DESIGN OPTIMIZATION OF MICROPROCESSOR HEATSINK AND ITS IMPACT ON PROCESSOR PERFORMANCE

S.Manivannan[1], R.Arumugam[2], N.M Sudharsan[3]
[1]Department of Electrical & Electronics Engineering, Anna University, India
[2]Department of Electrical & Electronics Engineering, SSN College of Engineering, India
[3]Sarvajit – CAE, India
E-mail : [1]asmani25@yahoo.co.in

Abstract

The number of integrated circuits (IC's) in a package is increasing multifold, putting stress on packaging material, thermal and structural stresses. With the miniaturization of electronic gadgets, the packaging engineers are forced to design the chips/ packages that can overcome the above problem in addition to Electro Magnetic Interference (EMI). The authors aim to develop a system to ensure optimum use of space with increase in speed. Although it is necessary to consider several factors, the authors propose to address the impact of thermal issues in an electronic package. Operating the system above the rated temperature range can degrade system performance, cause logical errors or cause component and/or system damage. Hence, an optimum heatsink design would mitigate the above problem. Thus, it was found that by optimizing the heatsink fins, not only there was a remarkable reduction in junction temperature, but also an increase in speed of processes.

It is therefore seen that the design of heatsink is of paramount importance. However, in addition to effective thermal dissipation, it must also be of a compact size. A genetic algorithm is performed for optimization of heatsink geometry. The impact of running the CPU stability tests on a processor with varying heatsink geometry (within the boundaries specified in the optimization program) was performed and the temperature distribution results are presented. It was observed that the temperature distribution was within the maximum operating temperature of the package.

Key words: Microprocessor, Heatsink, Design Optimization, Genetic Algorithm, Stability Analysis, Benchmarks.

I. INTRODUCTION

The objective of electronic component cooling is to ensure that the temperatures of all components in a system are maintained within functional temperature range. Within a temperature range, a component or electronic system is expected to meet its specified performance. Operating the system above the rated temperature range can degrade system performance, cause logical errors or cause component and/or system damage.

Hence, System integrators devote considerable engineering resources for optimizing power and cooling systems to avoid overheating, which can dramatically reduce component longevity. Temperatures exceeding the maximum operating limit of a component may result in irreversible change in the operating characteristics of that component. Since, latest processors are packaged with large number of IC's than ever before causing an increase in Watt density (Heat dissipated/ Unit area).

The design of an electronic package involves several factors like electrical performance and thermal related problems like overheating. This miniaturization is accompanied by the increase of dissipated power density. The increased power density in the system causes the system components to either operate at higher temperature which will reduce the performance or it will require better cooling which in turn will increases the cost of the system. Hence, efficient cooling solutions like heatsinks should be designed to remove the heat generated within the system.

Literature review performed by the authors indicates the design and optimization procedures for the heatsink as an efficient way to improve heat generation within the electronic systems. However, the impact of flat-plate heatsink design optimization on the processor performance has not been presented. Hence, the authors propose to study the impact of micro processor heatsink design on the processor performance and its thermal stability. Also, this research introduces the application of Genetic algorithm for the optimization of geometry of micro-processor heatsinks by minimizing the entropy generation and studies its impact on the performance of the Intel Pentium Core 2 Duo processor.

II. MOTIVATION

The Intel Pentium Core 2 Duo processor is taken for experimentation to study the impact of heatsink geometry on the processor performance. The extruded aluminum flat plate heatsink is selected for trials by varying its heights. The speed of the processor (processor performance) is adjudged with the help of benchmark utility. In earlier work, the processor benchmarks have been used only for comparing the performance of different processor configurations. In the present work, the authors aim at comparing the different heatsink designs of the same processor in identical system environments. An attempt to optimize the heatsink geometry has been done using genetic algorithm. Finally, the processor thermal stability tests were carried out by varying the heatsink design within the specified range. This benchmark study revealed that the fin height has an effect on the speed of the processor without affecting the thermal stability.

III. BACKGROUND

3.1 PROCESSOR PACKAGE

The processor is coupled to the heatsink using an Integrated Heat Spreader (IHS). The IHS spreads the non-uniform heat from the die to the top of the IHS, out of which the heat flux is more uniform and on a larger surface area. This allows more efficient heat transfer out of the package to an attached cooling device. The IHS is designed to be the interface for mounting a heatsink. The case temperature is defined as the temperature measured at the center of the top surface of the IHS.

