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STUDY AND OPTIMIZATION OF ADVANCED HEAT SINKS FOR PROCESSORS

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ABSTRACT

The main task of this project is the development of a modular heat exchanger to dissipate a TDP (Total Dissipated Power) of 140-180 W on a microprocessor. This exchanger should be able to dissipate the reference target TDP respecting the maximum operating temperatures (above these temperatures the CPU goes into thermal throttle) and the longevity temperatures (lower than the thermal throttle temperatures). This result should be achieved while providing product versatility (based on the concept to adapt the exchanger to each socket), acceptable noise, acceptable size and cost. The heart of the project is the design of a suitable fin surface to protect processors with high TDP. In this case, a significant increase in fan speed and in the size of the finned body is inevitable. In this way, an increase in the heat removal is obtained by larger airflow rate (high number of revolutions of the fan) and the large exchange surface. Considering the impact of these changes, the design of the exchanger is extremely critical in terms of size and noise level. Another physical limit is represented by the progressive and unavoidable phenomenon of electro migration that afflicts each circuit, the more the temperatures separate from those of longevity, the lower the useful life of the CPU. Once the longevity temperature is exceeded, the useful life of the processor decreases with increasing temperatures until the thermal throttle temperature is reached, which causes an abnormal system shutdown. The processors with a TDP from 65W to 95W are the most numerous. For this reason, most aftermarket solutions are designed to dissipate this TDP. The main purpose of this study is to examine the best geometry for a modular exchanger that is able to effectively dissipate the higher TDP (up to 180W) typical of modern high performance processors. For this purpose the Golden-section search is introduced for optimizing the number of fins. The heat exchange is simulated with fluid dynamic simulations (CFD). This new study allows obtaining an optimal design for the construction of the exchanger. The use of an optimal finned surface avoids the use of heat pipes. This approach simplifies the design. Moreover, by using materials with high thermal conductivity (such as copper alloys instead of aluminium alloys) we can certify the heat exchanger for TDP larger than the design one and therefore cope with even higher thermal loads. In this way, we can also effectively dissipate very performant CPUs (very uncommon) with extremely high TDPs such as FX-9590 with a 220W TDP (declared by the manufacturer AMD), maintaining in any case temperatures below the maximum thermal specifications.

Keywords: CFD, golden-section search, thermal analysis, CPU, microprocessors.

INTRODUCTION

Initially the project was aimed to the AMD CPU series called Ryzen Thread ripper (in its three versions 1900X 1920X 1950X), processors with non-canonical dimensions and not equipped with stock heat sink. The new heat exchanger should be able to dissipate the TDP of 180W with CPU wall temperature that falls within the operating specifications (68 DEG C per on a TR4 socket). This temperatures should be obtained with the use of a 80mm fan (8025-12H) positioned at the front in the specially designed hole. This assembly should increase the forced air flow and the dissipation by convection. The nominal TDP (Thermal Design Power) is the theoretical maximum design consumption, while the absolute maximum consumption in reality can be up to 30% higher than the indicated TDP. The high TDP (180W) requires a large exchanger (127mm X 140mm X 140mm) this implies the use of expensive technologies for the manufacturing like electrical discharge machining. This would have caused a really high unitary cost; therefore we opted for an assembled modular solution. A series of modular sections of the front / rear sections (127mm X 140mm X 25mm) and median section (127mm X 140mm X 20mm) were designed. The various parts can be realized with less expensive technologies, such for example, by using CNC machines for the first prototype and investement casting for the serial prodution. The modular geometry has also the advantage of making the project flexible and adaptable to many possible existing sockets; in fact, starting of different numbers of sections we can obtain optimal solutions for several scenarios. It is certainly convenient to work also on other sockets still on the market: AM3 +, AM4, 1150, 1151, 2066, TR4 and to be ready for the new ones coming. Once the sockets have been identified, it is necessary to know the TDP to be dissipated and in this way define the number of median sections to be used to obtain a sufficiently performing design. For example the aassembly of 3 parts with a single median section is indicated for CPUs with a TDP between 95W and 125W. Assemblies of 5 parts including 3 median sections are suitable for CPUs with a TDP between 140W and 180W. Table-1 summarizes the simulation data.

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Table-1. Simulation Data.

