RESEARCH PAPER

Power and Thermal Management Issues for Portable Processors

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A B S T R A C T:

The advancement of modern CMOS technology scaling causes an exponential rise of system's power dissipation and temperatures in submicron technology node, which growth production and operating costs. Thermal energy and generated heat are becoming a prominent major issue in the context of portable applications (telephony, PDAs, digital cameras ...) and must be considered at each design level. The performance of portable processors is critically affected by dissipated power and operational temperature. The designers are forced to design a proper cooling system, especially heatsinks which consistently allows a low power and low temperature regulation of high-speed processors .

In this article, several different heatsinks are modeled, tested, and designed to optimize the microprocessor's cooling system while ensuring proper thermal operation and lowest power dissipation. The proposed adopted heatsink and their selected design configurable parameters are analyzed theoretically for different validations conditions and operation modes in various real-time thermal conditions. Thermal Analysis Package is used for simulation the proposed heatsinks model. Results shows the specification improvements of the design model for ensuring power required to cool in time of 0.851 W, time to cool by 15s, and heat to remove is 12.77J which confirms theoretical fundamentals and sufficient improvement of temperature minimization and better performance of the cooling system was achieved.

1. INTRODUCTION

Current trends of portable processors have experienced a massive sustained growth in performance, platform's features, functionality, and complexity. This advanced technology translates into higher power dissipation and bringing forth-extra high temperatures, creates a massive demand for a novel cooling system design. The overall objective of thermal minimization in portable processors is to weaken the system operating cost while providing long-term device reliability.

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The evolution of power density in Intel processors is shown in Figure 1, and 40 years of microprocessors trend data is shown in Figure 2 (Smelt, 2018, Rupp, 2018, SULAIMAN et al., 2019).
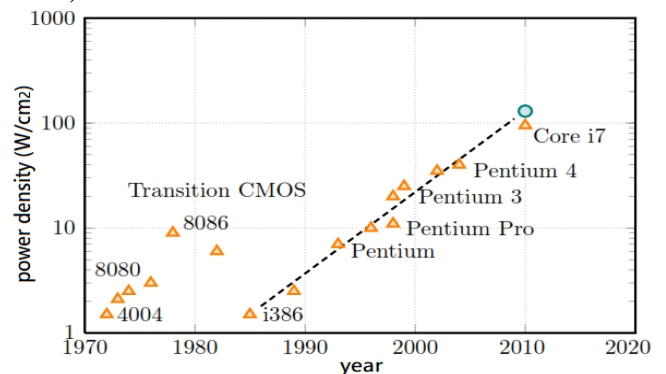

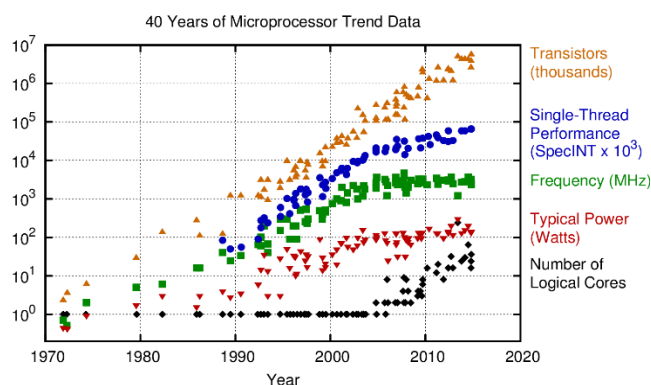**Figure 1:** Evolution of power density in Intel processors