3.2 MECHANICAL REQUIREMENTS

The processor package has mechanical load limits. These load limits should not exceed during heatsink installation and removal. For example, when a comprehensive static load is necessary to ensure thermal performance of the thermal interface material between the heatsink base and the IHS, this comprehensive static load should not exceed the compressive static load specification given in the processor data sheet.

The heatsink mass can also add additional dynamic compressive load to the package during a mechanical shock event. Amplification factors due to the impact force during shock have to be taken into account in dynamic load calculations. The total combination of dynamic and static compressive load should not then exceed the processor compressive dynamic load specification during a vertical shock.

3.3 THERMAL SPECIFICATIONS

3.3.1 Processor Case Temperature and Power Dissipation

Thermal information for the processor is given in terms of maximum case temperature specification and thermal design power. These values depend on the processor frequencies. Processor power is dissipated through IHS. There is no additional component, which generates heat on this package. The case temperature is defined as the temperature measured at the center of the top surface of the IHS.

3.3.2 Heatsink Design Considerations

For the Intel Pentium 4 Core 2 Duo processor, a typical aluminum extruded heatsink with an axial fan is used to cool for the entire range of thermal power. The goal of a cooling system is to keep the processor within the operational thermal specifications. Failure to do so will shorten the life of the processor and potentially cause erratic system behavior. For effective heat removal from the processor, three basic parameters have to be considered [9] such as the area of the surface on which the heat exchange takes place, the conduction path from the heat source to the heatsink fins and the heat transfer conditions on the surface on which heat transfer takes place.

IV. RESULTS AND DISCUSSIONS

4.1 BENCHMARK TEST RESULTS USING SPE CPU 2006

An experimental setup was developed in the Core 2 Duo Intel Pentium 4 processor, in which the height of the heatsink was varied. A typical experimental environment is ensured by using the same thermal interface material (which is applied between IHS and the heatsink), heatsink clip load arrangement, ambient temperature with the same fan size and speed.

The height of the heatsink was varied and the performance of the compute-intensive processor was estimated by SPEC CPU2006 [18] which is an industry-standardized CPU-intensive benchmark suite. SPEC designed CPU2006 provides a comparative measure of compute intensive performance across the widest practical range of hardware. The results of running selective benchmarks of CPU 2006 on Intel Pentium Core 2 Duo processor on Linux platform with varying heatsink heights are shown in Table 1. The results have been validated using X-bar or mean Quality control charts, the results of which shows that measurement process is within the statistical control.

Table 1. Results of benchmark tests on Intel Pentium core 2 Duo Processor.

Benchmark	Mean Completion time (s) of benchmarks with varying heatsink heights "H".		
	H = 35mm	H = 25mm	H = 15mm
H264ref	1342.2	1455.9	1531.4
Povray	555.4	580.6	602.5

The X-bar quality control charts are constructed for every benchmark program run with varying heights of the heatsink. The benchmark completion time for five samples, each of size four have been taken when the process is assumed to be in control. The means and ranges in each samples are calculated. Hence the control limits (LCL & UCL) for the charts are computed. Fig. 1

shows the control chart for the H264ref benchmark with the height of heatsink, H= 35mm. Similarly Fig. 2 and Fig. 3 shows the control charts for the H264ref benchmark with height of heatsink, H = 25mm and H= 15mm respectively. In all the Figures, it is observed that the points are within control limits and no specific pattern can be observed. Therefore the process variability is in control.

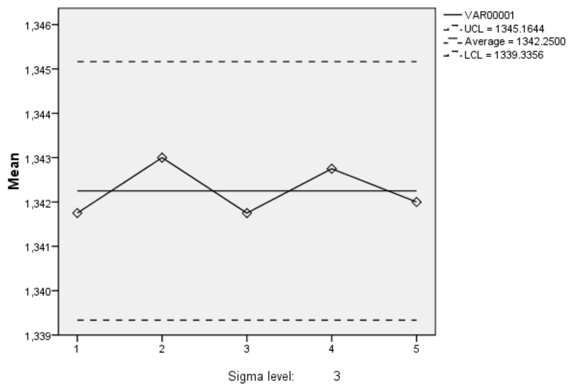

Fig. 1. X bar control chart for H264ref benchmark with H = 35mm.

