Ilker Tari and Fidan Seza Yalçin, "CFD Analyses of a Notebook Computer Thermal Management System and a Proposed Passive Cooling Alternative, IEEE Transactions on Components and Packaging Technologies, Vol. 33, No. 2, pp. 443-452 (2010).

CFD Analyses of a Notebook Computer Thermal Management System and a Proposed Passive Cooling Alternative

Ilker Tari, and Fidan Seza Yalcin

Abstract— **A notebook computer thermal management system is analyzed using a commercial CFD software package (ANSYS Fluent). The active and passive paths that are used for heat dissipation are examined for different steady state operating conditions. For each case, average and hot-spot temperatures of the components are compared with the maximum allowable operating temperatures. It is observed that when low heat dissipation components are put on the same passive path, the increased heat load of the path may cause unexpected hot spot temperatures. Especially, Hard Disk Drive (HDD) is susceptible to overheating and the keyboard surface may reach ergonomically undesirable temperatures. Based on the analysis results and observations, a new component arrangement considering passive paths and using the back side of the LCD screen is proposed and a simple correlation based thermal analysis of the proposed system is presented. It is demonstrated for the considered 16.1 inch notebook and for an ISO A4 paper sized notebook that placing the CPU, the motherboard, and the memory on the lid creates enough surface area for passive cooling.**

Index Terms— **Computational Fluid Dynamics, conjugate heat transfer, passive cooling, thermal management, system packaging, notebook computer.**

NOMENCLATURE

CFD	Computational Fluid Dynamics.
CPU	Computer Processing Unit.
HDD	Hard Disk Drive.
PCB	Printed Circuit Board / motherboard.
RHE	Remote Heat Exchanger.
TDP	Thermal Design Power.
A	Area, m^2.
$F_{hs\text{-}surr}$	View factor between heat sink and surroundings.
H	Fin height, mm.
L	Heat sink vertical length, mm.
Nu	Nusselt Number.
Pr	Prandtl Number.
Ra	Rayleigh Number.
Re	Reynolds Number.
T	Temperature, °C or K.
W	Heat sink width, mm.
g	Gravitational acceleration, m/s^2.
h	Convection heat transfer coefficient, $W/(m^2 \cdot K)$.
k	Thermal conductivity, $W/(m \cdot K)$.
q	Heat transfer rate, W.
s	Fin spacing, mm.

Greek Symbols

α	Thermal diffusivity, m^2/s.
β	Volumetric thermal expansion coefficient, K^{-1}.
ε	Surface radiative emissivity.
ν	Kinematic viscosity, m^2/s.
σ	Stefan-Boltzmann constant = 5.67×10^{-8} $W/(m^2.K^4)$.

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I. INTRODUCTION

THE increasing energy costs and consumer awareness on environmental issues together with the advances in related electronic components shifted the demand in the personal computer industry towards notebook computers which offer portability, low energy consumption and less noise compared to desktops. A typical notebook computer consumes 25-50W power while a desktop computer with comparable specifications consumes about 4-6 times as much (based on the observations of the authors that are also supported by the other references such as [1]). However, due to the compact chassis, thermal management of a notebook is more difficult than a desktop.

Heat dissipation to ambient air from a typical desktop computer can be easily achieved using forced convection due to available large air volume inside the chassis for circulation and large chassis surface area for placing the vents and fans. If the size of the desktop chassis is smaller, to overcome the reduced air circulation and the resulting reduced heat convection, a heat pipe system can be utilized. In extreme cases, water cooling or a refrigeration cycle can be used for dissipating higher heat fluxes.

For portability of a notebook computer, its size and weight should be as small as possible; therefore the chassis volume and surface area should be small. In a notebook computer, there is not much space left among the components that are placed very tightly. That reduces the available air inside the chassis to a level that convection can not be the main mode of heat transfer inside the chassis. As a result, conduction plates and heat pipes become the available options to transfer heat from sources to surfaces. Fans and remote heat exchangers (RHEs) that are used together with heat pipe systems constitute the active paths. Heat conduction plates that are used for heat transfer to the outer surfaces of the chassis are the passive paths for heat dissipation. Also, some components may be put in contact with the chassis surface for passive cooling.

In a typical notebook design, all of the components are packed inside the small chassis, except the LCD screen. Therefore, there is not much chassis surface area available for heat transfer to ambient air. When the LCD screen is upright, only very thin sides of the chassis and the chassis top surface where the keyboard is located are available for convective and radiative heat transfer. Heat dissipation through the bottom is usually with conduction to the thin air layer beneath the bottom surface and with radiation. In some recent designs, there are also some ventilation grills at the bottom to create convection paths.

In this study, the cooling system of a typical notebook computer that was manufactured in 2003 is numerically investigated in order to access the heat loads on the active and passive paths. After the analysis of the results, the objective of the study is to propose and thermally analyze an alternative notebook design using only passive cooling.

II. Background and Literature

The first part of this study involves a CFD analysis of a notebook computer. CFD has been used in thermal design of electronics very successfully for the last two decades. Electronic component boxes and computer systems of various sizes have been numerically modeled and CFD simulation results have shown very good agreement with experimental measurements. Among others, Argento et al. [2] studied system level electronic packaging; Yu and Webb [3] simulated a complete desktop computer; Ozturk and Tari [4] investigated heat sink designs for forced air cooling of a CPU by simulating a complete desktop computer. All of the previous studies showed that CFD can be very useful in design of thermal management systems. As a result, when the notebook computers first became popular and first difficulties with their cooling was observed, CFD found an immediate application. Hisano et al. [5], Xie et al. [6], Viswanath and Ali [7], Rujano et al. [8], Kobayashi et al. [9], Baek and Lee [10] and Dallago and Venchi [11] modeled notebook computers with various CPUs to find solutions to thermal management problems using CFD. In these earlier studies, the details of the models were limited with the available computers and software at the times they were performed. In the present study, we were able to use a very detailed model of a notebook computer and our computation times were reasonably short compared to those earlier works. There is also a significant difference in our analysis of the results: in the present study, we focused on determining heat loads on active and passive paths to observe whether it is possible to rely solely on passive cooling.

