the overall temperature gradient within the laptop and on the outer case by as much as 8°C [1]

The heat spreader was modeled in Icepak using the exact same dimensions as the original. Heat spreader was developed as a conducting thin plate. Conducting thin plates have same properties as conducting thick plates except that they have no physical thickness. In this paper, only hard disk, Battery, DVD drive and PCMCIA card are considered and are modeled as blocks. The blocks are placed on the heat spreader at the appropriate places and power is applied to them. Figure 4 shows the initial model of heat spreader.

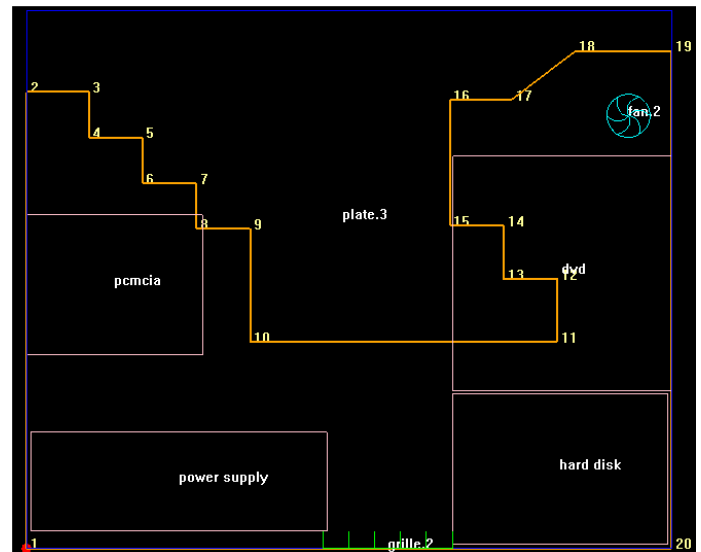


Figure 4: Initial heat spreader model developed with Icepak.

The model is solved as a forced convection controlled model and contains a free opening through which air enters under the influence of an exhaust fan that has sucks air at a mass flow rate of 12 CFM.

BOUNDARY CONDITION

The boundary condition considered for the heat spreader is thermal conductivity of 369 W/m-k with a thickness of 0.51mm. The material considered is natural graphite. Table 2 summarizes the boundary conditions for the blocks.

Table 2: Boundary conditions applied in the model

Part name	Conductivity	Heat dissipated
Power supply	19W/m-k	10W
Hard Drive	22W/m-k	16W
DVD drive	22W/m-k	0.5W
PCMCIA	1W/m-k	0.25W

BASELINE CASE

In this case, we considered all the blocks to be in their original places and applied boundary conditions, running the simulations, we obtained the results shown in Figure 5.

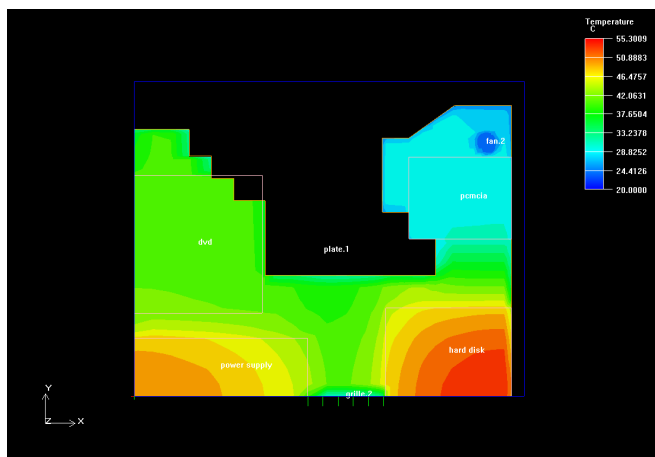


Figure 5: Temperature plots for Baseline model

The temperature gradient obtained was between 20 and 55°C degrees, with maximum temperature obtained on the hard disk which is underneath the right palm.