Figure 2: 40 years of microprocessors trend data

There are several techniques for power and thermal challenges in microprocessors for portable systems; a proper design of the chip heatsink has a vital role in the system. The heatsink design methodology generally takes design margins to prevent the uncertainty of the processors and guarantee operational functions and performance to ensure correct operation at the lowest cost (R. Sulaiman et al., 2017). The general structure of a heatsink and heat flow is shown in Figure 3. For advanced technological nodes, performance no longer means high frequency only, but also a lower power and temperature. Thus, to estimate the overall power and thermal energy efficiency, it is necessary to guarantee that for a certain frequency, the dissipated power and temperature consumed will be minimum. Nano technologies introducing the gains in speed and higher power consumption of microprocessors and digital circuits, hence, the design of heatsinks is no longer been negligible that affecting performance as well as robustness of the cooling system (HamaAli et al., 2019).
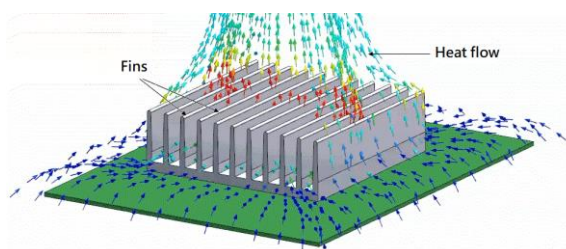

Figure 3: Heatsink general structure and heat flow

From microprocessors rigorous survey of power and thermal reduction in portable systems, it is observed that, there have been numerous articles, and published studies on the heatsink design and processor's power and thermal minimization techniques. To this end, number of

new works published recently has been pointed out.

(Hanafi et al., 2015) proposed radial plate fin heatsink with a new dimension for optimal design that maximizes heat dissipation and reduce the size of heatsink on CPU chip. The multi objective particle swarm optimization are investigated for finding optimal dimensions of heatsink radial plate fin design. The comparison of the model and fitness optimal value of fitness functions for radial heatsink are explained that confirms an increment of heat dissipation and area reduction. (Gierczak et al., 2016) presented analysis, modeling, and simulation of distributing temperatures in a heat-sink. The realization was carried out in the laboratory model of processor and source of heat was designed. Four different heaters were fabricated as thick-film resistors screen-printed on alumina substrate, and useful information in optimization heatsink process was collected. (Todmal and Mukherjee, 2017) Are comparing various design of heatsinks for different fin numbers, fin thickness, copper core height and rotation speed of the fan for CPU cooling which dissipating 130W heat, furthermore an optimized heatsink design is presented to dissipate a lower heat level. (Ahmed et al., 2018) performs a comprehensive survey on the optimization methods for hydrothermal design of heatsinks, and investigations were carried out for active and passive methods for improving heat removing in heatsinks by modifying fluid and solid domain. (Fornaciari and Soudris, 2019) presented the digital controller for microprocessors thermal management and designed as part of a project (HARPA) the goal of this proposal was the inclusion into a unified design of controlling temperature, performance /power trade-off, and stability analysis, was carried out. They were assessed and verified that using as a solid benchmark, and free to multi-physics configurations. The experimental results were carried out on a modern processor architecture and compared to previous studies which shows improvements that is easy to set up, calibrate and maintain. (Dede et al., 2019) presented design and optimization of a 3D heat flow scheme applicable for power electronics thermal management. This optimization method focused on temperature minimization simultaneously of multiple gate drive IC devices. The design, fabrication prototype, and

development of an experimental test bench were applied for thermal performance characterization, experimental results show highest temperature reduction for the gate drive IC devices in a laboratory environment. (Singh et al., 2020) proposed three individual mini-channels with differently configured interconnecting secondary channels heatsink geometry, based on finite volume method, they solved mathematical model in ANSYS to study the issue numerically. The results findings proved that, lowest base plate temperature of mini-channel heatsink is noticed at 10° secondary channel angle, and performance of electronic device will be analyzed at 10° secondary channel angle.

This article presented many different heatsinks, study, model, and the design were explored in order to optimize the microprocessor's cooling system while ensuring proper thermal operation. The proposed adopted heatsink design model was analyzed theoretically for different validations conditions and operation modes in various real-time temperatures and environmental conditions. The simulation and results are confirmed through Thermal Analysis Package which shows sufficient improvements of the design model for ensuring power required to cool in time of 0.851W, time to cool by 15s, and heat to remove is 12.77J which confirms theoretical fundamentals and sufficient improvement of temperature minimization and ensures better performance of the cooling system.

