

# Thermal Simulation

A Study and Evaluation of the Opportunities and Benefits of  
Thermal Simulation in a Development Process

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## Preface

It has been a great experience to work with this project. Throughout the months working on Axis Communications AB we have got the opportunity to meet experienced and inspiring people from various departments of the company. The creative and open minded environment on AXIS has also greatly contributed to an ideal outcome of the project.

First of all we would like to thank our supervisors at AXIS Lina Carlsson and Emma Dreher for the continuous support during our work. It has been great working with you. We have felt very welcomed throughout the whole process and hope that we will have the opportunity to work with you again in the future.

We would especially thank Marcus Hall for all his instructive help with the application during the simulations. Thanks also to Jussi Myllyluoma for sharing his thoughts and knowledge about general thermodynamics and thermal optimization.

Furthermore thanks to our supervisor from LTH, Per-Erik Andersson, and our examiner Robert Björnemo.

Finally we would like to thank other involved employees at AXIS, foremost Roger Magnusson, Per Zander and Mats Carlsson for taking the time to provide us with input data for the simulations.

Lund, August 2011

Majken Blixt & Markus Giver



## **Abstract**

A growing challenge when developing smaller electric devices is the increasing power usage due to higher performance which leads to increasing heat loss. The IT company Axis Communications AB, further referred to as AXIS, who develops network surveillance products is no exception. As a market leading company the demand for smaller as well as more complex future products pushes the demands for thermal design even further.

The aim of this project has been to investigate whether taking use of simulation applications is a currently possible option for a company like AXIS. Using simulation as a tool in the company would mean, except for the purchase of application licenses, sufficient education and training. After visiting AXIS, a company named Validus Engineering AB was contacted. With guidance from Validus, who sell simulation applications, a suitable application was chosen for the investigation at AXIS.

The working method for the project was to do a number of simulations on an already existing AXIS product. The reason for this was that it had to be verified that the simulation application was able to reflect a real scenario. Thus a number of heat tests were done on the test product. After having executed a simulation with the same scenario, the results from the simulation were compared to the results of the heat tests. The results turned out to be close enough and the simulation could be validated. To investigate the possibilities with the software a large number of modified scenarios were set up and simulated in the simulation software, where various parameters were modified. The model needed to be reduced and adjusted in order to make the software able to run the simulations. After the results were analysed conclusions were drawn about the different parameters' influence on the temperatures inside the product.

It was finally stated that using CAD-based simulations as a tool for thermal optimization on products like the one used in this study is clearly possible for a company like AXIS. Provided that the company has access to the right input data about their material and electrical components, it was concluded that CAD-based simulations could provide accurate and fast information about the thermal heat dissipation in future products under development.

### **Keywords:**

CFDesign, thermal simulation, FEM analysis, heat transfer



## Sammanfattning

En växande utmaning i utvecklingen av mindre elektriska produkter är den alltjämt tilltagande elförbrukningen då produkternas prestandakrav ökar, vilket leder till ökade värmeförluster och således överhettade produkter. IT företaget Axis Communications AB, i fortsättningen benämnt som AXIS, som utvecklar nätverksprodukter för övervakningssystem är inget undantag. Som marknadsledande företag ökar efterfrågan för mindre såväl som mer komplexa framtida produkter och höjer kraven för termisk optimering ytterligare.

Syftet för den här studien har varit att undersöka huruvida simuleringsmjukvaror är ett möjligt alternativ för ett företag som AXIS eller inte. Att använda sig av simuleringsverktyg inom företaget skulle innebära, förutom själva inköpet av mjukvarulicenser, tillbörlig utbildning, träning och erfarenhet inom företaget. Efter att ha gjort ett besök på AXIS kontaktades företaget Validus Engineering AB. Med vägledning från Validus, som är återförsäljare av simuleringsmjukvaror, valdes en lämplig mjukvara ut för studien på AXIS.