STRUCTURAL DESIGN

In order for the spreader design to be implemented it is important that it is strong structurally too. Hence, a thermal stress analysis of the same design was done in a ANSYS workbench. A solid model of the spreader with four components is created in Pro/E as assembly. The model was imported into ANSYS Workbench as IGES. Thermal boundary conditions applied to this model are heat transfer coefficient on top surface of spreader. There are two aims of this analysis. As there is no experimental work in this paper the software model is validated using another code. The second aim is to check the structural integrity of the spreader design. Mechanical boundary conditions in design are fixed support on lower face of all components and equivalent load of 5lb_f was applied on model to simulate the pinning down of heat spreader. Figure 6 and 7 shows the thermal and mechanical boundary conditions respectively.

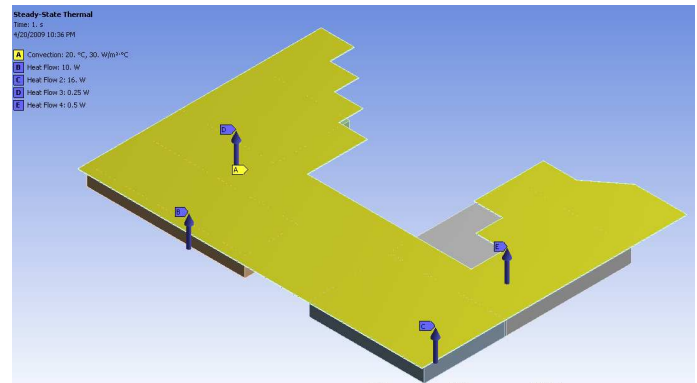


Figure 6: Thermal Boundary conditions applied to model

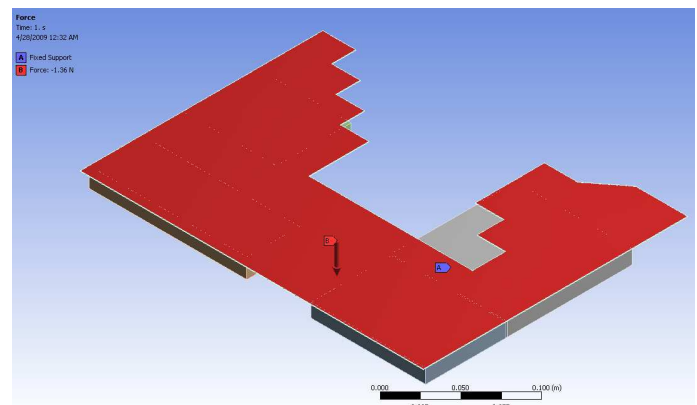


Figure 7: Mechanical boundary conditions applied to model

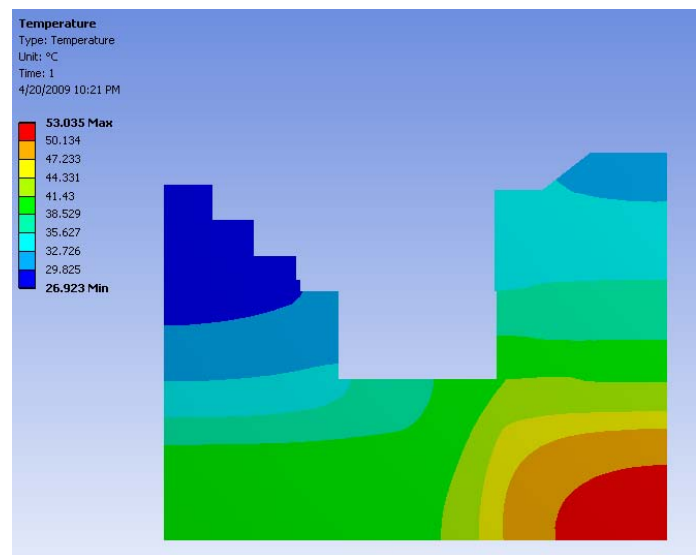


Figure 8: Temperature contours in heat spreader

It is evident that highest temperature occurs in hard disk and is 53°C. The temperature obtained in this case is

within 5% of the temperature obtained in baseline case solved in Icepak. Thus the computational model is validated.