2 HEATSINK DESIGN PARAMETERS AND CONSTRAINTS

A heatsink is a heat exchanger which transfers thermal energy/heat generated from a higher temperature microprocessor chip to a lower temperature environment. It reduces the chip temperature or hotspot by air convection and improves efficient energy consumption. Therefore, design a specific heatsink need to consider number of constraints and parameters. The constraints are primarily out of designer's control (Neyestani et al., 2019). The most significant constraint is the rate of removed heat, and is mainly has a fixed value that need to be adequate for processor's heat dissipation rate. highest operating temperature is another

constraint, and is defined by properties of the used material, it has to be higher than maximum operating temperature of the chip, and ambient average temperature must be taken into consideration for thermal resistance calculations (Markowski et al., 2019).

The heatsink design parameters contain the heatsink material, number and dimension of fins, fin alignments, and the base plate thickness as shown in Figure 4.
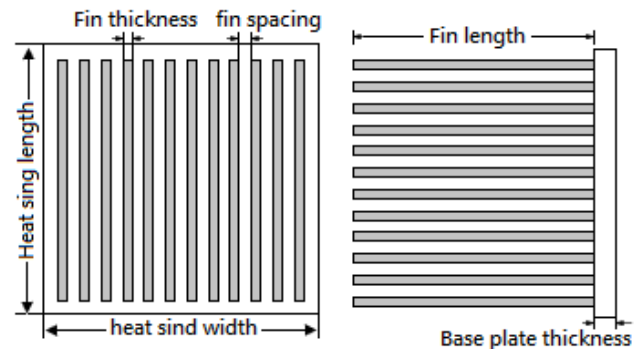

Figure 4: The design parameters of a heatsink

High thermal conductivity metal and relatively low cost are preferred, like Aluminum and Copper. More specifically, Copper is the most used effective material, because it has many desirable thermally efficient properties, durable heat exchangers, and thermal conductivity. However, in portable systems weight is a big concern, this is motivated designers to use Aluminum instead, and especially for microprocessor's heatsinks. It has also a good thermal conductivity, less expensive, lighter weight, and easier to work, making it a better choice for portable processors (Ilsche et al., 2019).

Shape and number of the fins are additional most important factors for heatsink performance, the heat spread area is enhanced by number and shape of fins. Alignment of fins on the base plate acts a vital role particularly for heatsinks which are cooled by. The thickness of base plate provides uniform distribution of heat through the base of heatsink, since the processor chip is mainly smaller than the heatsinks. The heat flow between the semiconductor chip and ambient air is modeled as a series of resistances to the heat flow, the sum of these resistances is the total thermal

resistance of the chip die to ambient air (Mjallal et al., 2018). In order to obtain maximum heat distribution and minimum thermal resistance, each of these parameters and constraints must be considered well as explained in the design procedure.

To ensure that the microprocessor does not overheat, finding an efficient heat transfer path from the chip to the environment is crucial. The heat transfer path can be from the chip /printed circuit board, to a heatsink, to the air flow supplied by a fan. Microprocessors are essentially having a maximum operating temperature which is called maximum junction temperature. The designer is necessarily having to prevent exceeding this temperature to prevent the chip damage. The component will produce heat during normal operation when operating in an environmental condition for a specified ambient temperature. The maximum power dissipation reduction amount is given by (SULAIMAN, 2016),

$$P_{D-\max} = \frac{T_j - T_A}{R_{total}} \qquad (1)$$

$$R_{total} = \theta_{sc} + \theta_{cs} + \theta_{jc} \qquad (2)$$

Where, PD_{-max} is maximum power dissipation, T_j is the maximum operating or junction temperature, T_A is ambient temperature, R_{total} is total thermal resistance to surroundings, θ_{sc} is the heatsink thermal resistance, θ_{cs} is the case thermal resistance, and θ_{jc} is the junction thermal resistance, this is explained in Figure 5.
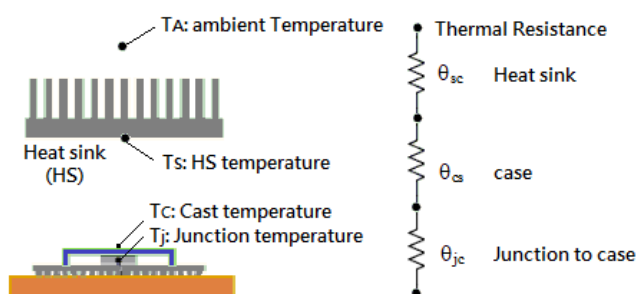