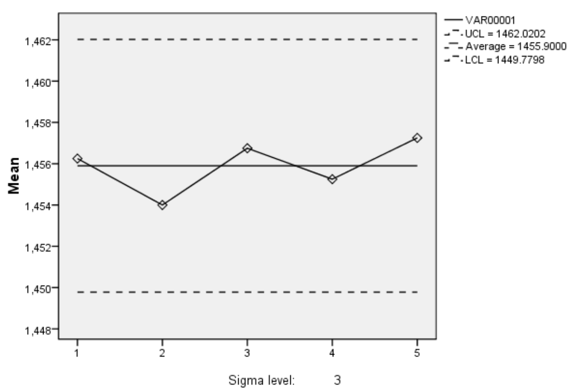

Fig. 2. X bar control chart for H264ref benchmark with H = 25mm.

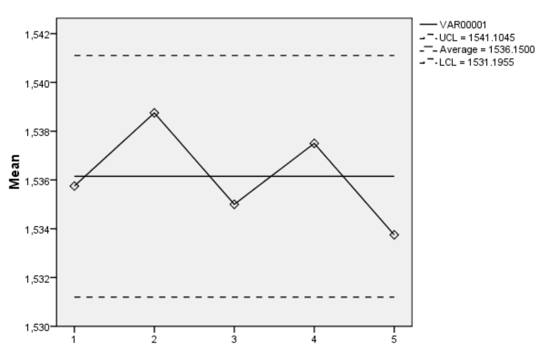

Fig. 3. X bar control chart for H264ref benchmark with H = 15mm.

Similar X-bar control charts were constructed for the other benchmark programs and the readings were observed to be in control. Fig. 4 is constructed from the results shown in Table 1 and it is evident that the height variation of the heatsink has a major impact on the performance of the processor, but restricted for installation in a system because of the space available on the mother board. Hence the geometry of heatsink needs appropriate optimization.

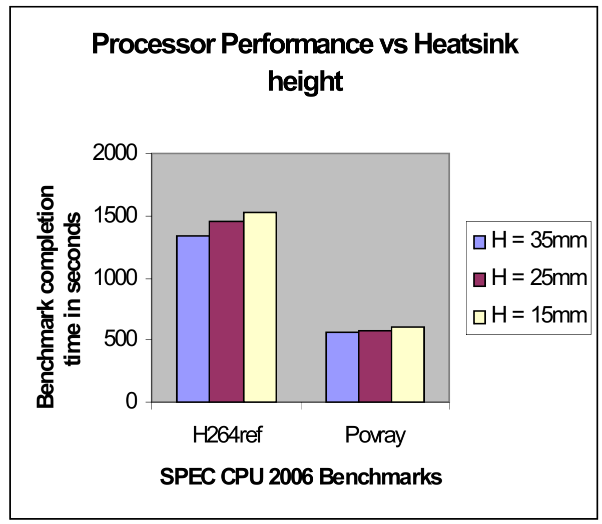

Fig. 4. Impact of heatsink height on processor performance.

From the above results, it is evident that the height variation has a major impact on the performance of the processor, but restricted for installation in a system due to the space restrictions on the motherboard. The benefit of speed was obtained by changing only one parameter namely heatsink height. However, the attempt is made to achieve the same speedup in a fin of lower height by varying the other parameters like length, thickness and the number of fins. The above study is only for one specific processor of a given Watt dissipation. In order to study the effect of various load conditions, an experimental model is setup, analyzed and presented in section 4.2. Also, to make the system more compact, the authors propose to make use of Genetic Algorithm to achieve the above objective and produced in section 4.3.

4.2 EXPERIMENTATION OF HEATSINK DESIGN

As discussed in 4.1, full scale experimentation is performed by mimicking the Watt density, i.e. the heat dissipated by various processors from 20 to 80 Watt. An experimental setup is arranged with an electric heater as a heat source to mimic a processor and it is supplied by a variac (Variable auto transformer). An aluminum plate acts like an Integrated Heat Spreader (IHS) is kept over the heater for uniform distribution of the heat above which the heatsink is placed. The heatsink rejects the heat into the air which is enhanced by placing the axial fan above the heatsink. The axial fan is charged by 12V D.C. The bottom side of the heater is insulated so as to ensure that all the heat from the heater is dissipated through the heatsink only. Twelve numbers of iron-Constantan thermocouples are suitably placed in and around the heatsink so as to measure the temperature; also they are connected to the data logger and computer setup (Data Acquisition System). Fig.5 shows the schematic representation of the arrangement inside the cabinet.