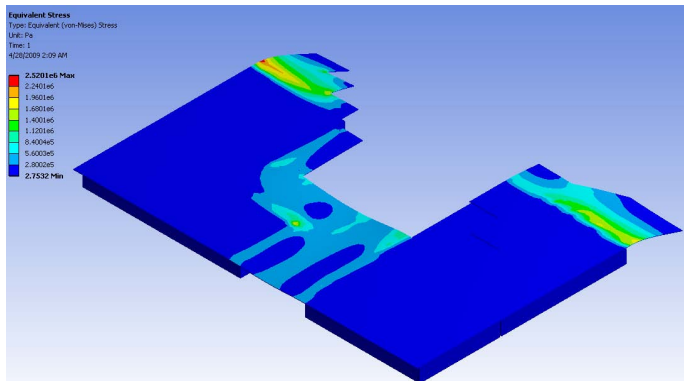


Figure 9: Von-Mises stress induced in spreader due to heat generation

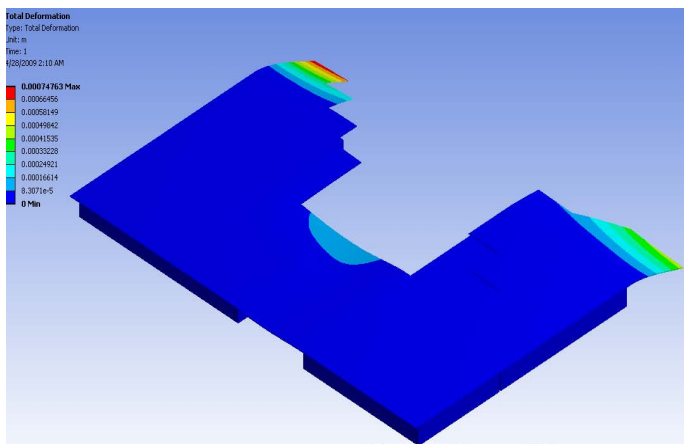


Figure 10: Deformation of graphite heat spreader

Figure 9 shows the mechanical stresses induced in graphite heat spreader. The stresses are maximum on the side of heat spreader, these are mechanical stresses that will be induced because of the deformation of graphite. The stresses that are induced in the middle are the ones that are induced because of the heat generation from components underneath it. One can infer from figure 10 that the maximum deformation induced in graphite heat spreader is 0.7 mm. This deformation can add tremendous contact resistance between the components and spreader and can be responsible for increase in temperature.

OPTIMIZATION OF HEAT SPREADER

The use of a heat spreader made a tremendous impact on cooling performance. However, a careful look at the temperature plot obtained in Figure 5 reveals that a significant portion of spreader, starting on right underneath the DVD drive, doesn't show any appreciable temperature gradient. Similarly, near the fan, air is exiting system at 20°C one can observe that the spreader also has a temperature also 20°C. Literally speaking, if the temperature of the spreader is 20°C, the spreader there is redundant. Every square millimeter of graphite

is costly; there is a need to minimize the spreader area by not sacrificing the maximum temperature across the spreader.

For the purpose of optimization, the heat spreader was divided into 11 parts. Each part contains one X and one Y dimension, which are considered optimization variables, yielding 22 design variables in all (Z dimension was considered fixed and hence not considered in optimization). The purpose of 22 design variables is that it gives us very good control for optimizing geometry of the spreader. Initial values of the variables are assigned in such a way that the baseline case of optimized model of the spreader replicates the original design. Figure 11 shows the optimization model.