Arbetsmetoden för studien innebar att köra ett antal simuleringar på en av AXIS redan existerande produkter. Anledningen till detta var att det måste verifieras att simuleringsmjukvaran kunde spegla ett verkligt fall innan ytterligare simuleringar gjordes. Följaktligen gjordes ett antal värmetest på den utvalda testprodukten. Efter att ha kört en simulering i mjukvaran på exakt samma scenario som under värmetesten jämfördes resultaten från simuleringen och värmetesten. Efter en del korrigeringar i simuleringsmjukvaran visade sig dessa resultat stämma överens tillräckligt bra för att simuleringsscenario kunde anses som validerat.

För att undersöka simuleringsprogrammets möjligheter sattes ett stort antal scenarion upp med testprodukten, där utvalda parametrar modifierades olika för var simulering. För att mjukvaran skulle klara av dessa simuleringar krävdes även att CAD-modellen av produkten förenklades innan den laddades in i simuleringsmjukvaran. Resultaten analyserades och slutsatser drogs sedan omkring hur de olika parametrarna påverkade temperaturen i en rad kritiska punkter inuti produkten.

Det var slutligen fastslagit att det är en klar möjlighet för ett företag som AXIS att använda CAD-baserade simuleringsverktyg som ett verktyg för termisk konstruktion och optimering. Förutsatt att företaget har tillgång till rätt ingångsdata om material och komponenter drogs slutsatsen att CAD-baserade simuleringar kan förse företaget med noggrann och snabbtillgänglig information om värmespridning och konvektionsflöde i framtida produkter under utvecklingsprocessen.





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# 1 Introduction

*The well-known fact that all energy eventually turns into heat comes with many complications. A particularly big area of difficulties is the cooling of smaller technical devices, such as computers, cameras and cell phones. These continuously tend to get smaller as well as more complex, and thus the temperature is rising rapidly. In many areas today the bottleneck that prevents the development of smaller products is not actual lack of capability of designing smaller components. It is rather the negative effects of the focused heat concentration in such devices. In order to face the demands for products of coming generations it is important to have a well-developed approach for evaluating the thermal situation.*

## 1.1 Background

The IT company Axis communications AB struggles alongside many others with optimizing the cooling of their products. AXIS is the market leader of network video and produces hardware and software solutions for security surveillance systems and remote monitoring. The main part of the hardware selection consists of network cameras and encoders. Even today many companies still stick with analogue surveillance systems but with the encoders it is possible to convert the analogue information from the cameras into digital information. Thus these companies are able to utilize Axis surveillance software systems without having to replace the cameras.

Since AXIS's products have a wide range of customer segments such as retail chains, airports, trains, busses and motorways, the environment demands are very high. Depending on how the product is mounted; outdoors or indoors, in sunshine or in shadow, close or far from other heat sources, the temperature inside the device differs greatly. Because of this, the operating temperature for the products could stretch over a wide range, depending on its surroundings. It is important to maintain a temperature inside the device that does not result in damage of the components. Because of this, the environmental demands make it necessary to develop different variations of a single product. Furthermore the future Axis products are anticipated to be smaller as well as more complex compared to the current ones, which pushes the demands for thermal design even further.

There are many possible ways to increase the heat dissipation, that is, efficiently transport the heat away from a device, preventing it from getting too hot. This could be done simply by a wise choice of materials and component placement. Spreading the heat generating components to avoid heat concentrations and take use of materials with high heat conductivity could both be examples of this. It could also be by using

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passive cooling like heat pipes and heat sinks or active cooling like fans and compressors. There is in other words an almost infinite number of ways to do a thermal design and it comes down to the process of optimizing the design. For this you need information about the relations between the temperature of the various components and their power consumption. It is also necessary to understand the relation between the components and their environment. However, thermodynamics and fluid mechanics is a relatively complex area, which makes calculations based on existing theory complex and time consuming.

Today AXIS does some calculations for anticipating the temperature in their products, but these are quite synoptically and lack the accuracy they often require. To increase the accuracy, AXIS put their products in heat chambers, using temperature sensors to determine the temperature of each critical component. Except for being somewhat time consuming, these tests only works for developed and produced prototypes. It will not work on half developed products and even less on product concepts. This makes it hard for Axis to predict the product temperatures once it is fully developed. They are forced to put great trust in comparing to earlier products and heat tests. AXIS is now searching for a better way of predicting heat generation of their products.