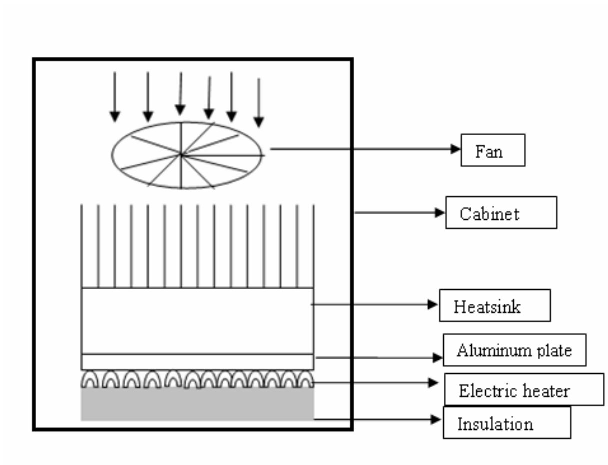

Fig. 5. Schematic diagram of the arrangement inside the cabinet.

The experiment was conducted for various heat loads. The temperatures at various locations are measured and recorded using data logger and computer. The temperature difference for various heat loads by experimentation is shown in Table 2.

Table 2. Temperature difference for various heat loads

Heat load (W)	Experimental ? $T = T_b - T_a$ (^{0}C)
84	24.13
62	17.57
40	11.8
20	5.91

All design equations used for computing the performance parameters are the same as given in [12]. Hence, the performance values of resistance and space occupied were computed and presented in table 3.

4.3 OPTIMIZATION OF HEATSINK GEOMETRY USING GENETIC ALGORITHM

As discussed in section 4.1, Genetic Algorithm is used to optimize the heatsink design, where the objective function is to minimize the entropy generation rate.

GA's are naturally suitable for solving maximization problems. Minimization problems are usually transformed to maximization problems by suitable transformations. In general, a fitness function F(X) is first derived from the objective function and used in successive genetic operations. For maximization problems, the objective function is kept as the fitness function.

Therefore the fitness function is:

$$F(X) = 1/Sgen$$

A systematic optimal design process and parametric study of the plate-fin heatsink by applying the theory of entropy generation rate [5] [6] is given by

$$S_{gen} = \frac{Q^2 R_{sin}}{T_c^{2}} + \frac{F_d V_f}{T_c}$$

This problem was solved by the augmented Lagrange multiplier (ALM) method [12] and in our approach we aim to extend the same Sgen optimization using Genetic algorithm. The assumptions made by Culham [10] are taken for solving our problem using GA:

no bypassing flow effect uniform approach flow velocity constant thermal properties uniform heat transfer coefficient and adiabatic fin tips.

The variables are length of the heatsink, height of the fin and number of fins. The ranges of variables are:

70mm	< length	<	90mm
0.8mm	< thickness	<	3 mm
10mm	< height of the fin	<	40mm
2	< number of fins	<	40

The constraints are

Optimal design mass<= original design mass

Aspect ratio = 10

Aspect ratio is the ratio of height of the fin to the spacing between the fins.

In order to optimize the present problem using GA, the following parameters were specified by practice, to get the optimal solutions with low computational effort.

Maximum number of generations	:	100
Population size	:	20
Total string length	:	20

Mutation probability : 0.01

and

Crossover probability : 0.9

Genetic algorithm is coded using the conventional programming language and the following optimum design parameters are obtained.

Thickness = 0.8mm

Length = 83mm

Height of the fin = 16mm

Number of fins = 28

The cooling effect on the processor can be enhanced by optimizing the heatsink. The results from Genetic Algorithm are shown in table 3. The numerical value of the performance parameters shows significant improvement.

Table 3. Results of optimization of heatsink using Genetic Algorithm

Performance factors	Original experimental design	Optimal design
Resistance ^{0}C/W	0.2891	0.1944
Space occupied m^3	0.001757	0.001153

4.4 IMPACT OF HEATSINK GEOMETRY ON PROCESSOR THERMAL STABILITY

Thermal management of the processor depends on the heatsink mounting on the processor, and effective airflow through the system chassis. The ultimate goal of thermal management is to keep the processor below its maximum specified thermal metrology.

The goal of performing CPU stability test is to maximize heat production from the CPU, putting stress on the CPU itself and the cooling system. Lavalys EVEREST [7] benchmark is used for performing System Stability Test with thermal monitoring to stress the CPU. The stability tests were performed when the CPU utilization was at its maximum (nearly 100%) as shown in Fig. 5. The temperature sensor graph was recorded at a frequency of every 5sec and the CPU usage/ throttling graph was recorded at a frequency of every 1 sec. It was observed that for varying heatsink design parameters, the thermal monitoring graph showed different max. Temperature recorded for the stability test implemented with the heatsink within the specified design parameters range.