Figure 5: The heatsink thermal resistance

The heatsink thermal resistance (θ_{sc}) consists of two resistors, the resistance of base (R_b), and the resistance of fins (R_f), it can be given by,

$$\theta_{cs} = \frac{t_b}{k A_b} \qquad (3)$$

Where t_b is the thickness of the heatsink base, k is the thermal conductivity of the heatsink material, and A_b is the area of the of the heatsink base.

Thermal resistance is used to describe the relative resistance of heat transfer that is present in a chip and is varied that could be found in data sheets (Rotem et al., 2013). And principally, the average ambient temperature will be minimized with time as illustrated in the following equation,

$$T_{A-av} = \frac{T_{air-in} + T_{air-out}}{2} \qquad (4)$$

Where, T_{A-av} is average ambient heat temperature, T_{air-in} is temperature of input air to the heatsink, and $T_{air-out}$ is temperature of output air from the heatsink.

The heatsink size calculation is basically depending on an established equation for estimating heatsink volume during the early stages of heatsink design, it generally estimates the overall heatsink volume within +/- 15% of the final design.

$$V = \frac{Q R_v}{\Delta T} \qquad (5)$$

Where, V is the estimated heatsink volume, Q is the heat source power, ΔT is the thermal budget, and R_v is the volume thermal resistance.

The required heatsink surface area for U shaped aluminum fins that are generally preferred because of its high-performance characteristics. The design contribution principles are to increase the heatsink surface area, and to reduce its weight and the mean distance of heatsink from the processor in to be cooled.

3 THE DESIGN PROCEDURE

The design of high-performance thermal suppression heatsinks of portable microprocessors is the core of this article goal. In order to achieve this goal, and better heatsink design to suit most current high-speed processors, the constraint and design factors of a specific heatsink were chosen as shown in Table 1. The designs of heatsinks with rectangular fins, the fin height, space, and thickness are varied to obtain the specification of; Power required to cool in time: 0.851 W, Time to cool:15s, and heat to remove;12.77 J. Table 2

shows the heatsink under test for the purpose of finding an appropriate heatsink that has the required specifications that are listed.

Table (1) The heatsink design parameters

Dimensions: Width, Height, Thickness (mm)	50,35,1
Material type	Aluminum Ex alloy, 6063 TS
Fin shape	Rectangular
Temperature range (^{o}C)	35-75
T_A: Ambient Temperature ((^{o}C)	35
Ts: Surface Temperature ((^{o}C)	75
T_{A-avr}: Ambient Temperature (^{o}C)	55
Heat to remove (J)	12.77
Total surface area (Cm^2)	38.40
Surface temperature constraint	<85°C
Total Volume (mm3)	341.0
Passive cooling load (W)	0.731
Active cooling load (W)	50.00
Total cooling load (W)	50.731
Time to cool (s)	15
Power required to cool in Time (W)	0.851
Fin Thickness (mm)	1
Heat transfer coefficient W/m^2 K	4
Dry air Density (ρ) at 35 ^{o}C (kg/m^3)	1.0755
Dry air Thermal conductivity (k) at 35 ^{o}C W/mK	0.28625
Dry air Prandtl number (P_r) at 35 ^{o}C	0.7215
Dry air (β) at 35 ^{o}C	0.0030
Material type	Aluminum Ex alloy, 6063 TS