### 1.2 Purpose and Method

The use of computer simulations is continuously increasing, due to the rapid development of the processor capacity. The simulations have been proven very useful for finding numerical solutions to problems too complex to solve algebraically.

By doing simulations early in the product development process, if only even a vague picture of the geometry exists by then, a lot of heat problems could be discovered and dealt with at an early stage. As it is today a lot of those problems are discovered first when a prototype of the product is tested in the lab. By this point it takes a lot of time to go back, reconsider, change and to design a new prototype. Thus simulations could save time and money in the long run for the company.

One particularly powerful simulator application when it comes to thermal dynamics and fluid mechanics is named CFDesign. The main purpose for this project is to find out if applications like this are suitable for analysing and thermal optimization of AXIS's products.

The course of action in this project was to create a suitable 3D CAD-model of an AXIS product and collect data about the component's power generation. By knowing how much the various components consume the computer calculated the temperature in every point of the model. Furthermore the software provided information about the convectonal airstreams inside and around the product and how the heat radiation affects the results.

The first step was to establish that the simulation was corresponding to the reality. In order to verify this, a number of initial heat tests were made on a chosen product. In

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these tests the components power consumption and their corresponding temperatures were measured. By comparing these results with the results of a simulation of an identical scenario it was verified that the setup of the simulation was correct.

The second step was to set up a large number of simulations with the same AXIS product where different variations on the product were made for every simulation. This could for instance be to vary the cover thickness, the air volume inside the covers, the placements of the PCB components and the choice of materials. From the results of these simulations conclusions were drawn about how the existing type of products could be thermally improved, that is, in a more efficient way transfer the heat away from the product and out to the surrounding air.

The final goal was to decide whether it would be proper for AXIS to spend time and money on using a simulation application like this for doing thermal optimizations during the development process for their future products.

### 1.3 Main Objectives

The main objectives are as follows:

- Establish a way of simulating thermal scenarios of AXIS products that corresponds to reality
- Draw conclusions from a number of simulations where various parameters are modified
- State a number of useful thumb rules during thermal designing from the conclusions made
- Decide whether it is or it is not a current possibility for AXIS to start using simulation applications as a thermal design tool

### 1.4 Research Questions

Along the way a number of questions came up whose answers could be of interest even for a broader purpose than designing AXIS products:

- What are the relation between conduction, convection and radiation when heat travels from a heat source through air or solids and out to the surrounding environment. What parameters affect this relation?
- What degree of accuracy could be expected from these types of simulations?

### **1.5 Limitations and Delimitations**

Focus in this study will lie on the fourth main objective; to decide if using simulations is a possibility for AXIS. If further time is given a number of conclusions or "general rules" are to be stated, based on the analyse of the simulation results.

There will be no focus on solving any existing cooling problems, since this is considered to be too time consuming. Furthermore it is not within the borders of this study to investigate any economic aspects. Thus no opinion whether using simulations is a lucrative alternative or not can be made in this study; only if using simulations is a *technical and practical alternative* for the company.

The fact that the study relies on simulation software implies that there will be obvious limitations since every simulation takes a certain number of hours to run, depending on the complexity of a specific scenario.

The fact that there will only be two persons, with low laboratory experience, strongly limits the number of heat tests that are possible to perform on the test product.

Since the authors has never been part of a development team and followed a development process for a new product it is hard to predict exactly how the simulation software is to be used if the company would purchase it. This can be seen as a limitation when considering whether the software is a practical alternative or not.

As long as the main simulations are executed and the main objectives lies as first priority, the authors are allowed to do smaller and more focused studies along the way, as long as they contributes to support the final decision of the project.



## 2 Theory

*This section contains the theoretical framework for this study. The first part describes the fundamental thermodynamics that is needed to understand the simulation results and final conclusions. Secondary there will be a short summary of the finite element method, how it works in theory and how it is used.*

### 2.1 Fundamental Thermodynamics and Heat Transfer

In thermodynamics, heat is energy transferred from one thermodynamic system to another due to thermal contact when the two systems are at different temperatures. This transfer process is referred to as heat transfer and consists of three different types; conduction, convection and radiation. Below follows a description of each of these three phenomena that includes their underlying theory and the practical limitations of using this theory for describing the reality.