Benchmarking has been done with POV-ray [14], which does a heavy test of CPU ability and corresponding processor temperature has been observed. The temperature observed for the case of boxed Intel Pentium Core 2 Duo processor with the variable heatsink designs are shown in Fig. 6 and Fig. 7 respectively. In all the experimental trials with different types of heatsink, the impact of heatsink design was studied against its processor thermal stability and it was observed that the maximum temperature was less than 61.40c [Intel Pentium Core 2 Duo processor E-2000 series at Tc-max is 61.40c], which is the reference range specified in the Intel Reference manual [9].

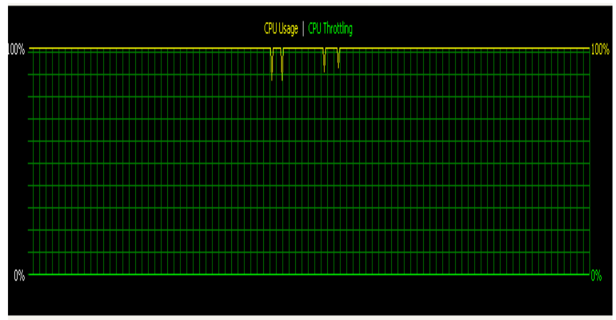

Fig. 5. CPU utilization at its maximum during thermal stability analysis.

Illustrations

Benchmark used: POV-ray. Tool used to test thermal stability: Lavalys Everest CPU stability test performed on: Intel Pentium Core 2 Duo processor E-2000 series.

The different heatsink parameters mainly considered for the illustrative trial experiments were length and the height of heatsink. The ranges of variables are chosen well within the range as chosen for the optimization boundary limits:

70mm < length < 90mm

10mm < height of the fin < 40mm

Table 4 shows the sample experimental trial designs with varying heatsink design parameters that were used to study the impact of heatsink design on processor thermal stability and hence its impact on the processor performance. The maximum temperature of the processor was studied for both the designs as shown in Table 4. Thus it was found that the design of heat sink has a great impact with the processor temperature.

Table 4. Illustrative trials of Different heatsink parameters

Heatsink parameters	Length (mm)	Width (mm)	Height (mm)	Tc max
Design 1	86	69	35	52^0c
Design 2	83	69	40	49^0c

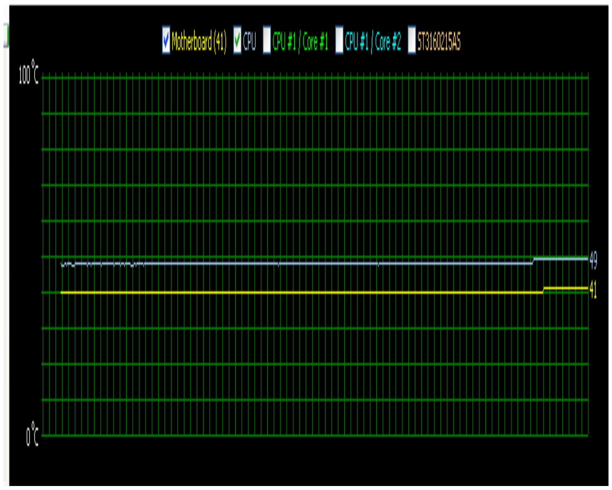

Fig. 7. CPU Stability test with heatsink design-2 showing Tc-max at 490c

V. CONCLUSION

The study of impact of heatsink geometry on the processor performance was carried out. Several benchmark utilities were run to find the impact on processor performance in terms of processor speed by varying the height of the heatsink. Hence, we intended to optimize the heatsink design to suit the requirements of the thermal aware processors. Genetic algorithm was considered for this purpose with the entropy generation minimization as the objective function and the optimal design parameters were obtained for the heatsink selection. Also, a study carried out with varying designs of the heatsink revealed that the temperature of the Intel Pentium Core 2 Duo processor never overshot above the maximum reference temperature given by the processor vendor when the system stability test was carried out by varying the heatsink design within the optimal specified range.

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S. Manivannan

He is currently a Research Scholar registered in the Department of Electrical & Electronics Engineering, Anna University, Chennai. He has completed his Masters in Applied Electronics from Dr.MGR Engineering College (Madras University). His research interests are the areas of Thermal management of electronic packages.