Designing and rating the thermal management system of a notebook computer requires detailed CFD simulations involving conjugate heat transfer modeling. CPU is the main heat source in a notebook computer. Thermal design power (TDP) and maximum allowable operating temperature (sometimes referred to as junction temperature) are the most important thermal design parameters for a CPU. TDP can be interpreted as the heat dissipation of a CPU. Other components in a notebook computer dissipate much smaller heat rates. Nevertheless, even the smallest heat dissipation should be considered, because the components are packed together inside the chassis very tightly and component temperatures depend on all heat sources. If a heat source is not cooled adequately, some of the components may exceed their allowable operating conditions.

Early notebook designs had CPUs with low TDP values, e.g. Mobile Pentium II CPUs using ball grid array had maximum TDP (TDP_{max}) values in the range of 7.9-13.1 W. With increasing computing power and clock speeds, TDP_{max} at one point reached up to 88 W in Mobile Pentium 4 HT CPUs. However, due to improvements in chip architectures and fabrication technologies, those numbers dropped to smaller values in recent years, e.g. TDP_{max} ranges for Intel Core Duo and Intel Core 2 Duo are 9-31 W and 10-35 W, respectively [12].

Newer designs use heat pipes to transfer larger heat loads from the CPU and remote heat exchangers (RHEs) to dissipate heat to ambient air. When conduction plates or heat pipes are used with heat sink fan assemblies or RHEs, they form an active path for heat dissipation. Heat dissipation from other components is usually done by using conduction plates. If a conduction plate is used for spreading heat to notebook surface, in which case heat dissipation occurs with conduction and natural convection, the path is a passive path. Small ventilation holes or grills without fans that are usually used at the bottom of the chassis in recent designs are also passive paths with natural convection being the heat transfer mode.

Dozolme et al.[13] used CFD modeling for optimizing the heat transfer paths and adjusting the placement of the heat sink on the side surface. Nguyen et al. [14] investigated heat pipe use with heat spreading plates together with a proposed hinged heat pipe configuration using the back side of the LCD for heat dissipation to ambient air. As an alternative to heat pipes, Guarino and Manno [15] investigated jet impingement, however their proposed system is an active cooling system.

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Active cooling consumes battery or AC power and generates noise. Yazawa et al. [16] suggested thermoelectric conversion to make the active cooling self sufficient in terms of power. That may solve the electricity consumption problem but the noise problem still remains. With the recent trend of reducing CPU heat dissipation, it may be possible to rely solely on passive cooling which solves both electricity consumption and noise problems; however, that may require a radical change in notebook computer designs.

In the current designs including the one investigated in this study, LCD surface is not used for heat dissipation. That limits the available surface area for heat transfer to ambient air. The bottom surface, the keyboard surface and the leftover surface from the connectors and components on the sides are the available heat transfer surfaces. Heat should be dispersed on the bottom and keyboard surfaces for passive cooling, and forced convection is the only option for heat transfer from the sides.

When passive cooling limits for notebook computers were investigated by Bar-Cohen and his coworkers [17][18], it was seen that LCD front and back surfaces play an important role. The hinged heat pipe designs in Nguyen et al. [14] and Varadarajan et al. [19] use the back surface of the LCD. These clever designs are steps forward in utilizing the back side surface of the LCD that is not used for anything; however there may be reliability issues related to the use of hinged heat pipes.

Instead of transferring heat to the back side of the LCD, we propose transferring the major heat dissipating components there. After investigating a typical notebook thermal management system with both active and passive cooling, we propose a passive cooling solution involving reorganization of the component placement and full use of the LCD screen back surface. The feasibility analysis of the proposed passive cooling system is done by using available correlations in the literature that were shown to be sufficient for such analysis in [16] and [17].

III. CFD Simulation Approach

A desktop replacement consumer notebook (Sony Vaio PCG-GRX316MP) is considered in this study on which a hybrid thermal system is used (Fig. 1 top). The whole notebook chassis is the computational domain, which is shown in Figure 1 (355 mm x 292 mm x 44.4. mm). In this chassis; CPU, CPU heat sink, heat pipes, heat exchanger, fans, aluminum heat dissipation plates, RAM, DVD, battery, PCMCIA card, hard disk drive (HDD), speakers, ventilation holes, PCB and miscellaneous cards attached to PCB are modeled according to measured dimensions and manufacturers' specifications. The components which have no or little effect on the fluid flow and heat transfer are not modeled.

There are two fans in the system; one of them (Fan 1) is used to provide airflow to the fin-tube type remote heat exchanger (RHE), and the other one (Fan 2) is attached to an aluminum heat dissipation plate on the graphics chip and south bridge. The RHE is attached to the condenser ends of two heat pipes which transfer heat from the heat sink attached to the CPU. The heat pipes are represented as solid rods having the same physical dimensions with the actual heat pipes and a high thermal conductivity in the axial direction that is taken as 40000 W/mK after an analysis similar to the one suggested in [14], the details of the analysis are given in the thesis by Yalcin [20]. The thermal conductivity of heat pipes in radial direction is taken as the conductivity of the pipe material which is aluminum.

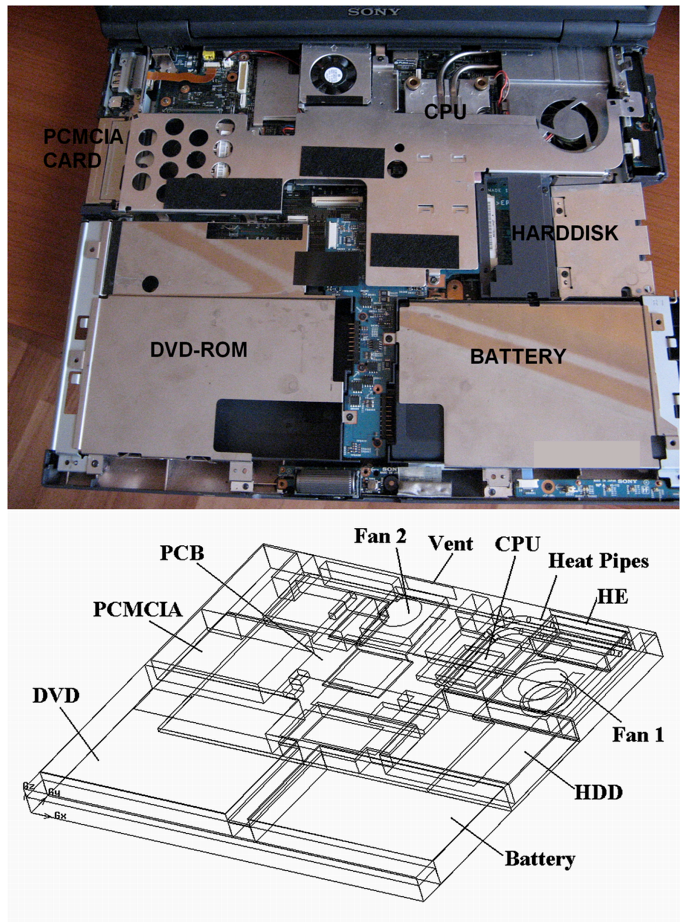

Fig. 1. Computational domain.