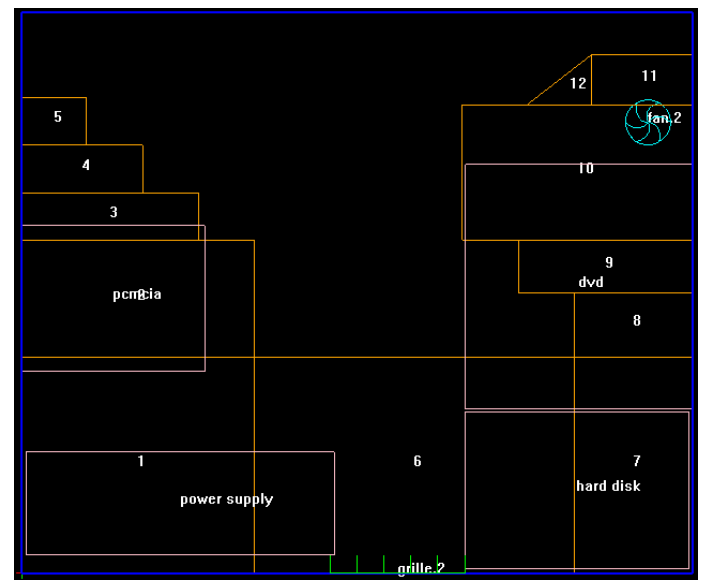


Figure 11: Optimization model of heat spreader.

Table 3 gives the dimensions of the different parts and the total area of heat spreader; the Total area of which is 48591.01 mm². This corresponds to a net weight of 42 grams, cost of just graphite will be \$0.45. [21]

Table 3: Non-Optimized (Original) Dimensions of the heat spreader.

Block	X Length (mm)	Y Length (mm)
1	104	96
2	104	52.4
3	79	21.2
4	54	21.2
5	29	21.2
6	143	96
7	53	96
8	53	28.95
9	78	23.45
10	103	60.46
11	45.56	22.14
12	28.49	22.14

Constraints on the design variables depends on the location of part (*e.g.*, parts that are placed on high heat dissipating components, such as power supply and hard disk, will have smaller constraints compared to the parts located underneath PCMCIA, DVD, and near the fan). Equation 1 gives the optimization function

$$Totalarea = \sum_{n=1}^{12} X * Y \text{ ----- (1)}$$

The monitor variable for optimization is the global temperature. The constraint on temperature is 56°C. This algorithm generated over 100 scenarios. But the scenario wherein, the area of spreader was least is shown in figure 12.

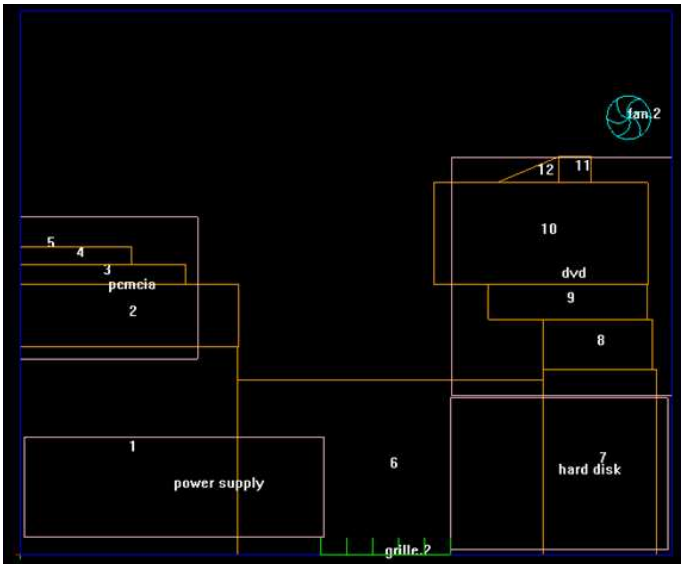


Figure 12: Optimized dimensions of heat spreader.

One can assert by comparing figure 4 and figure 12 that there is a significant change in dimensions of heat spreader. Figure 13 shows the temperature contours associated with the model. The maximum temperature obtained in the model was 55.9°C. Thus, by sacrificing 1°C temperature globally, we got a huge reduction in net cross-section area of the spreader. The new dimensions of spreader are listed in Table 5. Figure 14 shows the different scenarios that were solved with the optimization routine.