Description	Value	Unit
Ambient temperature	293	K
Thermal Conductivity at 20 ° C of aluminum alloy 6061-T6 @ 293K	155	W m^{-1} K^{-1}
Outlet pressure with 1 fan in front suction	1	bar
Power to dissipate at TDP	180	W

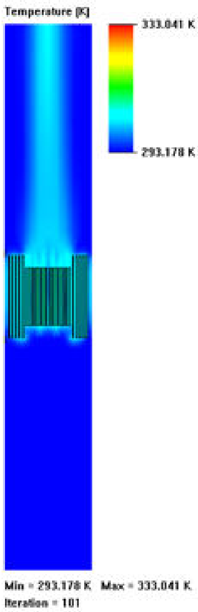

Figure-1. Air temperature from above.

Figure-1 shows the temperature distribution of the air (topview) in a 180 W heat exchanger.

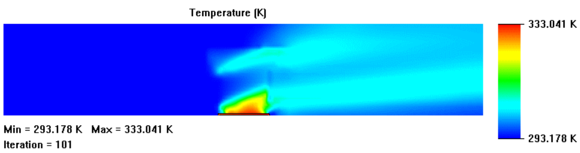

Figure-2. Air temperature in a meridian section

Figure-2 shows the same simulation in a meridian section of the heat exchanger of Figure-1 Figure-3 shows the temperature in the middle transverse section parallel to the CPU wall. After a careful series of CFD simulations [1-5]} with it became clear that each module of the modular geometry is able to cope effectively with 95W @TDP, with a reduction of the maximum temperature of about 54 K. This initial non optimized design, based on manufacturing requirements, proved to be quite satisfactory. However, it necessitates of further refinements. Therefore, an optimum solution is looked for [6-15]. Since the only reasonable parameter is the number of fins. A single variable optimization is performed. The limits of this optimization are given by technological boundaries.

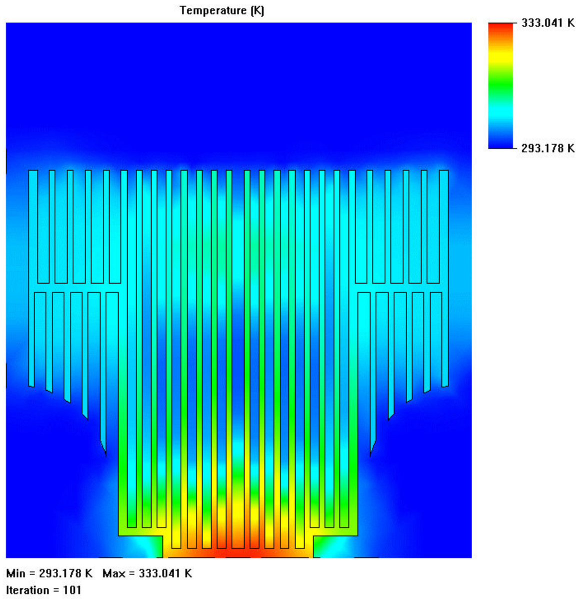

Figure-3. Air temperature in transverse section.

Golden-section search

Now it is possible to improve the results obtained by a Golden-section search [16] to determine the optimal number of fins The distance R between the 3 test points (Rate of Gold) can be calculated with equation 1.

$$R = \frac{\sqrt{5}-1}{2} \approx 0.618 \qquad (1)$$

R is the complementary to the golden number. In fact, the two solutions of equation (2) are (3) and (4).

$$x^2 - x = 1 \qquad (2)$$

$$x \approx 0.618 \qquad (3)$$

$$x \approx 1.618 \qquad (4)$$

Then, given an interval [max, min] the two test points x_1 and x_2 will be (5) (6)

x_1 = max - R (max-min) (5)

x_2 = min + R (max-min) (6)

The golden section interactive optimization is aimed to minimize the temperature as the number of fins varies in the design interval. The initial interval values are:

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max=27 and min=3 fins. Therefore, two new geometries should be modeled with x_1 and x_2 number of fins at each iteration. It is then possible to perform the CFD analysis and find the temperature for each case. The CFD model uses only the heat sink core, a finned parallelepiped of 80x80x60mm that dissipates the major part of the heat energy due to the forced ventilation given by the 80x80mm frontal fan (yellow part of Figure-4). In fact CFD simulations showed that the remaining part of the heat sink adds a minimal contribution to the heat dissipation process (Figure-5).

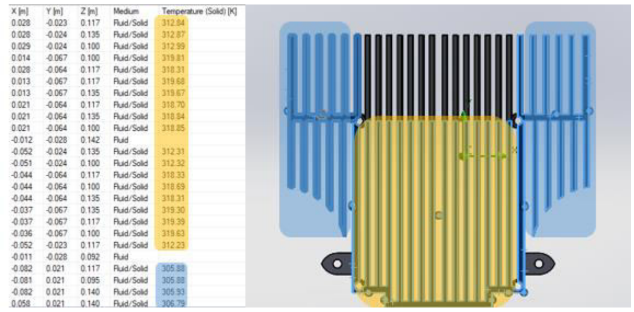

Figure-4. The heat dissipation is mostly due to the core (yellow).