The CPU is modeled as three blocks which represent the encapsulant, polyamide tape and die components of the CPU as in [7]. In Figure 2, the model of the CPU is shown with its main cooling system. When CPU level packaging is important, there is a need for a CPU model with more detail and a realistic heat flux distribution. However, in the present study, the main interest is on the heat dissipation from the CPU and other components.

At the condenser ends of the heat pipes, there is a RHE with 0.5 mm thick aluminum plates that are attached with 1 mm spacing. There are 43 fins in the heat exchanger as shown in Figure 3.

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There is a temperature limit for each component inside the notebook. The main aim of a thermal management system is to assure that the components are working below their maximum operating temperatures (T_{max}). Maximum operating temperatures are defined by the manufacturers. The typical values for the maximum operating temperatures that are obtained from [21] and [22] are presented in Table I.

The ambient temperature is taken as 25 °C. Inside the chassis, radiative transfer and compressibility effects are neglected, after showing that they are negligible [20]. With a conservative approach, radiative transfer from outer surfaces of the chassis to the surroundings is also neglected.

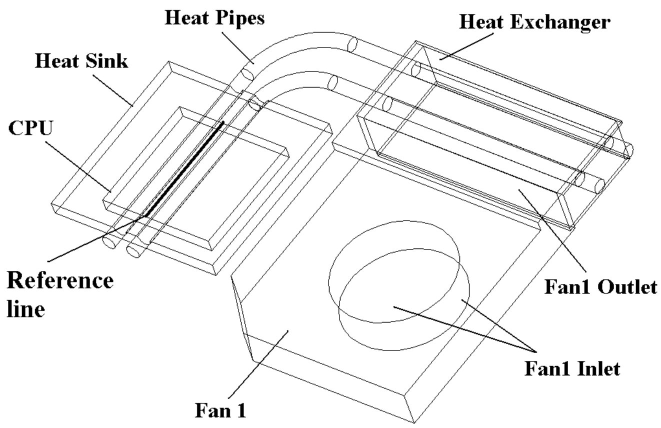

Fig. 2. CPU cooling system with the location of the reference line that is used in comparisons.

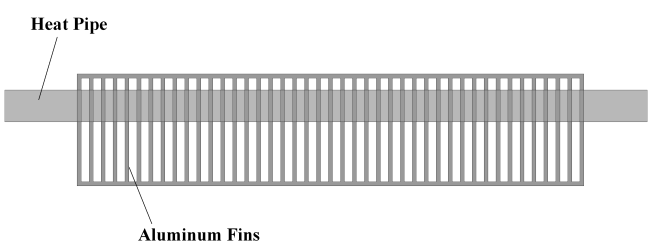

Fig. 3. Heat exchanger model.

The operating conditions of the components are not steady in a notebook computer; which change the heat dissipation rates of the components. However, in this study, considering the specifications of the manufacturers, an operating condition is chosen for each component in each analyzed case (Table I) and the calculations are performed according to the steady state assumption. Transient thermal management of a notebook is a different issue requiring dynamic control strategies.

No slip boundary condition is applied for the chassis and the component walls in the domain.

The heat transfer mechanism outside the notebook chassis is assumed to be natural convection. The convective effects of the flow coming through the fan exits and the ventilation holes are neglected. Average heat transfer coefficients are defined for the top and side surfaces of the chassis separately. An iterative CFD approach is used to obtain the heat transfer coefficients for each case using available correlations for natural convection [23] (for details refer to [20]).

The main heat transfer mechanism of the bottom wall of the chassis is conduction since Ra_L is calculated as 35 for the 3 mm air gap, which is less than critical Ra. At steady state, since the table surface on which the notebook is placed will be at a similar temperature to the bottom surface temperature, radiative transfer from the bottom is neglected. Therefore the thermal conductivity of air (0.026 W/mK) is used for the heat transfer from the bottom wall.

TABLE I HEAT DISSIPATION VALUES, AVERAGE AND HOT SPOT TEMPERATURES OF THE COMPONENTS

Component	CASE Heat Dissipation (W)					T_{max} (°C)	CASE CFD Avg. T (°C)					CASE CFD Hot spot T (°C)				
	I	II	III	IV	V		I	II	III	IV	V	I	II	III	IV	V
CPU	21	21	21	30	30	100	53.5	53.9	54.6	65.6	67.1	57.8	58.2	58.9	71.8	73.2
RAM	0.5	0.5	0.5	0.5	0.5	70	43.2	44.3	47.2	50.0	54.9	45.7	46.6	48.2	54.3	57.7
HDD	5	5	5	9	9	60	47.9	49.5	49.9	61.2	64.3	49.1	50.7	50.9	63.6	66.6
Graphics card	2	2	2	2	2	85	44.8	45.3	47.7	49.9	53.4	45.2	45.7	48.3	50.4	53.9
South bridge	0.5	0.5	0.5	0.5	0.5	85	43.8	44.5	46.9	49.9	53.6	44.2	44.9	47.2	50.8	54.5
PCMCIA	1	1	1	1	1	70	40.8	41.5	45.6	45.2	50.4	41.4	42.1	46.1	46.2	51.4
DVD	0	0	5	0	5	60	35.3	36.4	47.2	38.6	51.2	41.3	42.9	48.5	48.0	54.4
Battery	0	2	0	0	2	55	34.9	42.0	37.4	39.4	48.5	45.0	47.3	47.3	55.6	59.9
PCB	0	0	0	0	0	70	43.2	44.1	46.8	50.0	54.4	57.1	57.6	58.2	69.8	72.3
TOTAL	30	32	35	43	50											

*Compiled from Refs [21] and [22].