Table (2) Heatsinks undertest

Heatsink Base Dimension (50, 35, 1) mm			
#	Fin Dimensions (mm)	Heat Reduction in 15s (J)	Power Reduction in 15s (W)
1	2, 2, 1	10.23	0.732
2	2, 3, 1	7.58	0.495
3	2, 4, 1	5.24	0.322
4	3, 2, 1	12.77	0.851
5	3, 3, 1	9.36	0.659
6	3, 4, 1	7.24	0..442
7	4, 2, 1	11.35	0.782
8	4, 3, 1	8.52	0.527
9	4, 4, 1	6.16	0.380
12	2, 2, 2	6.75	0.645
13	2, 3, 2	5.23	0.410
14	2, 4, 2	4.93	0.286
15	3, 2, 2	6.12	0.536
16	3, 3, 2	4.85	0.375
17	3, 4, 2	4.31	0.213
18	4, 2, 2	5.42	0.472

The fin dimensions is calculated as shown in the following steps:

Fin spacing:
to find optimum fin spacing, it is first necessary to find out Rayleigh number (R_a).
$R_a = 0.00788*10^7*T_{A-av} = 0.00788*40*10^7$
    $= 0.4334*10^7$
Fin Spacing (centre-to-centre)$= 2.714*L/R_a^{0.25}$
$= \{2.714*0.05/(0.4334*10^7)^{0.25}\}-0.001$
$= 0.00322-0.001$
$= 3$ mm
Exact Fin Spaceing: 3mm-0.5mm-0.5mm=2mm

Number of fins:
Base Width/(fin Thickness*Fin space)
$= 0.035/(0.001*0.002) *15\%$
$= 17.5+2.625$
$= 20$ fins

Total cooling load (TCL):
TCL=heat transfer coefficient*A* T_{A-av}
$50.731 = 4*A*55$
$A = 0.2305$ m^2 =Total Fin Area + Base area
$A = 4*N_F*L_F*H_f)+ (L*H)$

Heatsink Height (H_f):
$H_f = A-(L*H)/(4*N_F*L_F)$
$= (0.2305-0.00175)/(4*20*0.001)$
$= 3$ mm

Therefore the Fin Dimensions (Heigh, Space,Thickness) is (3, 2, 1)mm.

A typical design includes thermal reduction as well as power dissipation reduction that representing the heatsink performance. Therefore, the heatsink of the base dimension (height, width, thickness) of 50mm, 35mm, 1mm, and the fin dimensions (height, space, thickness): 3mm, 2mm, 1mm are selected which it meets the factors and requirements mentioned that fits the qualifications of portable processors.

4 SIMULATION RESULTS & DISCUSSION

This study concerns a simulation via the Thermal Analysis Package software for the proposed heatsink design which is suitable for most of portable processors. The base plate

dimension is (50mm, 35mm, 1mm), as shown in Figure 6, the heat source is applied to the specified location based upon the hottest spot of the processors that is validated in previous studies.

The rectangular fins are designed (3, 2, 1) mm, this is shown in Figure 7, the number of fins that are covered the base plate is 20 fins.

The effect of ambient temperature is tested, this is shown in Figure 8, and the temperature contours is shown in Figure 9.

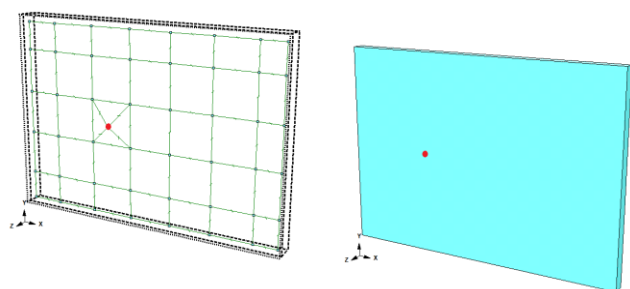The rate of temperature reduction vs time is shown in Figure 10.