In fact, lateral regions (blue in Figure-4) are not invested by the forced ventilation air (see also Figure-5). In the golden section optimization, at the first step we have that x_1, calculated with equation (5), is equal to 12 and the resulting wall temperature is equal to 336 K; while x_2, calculated with equation (6), is equal to 18 and the temperature reaches 318K. Therefore, for step 2 is xmin=12, while xmax remains equal to 27. At step 2, x_1 is calculated again with equation (5). Then x_1 is equal to 18 with a temperature of 318 K (a case already calculated in step 1). While, x_2, again calculated with equation (6), is equal to 21 with a temperature of 319K.

$$\{x_1,x_2\} = 27-R * (27+/-12)\approx\{18,21\} \qquad (6)$$

Therefore it is not convenient to exceed 21 fins. The new interval is {12,21}.

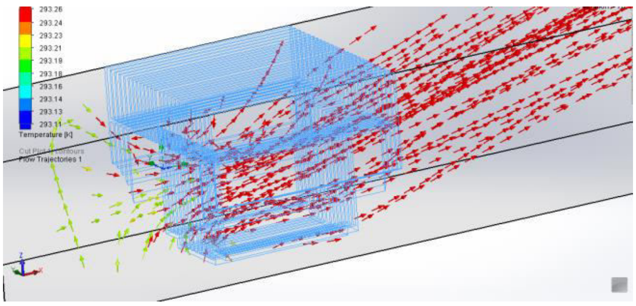

Figure-5. Most of the airflow passes through the central core.

This result is due to the fact that temperatures decrease by increasing the exchange surface but as the number of fins increases the benefit is reduced (from 18 to 19 fins the benefit is minimal). It is also clear that over a certain number the fins the heat exchange is reduced because an excessive crowding limits. In this case the limited air flow between the fins reduces the heat exchange by convection. However, a further increase in the number of fins improves the heat dissipation again and the temperatures start to decrease. This is due to the increase of the heat exchange by conduction, (as you can see passing from a geometry from 20 to 21 fins). Therefore, after 3 iterations we can conclude that the best result is obtained with 19 fins in the central core (see Table-2).

Table-2. Number of fins vs. temperature.

Number of fins	Temperature [K]
12	336
18	318.4
19	318.2
20	319
21	318.9

The prototype

A first prototype was made entirely with CNC (Computer Numerical Control), by chip machining a solid block of 6061-T6 aluminum alloy. Serial production will require the use of the more economical extrusion technology or investment casting. Figures 5 an 6 show the CAD 3D models of the heat sink to be tested. Figures 7 to 10 show the experimental apparatus. The tested heat sink is labeled A3.

Temperature disambiguation

The processor (CPU) is a very complex component made of 3 main parts:

a) IHS (metallic cover made of conductive material);

b) DIE (the actual processor made up of one or more integrated circuits);

c) PCB (motherboard inteface).

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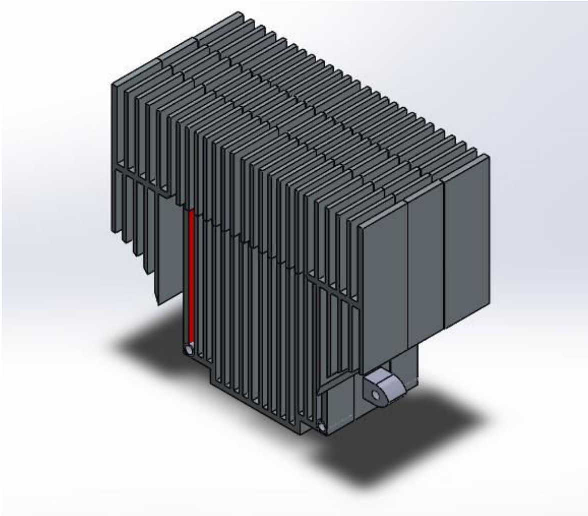

Figure-6. The heat dissipation module assembled.