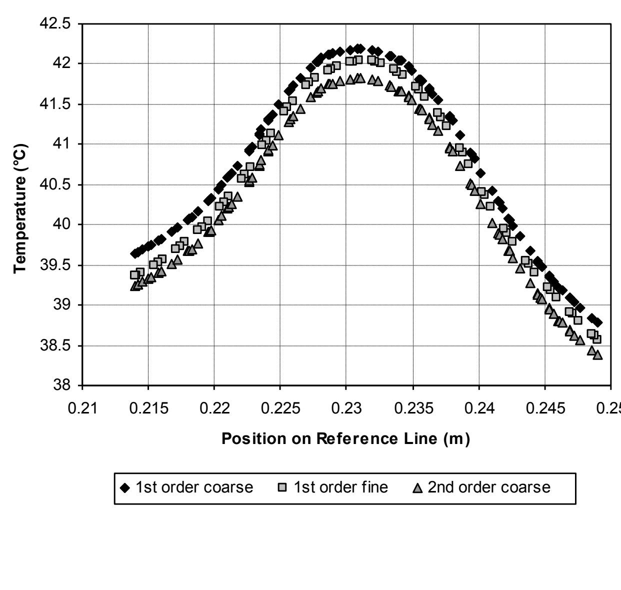

Fig. 4. Temperature plots on the reference line for the first order and the second order discretization schemes with the coarse mesh configuration, and the first order discretization scheme with the fine mesh configuration.

The governing equations are solved for the incompressible laminar flow model neglecting the radiation heat transfer effects. For Case I of Table I, a coarse mesh (with 1,883,191 elements) and a fine mesh (with 2,695,579 elements) are generated for mesh selection. First and second order discretizations are considered. For comparison of two mesh densities and discretization schemes, a reference line is defined in the center of the CPU heat sink (Figure 2). When the results in Figure 4 are compared, it is seen that there is not much difference between two mesh densities but the second order discretization may offer higher accuracy than the first order discretization. Thus, the second order discretization with the coarse mesh is selected and used throughout this study.

IV. Results and Discussions

A. Simulation Results

The simulations using the model of the notebook are performed for five different cases that are given in Table I. Case I corresponds to the standard use of the notebook. Case II is for the standard use while charging the battery. Case III corresponds to the optical drive use. Case IV is for 100% CPU load. Case V is the extreme case that stresses the thermal management system of the notebook. Here, only Case I and Case V are analyzed in detail, but the analysis results of all five cases can be found in [20]. For each case, a separate simulation run is performed using the aforementioned modeling details together with the given heat dissipation values in Table I.

The simplified thermal path diagram for Case V is presented in Figure 5. In this diagram, there are two types of heat dissipation paths given. One of them is the active heat transfer path, presented with dashed lines, in which heat is dissipated by active cooling. In this study, the active cooling methods are the two fans which are transferring heat from the CPU, the graphics card and the south bridge chip. The other type of path shown in the figure is the passive heat transfer path, presented with dot-dashed lines. The main heat transfer mechanism for this path is conduction and natural convection. In the figure, some heat transfer paths are left as solid lines, because both active and passive methods are effective in these paths. The main heat sources which are taken into account in this analysis are presented with circled arrows. In Figure 6, at two cut planes of the chassis, velocity contours are given from which, it is observed that the velocities of air inside the chassis are very low. High velocities occur inside the fan boxes and in the RHE. It is observed that the contribution of convection inside the chassis is negligible. The CFD data for heat transfer rates from the components are also examined as convection and non-convection paths. Only the convection paths to air inside the chassis are considered. Hence, the heat pipes ending in the RHE are considered as non-convection paths. The results of this analysis for Case V are presented in Table II. The table data also confirms that the contribution of convection in cooling of the major heat sources is negligible. It only contributes to cooling of HDD and PCMCIA card due to the proximity of these components to the system fans.

The average and hot spot temperatures of the components are given for each case in Table I. The temperatures exceeding the $T_{\max}$ values are marked in gray. All of the component average temperatures are below the maximum allowable operating temperature limits, except the HDD average temperature in Case IV and V. There is a considerable variation in the average temperatures of the components which dissipate different rates of heat in different cases. The average temperatures of the components either in their close vicinity, or on the same heat dissipation path are also affected. When hot spot temperatures are considered, besides the HDD, the battery and the PCB also reach to temperatures above their T_{max} values, locally. Since both the HDD and the battery are defined as solid boxes with uniform heat generations, these hot spot temperatures may not be realistic. In a component level CFD study, these components should be defined in detail.

The temperature distributions of the top surface of the PCB for Case I and Case V are compared in Figure 7. In both sub-figures, the effect of the CPU which is on the upper right of the PCB, the graphics card which is on upper left of the PCB, and the HDD which is on the lower right of the PCB can be clearly seen. There is a noticeable temperature difference between the position on which the CPU is attached and its vicinity. This is mainly caused by the difference between the in plane thermal conductivity of the PCB and the thermal conductivity of the thermal contact grease used under the CPU. The former one has a higher value.