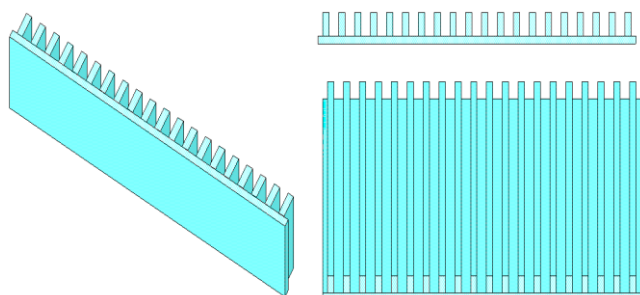**Figure 6:** The base plate (50, 35, 1) mm with heat source

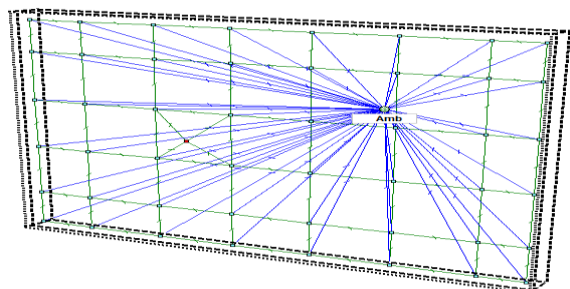**Figure 7:** The heatsink fins (3, 2, 1)mm

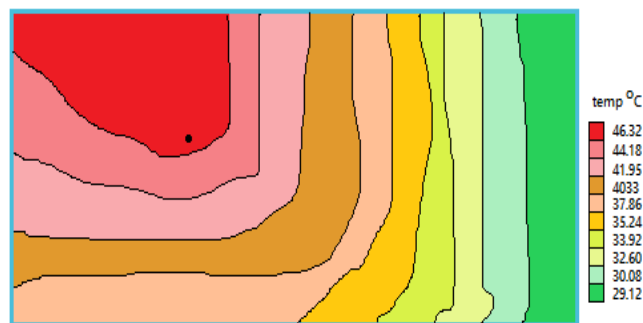**Figure 8:** The effect of ambient temperature
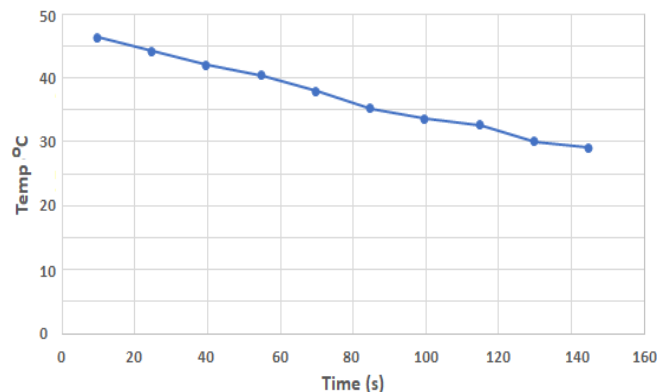

Figure 9: The temperature contours

Figure 10: The temperature reduction Vs time

These results verifying that, the proposed heatsink can reduce 0.851 W and 12.77J at 15s, and it suitable for power and temperature limits of portable processors, the processor have a minimum average safe temperature bound and power consumption using the proposed heatsink to a high-performance estimation. It is verifying power as well as temperature aware to the processor designers in their verification efforts, all results are obtained in a real-time simulation setup. Therefore, the proposed design will help to the design corner requirements rather than power and thermal improvements as well as space reduction and material savings were attained.

5 CONCLUSIONS

The design and simulation of many different heatsinks are performed in order to achieve a low temperature, low power, and active operation of portable processors. The computer simulation and thermal analysis of different base dimensions as well as shape and dimensions of fins are used. From simulation results, the heatsink of the base dimension (height, width, thickness) of 50mm, 35mm, 1mm, and the fin dimensions (height, space, thickness): 3mm, 2mm, 1mm are identified

and selected which it meets the factors and design parameters. Results shows the specification improvements of the design model for ensuring power required to cool in time of 0.851 W, time to cool by 15s, and heat to remove is 12.77J which confirms theoretical fundamentals, sufficient improvement of power and temperature minimization, and better performance of the cooling system was achieved.

The maximum temperature reduction values are different for all heatsink profiles, it is clear that, the fin height and spacing has higher effects than the other parameters for obtaining maximum temperature reduction, it is mainly was $2^{o}C$ at 15s. The followed procedure in this article is significantly reducing time required for heatsink design and simulation model. Therefore, the presented design can be considered as a proper design constraint for portable processors

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