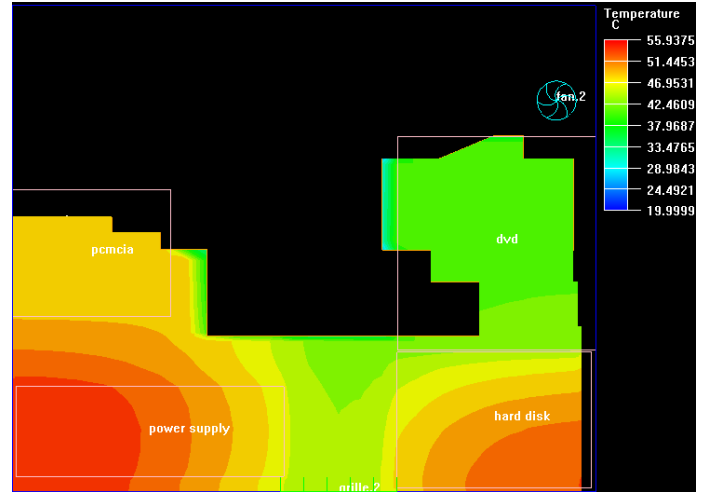


Figure 13: Temperature plot with optimized dimensions of heat spreader

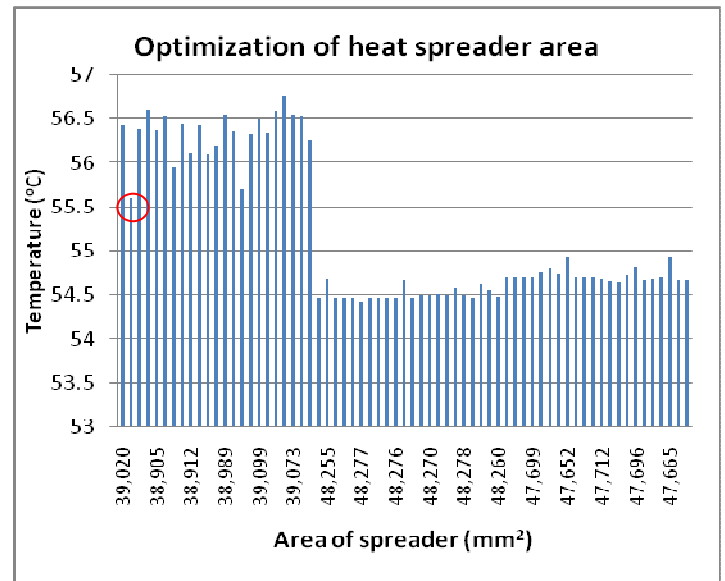


Figure 14: Optimization Scenarios for heat spreader .

On the X-axis in Figure 14 are the areas of heat spreader obtained in various scenarios that were solved using the optimization algorithm. The optimal scenario is scenario 2, in which generates the least area among all different cases. Table 4 gives the optimized dimensions of heat spreader.

Table 4: Optimized dimensions of heat spreader.

Block	X length (mm)	Y Length (mm)
1	102	96
2	104	30
3	79	10
4	54	9
5	29	3
6	143	83
7	53	85
8	53	25
9	78	18
10	103	50
11	20	15
12	28.49	22.14

The total area of the optimized spreader is 38828 mm². The net saving in area is 48591.01 – 38828 = 9800 mm², which is nearly 20% smaller than the original design. This corresponds to a net weight of 34 grams, cost of just graphite will be \$0.36 [21] which is almost 20% reduction in cost of graphite. A structural design simulation of the new optimized heat spreader revealed that maximum deformation induced in spreader is 0.24mm. Primary reason for this is extension of heat spreader is cut off and is pinned down directly onto the PCMCIA card and DVD. However, the maximum stress induced in the spreader is more than the in the original design, but is still less than the maximum strength of graphite and hence can be considered as safe.

CONCLUSION

The optimization of heat spreader to reduce its fabrication cost was considered in this study. The spreader was divided into 12 parts and each part was assigned two variables. Using optimization algorithm we were able to reduce area of the spreader by almost 9800 mm² which corresponds to 20% of the original design area, and reducing cost of graphite from 45cents to 36 cents. This particular paper was done for a laptop. According to Eetimes a total of 177 million notebooks will be sold in 2009.[22] If it is assumed that all notebooks have a graphite heat spreader and total cost of installing graphite heat spreader is one dollar then a net reduction of 20% in cost of graphite spreader will correspond to a saving of 79.65 million - 63.72 million = 15.93 million dollars.

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