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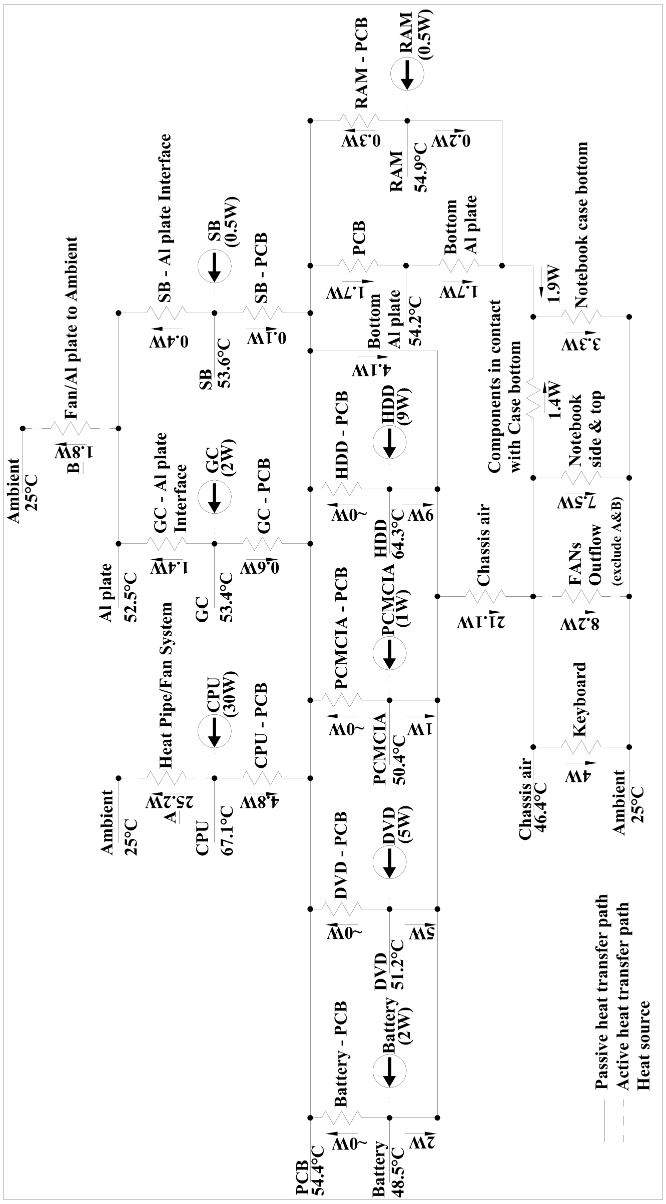
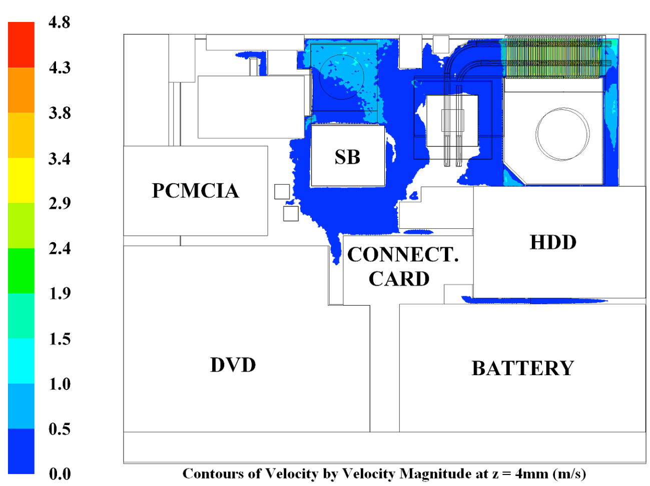


Fig. 5. Thermal path diagram for Case V.



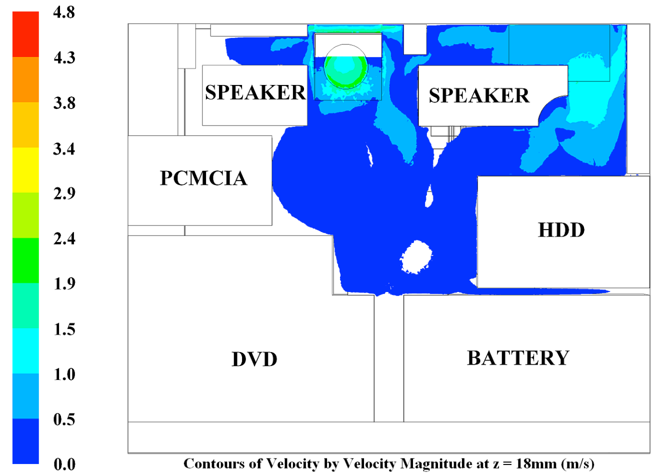


Fig. 6. Contours of velocity on different planes in z axis for Case I.

TABLE II CONVECTION-TO-CHASSIS AND NON-CONVECTIVE HEAT DISSIPATION RATES FOR INDIVIDUAL COMPONENTS AND THE CORRESPONDING PERCENTAGES FOR CASE V

Component	Heat Dissipation (W)	Non-Convection		Convection	
		W	%	W	%
CPU	30	30	100	0	0
RAM	0.5	0.5	100	0	0
HDD	9	2	22.2	7	77.8
Graphics card	2	2	100	0	0
South bridge	0.5	0.5	100	0	0
PCMCIA	1	0.2	20	0.8	80
DVD	5	4.8	96	0.2	4
Battery	2	1.8	90	0.2	10
TOTAL	**50**	**41.8**	**83.6**	**8.2**	**16.4**

The user of the notebook will feel the heat on the parts of the top surface where the temperature exceeds 40 °C [24]. These parts are shown in Figure 8 for Case I and Case V. The rectangle shown in the figure represents the keyboard. The temperature contours that appear above the keyboard, at the right and left sides of the keyboard do not affect the user since these regions are not used actively. However the high temperatures on the keyboard and below the keyboard where the touchpad is located may disturb the user. In Case V, especially on the right where the HDD is located, the temperatures are well above the comfort limit (40 °C). These extreme temperatures, besides shortening the life of the HDD, cause discomfort to the user [24]. But it should be noted that Case V is an extreme case that only happens for a short period of time. Considering that the fingers of the user are not in contact with the keyboard at all times, the temperatures in Case I are ergonomically acceptable.

The discussions in the following section are selected to be qualitative, due to the lack of experimental verification data.