Heat transmission by conduction between IHS and DIE is fundamental. The continuity of material is impossible. In fact IHS is made of metal and the DIE is made of silicon. From the Intel 5000 series onwards, the welded junction was replaced by a heat-conductive paste. This choice led to a drastic increase of the temperatures even if with the standard clock rate. The temperature indicated by the term "Package" refers to the warmest core inside the DIE. The Tjunction, is the temperature measured directly in the hot spots where the transistors are connected to each Core through digital thermal sensors. Since the manufacturer calibrates these sensors, there is an accuracy of about ±5 DEG C. The sensors are more accurate at the higher temperatures. The temperature indicated by the term "TEMPIN0" refers to the temperature of the IHS, in some versions of the software, the word CPU appears in its place. The throttle temperature (also called Tj-Max or Tjunction Max) is the temperature at which the processor cores go into throttle. In this case the built-in protection software reduces the frequency, deactivates the cores and in case the temperatures do not go down sends the CPU in protection to avoid an internal thermal damage. AMD processors are designed to operate at a maximum temperature of 72 DEG C. Generally the Manufacturer do not recommend temperatures above 62 DEG C for AMD CPU, to guarantee stability, performance and longevity over time. The temperatures reached by the processor depend on the Vcore. This is the power supply voltage of the processor. Excessive temperatures could lead to a phenomenon called "Electromigration" that involves the erosion of traces and welds between the levels of the processor and the nanocircuits, due to the excessive motion of the conduction electrons that impact on the atoms during their passage, imposed by the potential difference of Vcore. This leads to blue-screen crash situations, which will become increasingly common until the final CPU funeral. To limit this phenomenon, there are recommended values of the maximum applicable voltage.

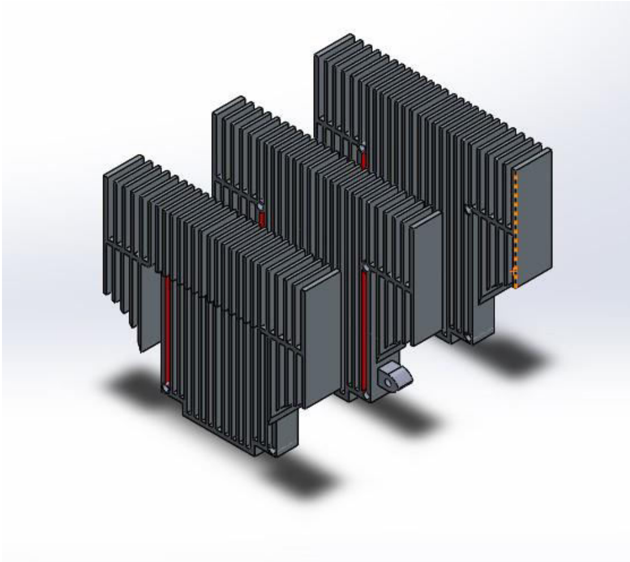

Figure-7. The heat dissipation module disassembled.

These values change from processor to processor. Tables 3 and 4 summarize the data for the AMD FX 6300 CPU (Vishera architecture), which has been tested.

Table-3. Vcore values for AMD FX 6300 CPU.

Vcore Stock	1.37 V
Vcore Recommended	1.4 V
Max Vcore recommended	1.56 V
Vcore Max with unconventional cooling (like liquid Nitrogen)	1.71 V

Table-4. Temperature values for AMD FX 6300 CPU.

Temperature (DEG C)	Condiition
72	Boiling (Throttling)
70	Very hot
62	Hot (100% load)
60	Normal
55	Normal (average load)
45	Normal
35	Cold (minimum load)

Tests

The software used on the test bench for the collection of experimental data are: Microsoft Windows 10 pro 64 bit, Hwmonitor VERSION 1.33, Intel Burn Test VERSION 2.45, Core Temp VERSION 1.10. Environmental and experimental conditions are summarized in Tables 4 and 5. The high stress condition corresponds to Vcore=1.56V, while standard stress has Vcore=1.4V.

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Table-5. Envionmental conditions.

Ambient temperature [DEG C]	**22**
Relative humidity [%]	50

Table-6. Stopping conditions.

Thermal throttling temperature [DEG C]	**72**
Noise limit [%]	60
SW limit	Blue screen