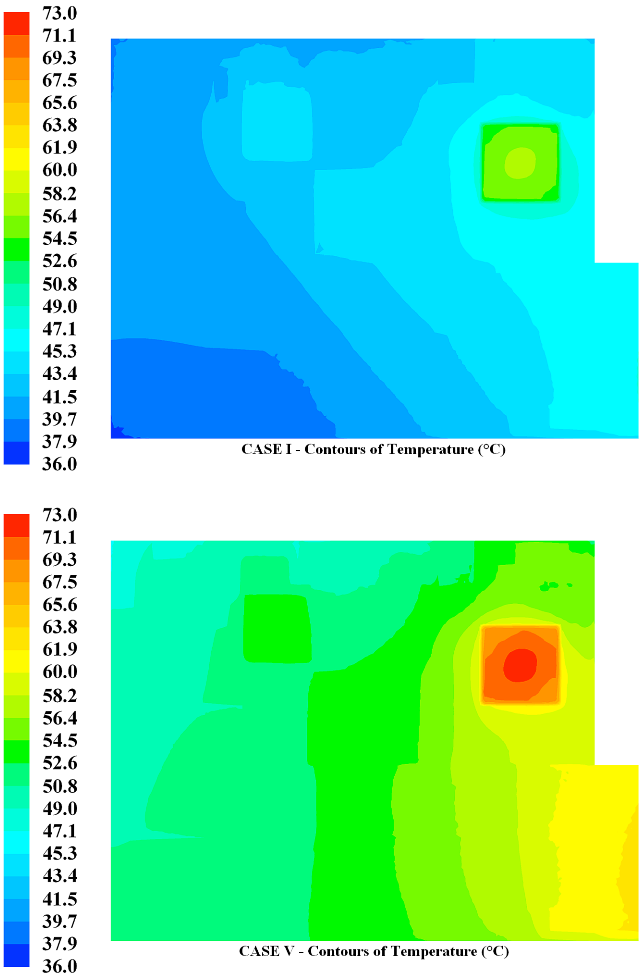


Fig. 7. Temperature distributions of the PCB top surface for Case I (top) versus Case V (bottom).

B. Discussions and Proposed Modifications

By analyzing the thermal management of the considered notebook computer that has a typical layout in terms of the locations of the components a few observations can be made and based on them, one may modify the design.

When the thermal management system of the notebook computer is analyzed, it is observed that the active cooling paths are mainly used for cooling the CPU. Cooling of the other heat dissipating components is achieved through the passive paths that carry the heat from the source to the surfaces using high conductivity aluminum plates.

The air circulation inside the chassis is observed to be very weak; therefore convection is not a major heat transfer mode for cooling the components. The fans are mainly used for forced convection heat transfer from RHE and conduction plates. In this specific notebook design, there is no ventilation grill at the bottom that is common in newer designs to improve air circulation.

There are more than one heat sources attached to the same heat dissipation plate. When all of the components are running at the same time such as the considered case V, the surface temperatures above and at the end of the dissipation plate reach to very high values. Even worse, due to inadequate cooling, some of the component temperatures, such as that for HDD, reach above the maximum operating limits. That result should direct the thermal designer to separate the components on the same path from each other.

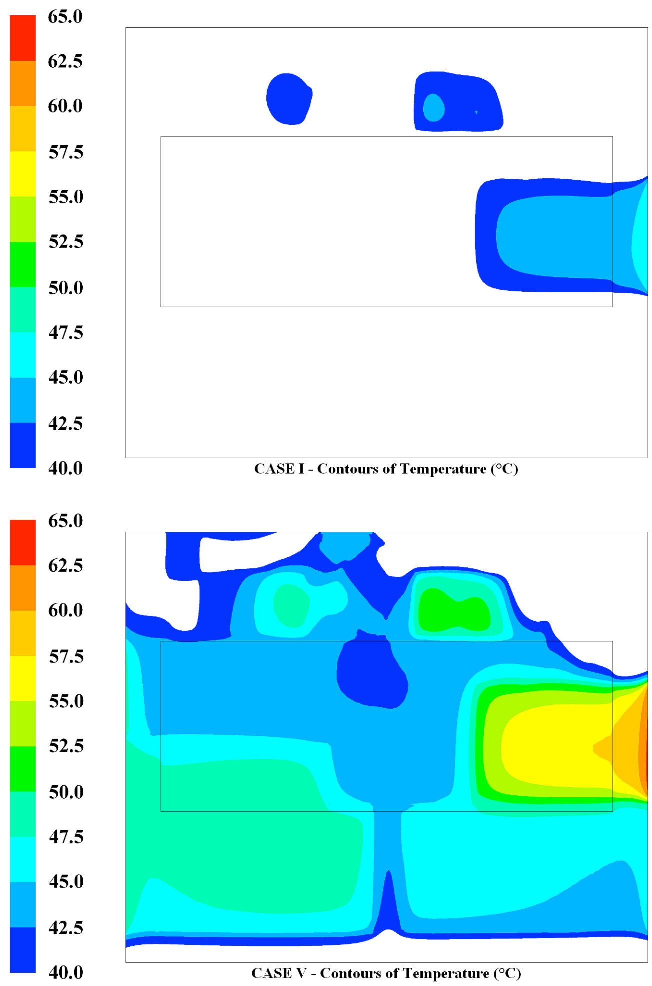


Fig. 8. Temperature distributions that are above comfort level (> 40 ºC) on the top surface of the chassis for Case I versus Case V.

Based on these observations, a better thermal management solution can be offered. Such a solution is given in Figure 9. In this suggested design, we propose to put the CPU, the motherboard and the RAM behind the LCD screen. Usually notebook computers are used when the LCD screen is upright. If a CPU with a low TDP is on a vertical surface, it can be cooled by natural convection with the help of rectangular cross section fins on the backside of the cover. If the TDP is low enough, it may even be possible to use a flat bare plate instead of a heat sink with fins. The thicker and low heat dissipation components (HDD, DVD and battery) are left at the base. These are the components that can be connected to the motherboard (which is inside the lid) with ribbons passing through the hinges without causing any signaling problems. Their power budget is small enough so that they can be cooled passively by putting them in contact with the chassis surface. This component rearrangement is much easier to implement than the hinged heat pipe idea that was suggested in [14] and [19]. In the present proposal, a heat pipe spreader (a combination of heat pipes and heat spreader plates or a flat heat pipe) is suggested to spread heat from lid components to the base of the lid heat sink. The details of such a system should be worked out together with the motherboard design, thus, we assumed a uniform heat sink base temperature that is conservatively below the assumed surface temperature of the lid components.

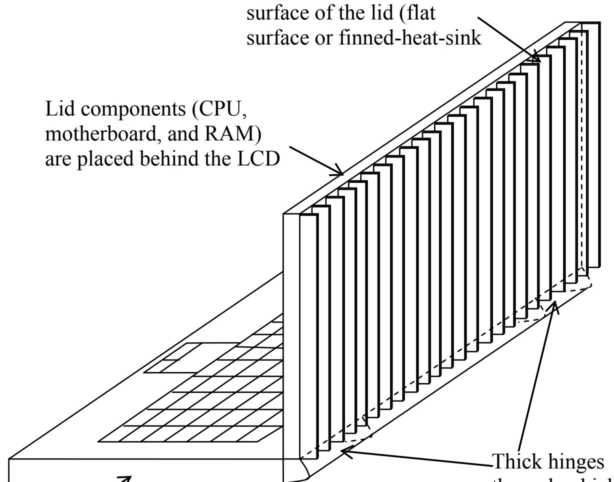


Fig. 9. The proposed re-arrangement of components by placing the CPU, the motherboard and the RAM on the back side of the lid.

The thermal analysis of this proposed design is done by using available correlations. CFD analysis is not preferred due to the fact that the geometric details together with many other design parameters are not certain at this stage. The analysis that is presented below can be considered as a thermal feasibility assessment of a design idea.

C. Thermal Feasibility Analysis of the Proposed Design Idea

The surface temperature of the components and the uniform base temperature of the heat sink are assumed as 60 and 50 °C, respectively. This assumption corresponds to a 10 °C temperature jump due to thermal contact resistances and the thermal resistance of the heat pipe and heat spreader system that are between the lid components and the lid heat sink. This assumed value is rougly based on the experimental study using a similar integrated heat pipe with heat spreader arrangement by Take and Webb [25] in which they report 60.0-49.2 °C and 59.9-56.1 °C as hot-cold side temperatures for two different heat spreaders. The temperature difference may even be lower mainly depending on, among other parameters, the design of the heat spreader system and the motherboard design. Regardless of how good the heat spreader might be, there will be a non-uniform temperature distribution at the base of the heat sink. However, for an initial thermal feasibility analysis assuming a uniform temperature is acceptable.

The analyses are done for two different lid sizes: the first one is the size of the 16.1 inch notebook in the first part of the study (292 x 355 mm) and the second one is ISO A-4 paper size (210 x 297 mm) corresponding to a 12.1 inch notebook. For both of these sizes, a bare flat plate and plate finned heat sinks with 1 mm thickness and with fin heights in the range of 1-10 mm are considered. Available heat transfer areas of these heat sinks are calculated and after determining average heat transfer coefficients, convective heat transfer rates are calculated for the base-to-ambient temperature difference of 50-25 = 25 °C. Radiative heat transfer rates are also calculated after calculating the view factors between the heat sinks and the surroundings at 25 °C. The heat sink is assumed to be made of aluminum and covered with a thin layer of anodized aluminum with surface emissivity of 0.8. Here, the anodized layer also works as an electrical insulator.

The first option as a heat sink is a bare flat plate made of aluminum covering entire back side surface area of the lid. For this case, we used Churchill and Chu correlation as presented in [23] for average Nu over the vertical length L of the vertical flat plate:

$$\mathrm{Nu}_L = \frac{\bar{h}L}{k} = 0.68 + \frac{0.670\mathrm{Ra}_L^{1/4}}{[1+(0.492/\mathrm{Pr})^{9/16}]^{4/9}}, \quad \mathrm{Ra}_L \le 10^9 \tag{1}$$

where

$$\mathrm{Ra}_L = \frac{g\beta(T_s - T_\infty)L^3}{\nu\alpha} \tag{2}$$

Using Eq. (1), the possible heat transfer rate that can be dissipated from a vertical plate can be calculated with:

$$q_{conv,flat} = \frac{\mathrm{Nu}_L k}{L} A(T_s - T_\infty) \tag{3}$$

The second option is a plate finned aluminum heat sink that is configured as shown in Fig. 9. There is an experimental study that is performed with similar plate fin heat sinks by Yazicioğlu and Yüncü [26] where they obtained a correlation for optimum separation between the plates that is taken as the separation distance in the present study:

$$s = s_{opt,[25]} = 3.53\, L\, \mathrm{Ra}_L^{-1/4} \tag{4}$$

They also presented a correlation for the heat transfer rate for a heat sink with optimum plate separation distance by considering the enhancement over $q_{conv,flat}$:

$$q_{conv,[25]} = q_{conv,flat} + 0.125\, \mathrm{Ra}_L^{1/2} kH\Delta T \frac{W}{L} \tag{5}$$

However, the convection heat transfer rates obtained from Eq. (5) are conservative and can be considered as minimum

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limits. The maximum limits that are not practically achievable can be obtained by taking the entire finned heat sink area as if it is a flat surface and the overall surface efficiency as 1. The actual heat transfer rates should be between these two limits.

After calculating the view factor between the heat sink and the surroundings, $F_{hs-surr}$ using view factor catalogue as explained in [27], radiative heat transfer rates from the finned heat sink can be obtained from:

$$q_{rad,finned} = (N_f - 1)(2A_{side} + A_{base} + A_{tip})\sigma\varepsilon F_{hs-surr}(T_b^4 - T_\infty^4) + \sigma\varepsilon(2A_{side} + A_{tip})(T_b^4 - T_\infty^4) \quad (6)$$

The details of the correlation based approach and the results for a wide range of LCD sizes are given in Ref. [27] and in Ref. [28] (for larger display panel sizes).

When only the bare flat plate heat sink geometry is considered, the convection only and the combined convection and radiation heat transfer rates are for the 16.1 inch notebook: 11.25 and 25.35 W, and for the A4 sized notebook: 7.38 and 15.86, respectively. The heat transfer rate results of fin heights in 1-10 mm range for the 16.1 inch notebook and for the A4 sized notebook are given in Figures 10 and 11, respectively. In these figures, the flat limit values are the maxima and Ref. [26] values are the minima. Due to the high emissivity of anodized Aluminum, there are big differences between convection only and radiation included results. As a conservative approach by considering the minima, one can observe from Fig. 10 that it is possible to remove 19.56 W from the 16.1 inch lid by convection only with 10 mm fin height. When radiative transfer is included, that value can reach up to 44 W for the 1 mm fin height. Since the view factor gets smaller with increasing fin height, for larger fin heights, the contribution from radiative transfer is less. The 44 W value is more than enough for most of the current notebooks with high TDP mobile CPUs. Considering that the emissivity value of 0.8 may not be achieved, or due to surface conditions, emissivity may degrade over time, the actual heat transfer rate will be in 20-44 W. If a CPU with 25 W TDP is used, with the addition of 5 W for the rest of the lid components (the motherboard and the RAM), 30 W of heat dissipation may be required and this value can be achieved with the proposed finned heat sink. If the CPU has a low TDP such as Intel Atom N270 CPU [29] which has TDP of 2.5 W, bare flat plate heat sink is sufficient.