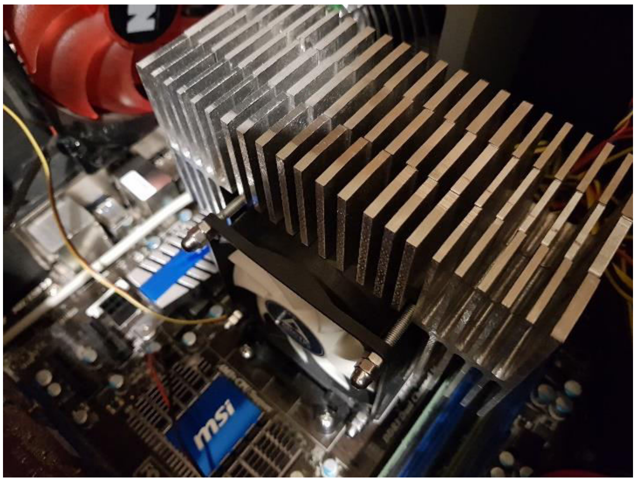
The thermo-conductive paste is the ARCTIC MX-4 8.5 with nominal heat conduction of 8.5 W/mK. Three heat sinks were used for the tests: the heat sink A1 that is the stock heat sink (A1) supplied with the AMD CPU FX 6300. It is certified for a TDP (Total Dissipate Power) of 95W. The (A2) which is the stock heat sink for the AMDCPU FX 8350. It is certified for a TDP of 125 W. The newly designed heat sink (A3) which is designed for 95W. The test apparatus is shown in figures 7-10. The test results are summarized in Table-7.

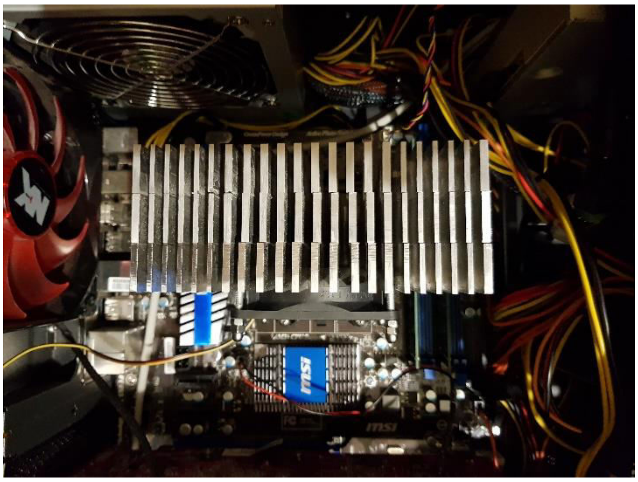
Table-7. Test results.

heat sink	**Standard Stress**	**Very High Stress**	**Decibel**
A1	65 °C	.	Over
A2	53 °C	53°C	45 dB
A3	55°C	56°C	40 dB
A3 simulation	54°C	54°C	-

CONCLUSIONS

The A3 heat exchanger is a success, the designed module is able to manage the target TDP (95W) in an effective manner, with temperatures of 54-56 DEG C. This temperatures are well below the maximum allowed by the manufacturer. AMD declares for the FX-6300 CPU, a thermal limi tof s 70.5 DEG C. Moreover, 54 DEG C is lower than the longevity temperatures of the CPU (62 DEG C). A minimum error between the experimental and the simulated data was measured, since not all the variables present in reality are possible to be incluede in simulation. For example the TDP target of the simulation was set to 95W corresponding to the real TDP indicated by the CPU Manufacturer. However, as explained above, this value does not correspond to the maximum absolute power that the CPU can generate under abnormal conditions of full load; therefore the real TDP may be up to 30% greater than the indicated average TDP. The rpm of the fan in the simulation is constant. In real world, it varies according to the load on the CPU thanks to the PWM (Pulse Width Modulation) controller integrated in the fan. The golden section optimization showed that a 80mm x 80mm x 60mm core with 19 fins of 2 mm each is the optimum for a TDP of 95W.





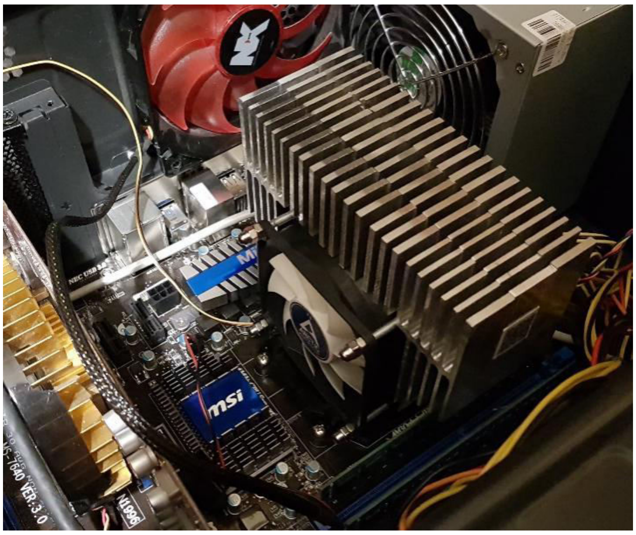


Figure-8, 9, 10, 11. Pictures of the experimental apparatus.

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