Following the same approach the conservative heat transfer rates for A4 sized notebook with and without radiative transfer are 27.79 and 13.27 W, respectively. In this case, it may not be possible to use a high-end CPU. However, considering the trend of increase in CPU power to TDP ratio, it can be said that a reasonably powerful CPU can be cooled with the proposed approach in an A4 sized lid. The conservative convection only heat transfer rate of 7.38 W for bare flat plate heat sink shows that this heat sink in A4 size can only be used for the computers with netbook CPUs.

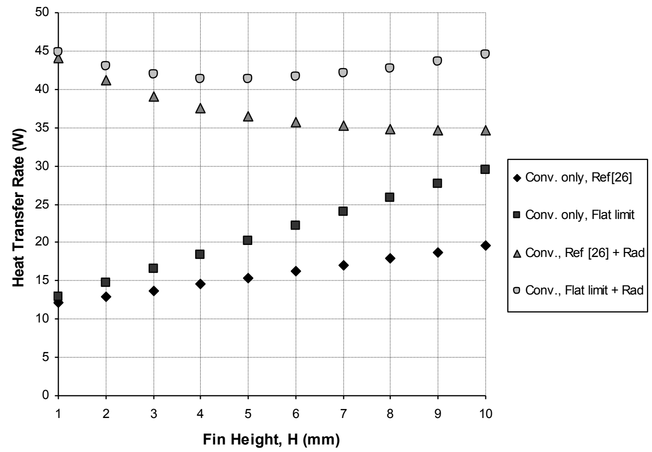

Fig. 10. Heat transfer rate limits for different heat sink heights for the 16.1 inch notebook.

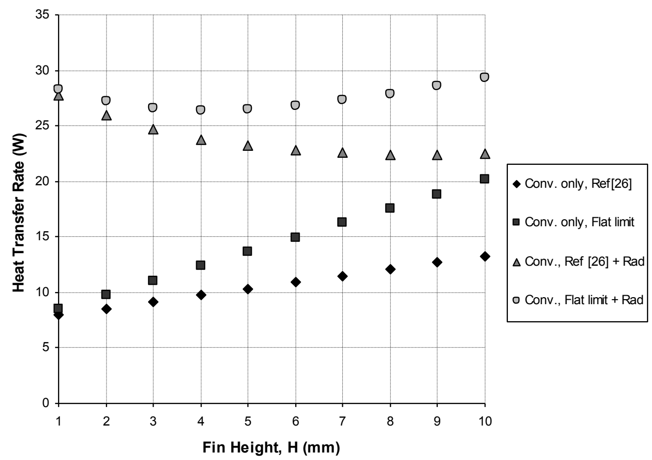

Fig. 11. Heat transfer rate limits for different heat sink heights for the A4 paper sized notebook.

Overall, it can be said that the proposed design is a feasible passive thermal management solution, provided that a heat spreader heat pipe solution can be designed to connect the lid components to the lid heat sink. The heat pipe technology has been improving very rapidly in the last few years, especially, there are improvements in flat heat pipes. By considering the motherboard design together with the heat pipe design, a heat spreader can be designed for the proposed lid cooling arrangement.

V. CONCLUSION

In the first part of this study, the thermal management of a typical notebook computer with both active and passive heat dissipation paths is investigated with the help of a commercial CFD software package, ANSYS Fluent. The CFD results of the study are not experimentally verified, therefore they are only used qualitatively and only to make general observations. It is observed that due to the compactness of the notebook, there is not much air circulation in the chassis and heat is transferred to small side areas of the chassis and the bottom and keyboard surfaces with the help of thermal dissipation plates and heat pipes. Below the bottom surface heat is only dissipated by conduction through the thin air gap which acts more like an insulating layer, due to lack of any ventilation grills in the considered notebook design. The keyboard surface is observed to be very useful for heat dissipation, however that path should be used by limiting the heat transfer to prevent ergonomically undesirable keyboard or touchpad surface temperatures. Heat can only be removed actively from the small side areas with the help of heatsink-fan assemblies or RHEs which consume power and generate noise. It is observed that passive cooling of the considered notebook is not possible with the existing component arrangement.

After observing that there is not enough chassis surface for purely passive cooling, the unused back surface of the LCD screen is suggested as an additional surface. Contrary to the previously proposed designs that transfer heat to the lid with the help of hinged heat sinks and use the lid area only for heat transfer, we suggest placement of the CPU, the motherboard and the RAM on the back side of the LCD. The rest of the components (HDD, DVD, battery etc.) are left in the horizontal chassis and due to their low power budget, they can easily be cooled by passive means. The lid and chassis components are connected with ribbons that run through thick hinges between the lid and the chassis. Thus, neither signaling nor power delivery problems are expected in the proposed arrangement. Inside the lid, the CPU is the major heat source and cooling it passively and allowing a small margin for the other lid components is enough to make the notebook passively cooled. Considering that the current mobile CPU TDP values are in the range of 2.5-25 W, a thermal analysis with the help of available empirical correlations is performed. The analyses are done only for the 16.1 inch computer in the CFD part and for a 12.1 inch A4 paper sized notebook. It is observed that, for both cases, the proposed heat sink with plate fins provide sufficient surface area to cool the lid components. For lower TDP values such as the ones used in netbooks, even the bare flat plate (the back surface of the LCD) is enough as a heat sink. There are recently announced system-on-chip designs that can easily be used with the proposed thermal management solution. The only foreseeable disadvantage of the proposed solution is the increase in the lid thickness that is against the trend of reducing the lid thickness in the industry. However, the proposed passive cooling solution has the advantages of fan-less operation compared to the existing active cooling solutions such as the noise-free operation, lower energy consumption and higher reliability. A further study of the proposed component re-arrangement by the electrical system designers may be required to address the possible issues with interconnect delays due to longer connection lengths between the components.

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