#### 2.1.1 Conduction

Conduction, or *thermal conduction*, is the transfer of heat between regions solely due to a temperature gradient. As opposed to convection and radiation the heat during conduction flows through the region of matter itself. Conduction takes place in all forms; solids, liquids, gases and plasmas. Conduction however does not, as convection, require any bulk motion of matter. During conduction in solids the heat is transferred with free electrons. In fluids the heat is transferred due to the colliding and diffusion molecules during their random motion. The heat energy due to conduction could be described with Fourier's law:

$$q = -k\nabla T \quad (2.1)$$

where:

- $q$  is the local heat flux per unit area,  $\text{W/m}^2$
- $k$  is the material's thermal conductivity,  $\text{W/mK}$
- $\nabla T$  is the temperature gradient,  $\text{K/m}$

The temperature gradient describes how the temperature varies with the distance in which direction the heat is transferred. Eq. 2.1 is a general formula that covers all directions.

The one-dimensional form would be:

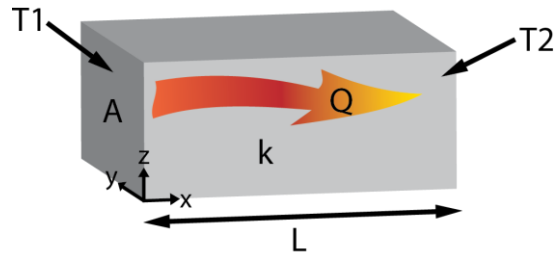
$$q_x = -k \frac{dT}{dx} \quad (2.2)$$

and by integrating (2) over the materials surface we get:

$$\frac{\Delta Q}{\Delta T} = -kA \frac{\Delta T}{\Delta x} \quad (2.3)$$

or, as more commonly written:

$$\dot{Q} = kA \frac{T_1 - T_2}{L} \quad (2.4)$$



**Figure 2.1** Heat flows through a solid body

See figure 2.1 for better understanding of eq. 2.4. This formula states in other words that the time rate of heat transfer is proportional to the area through which the heat is flowing. The heat transfer is also proportional to the temperature difference over the distance  $\Delta x$ . In this project it is never the heat energy  $Q$  that are important but always the heat flux  $\dot{Q}$ . Therefore the heat flux will be expressed as only  $Q$  instead of  $\dot{Q}$  from now on.

### 2.1.2 Convection

Convection is the movement of molecules within fluids, in many cases air or water. In this study however convection is referred to as *heat transferred by convection*. This implies heat transferred by the movement of molecules within fluids. These movements consist both out of diffusion and advection. Diffusion can be described as the random motion from regions with higher concentrations to regions with lower concentrations. Advection is rather a fluid current, for instance if the heat is transferred due to a fan that puts the air in motion.

In practice, convection is often referred to the heat transfer between a solid surface and a fluid, even though this actually even includes conduction right up against the wall. More than this, there are two types of convection, natural and forced. Natural convection occurs only due to the fact that the fluid density varies with the fluid temperature, and due to this currents will arise in the fluid. Forced convection, on the other hand, occurs due to an outer force that puts the fluid in motion, like for instance a fan.

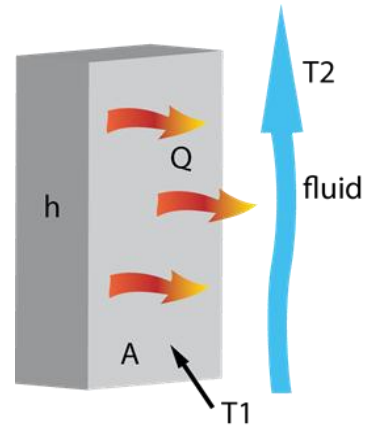
Convection is, compared to conduction, a complex phenomenon. It is often described with Newton's law of cooling. This law states that the rate of heat loss of a body is proportional to the difference in temperatures between the body and its surroundings.

Newton's law is given as the differential equation:

$$Q = hA(T_{surface} - T_{\infty}) = hA\Delta T \quad (2.5)$$

where:

- $Q$  is the heat flux, J/s
- $h$  is the heat transfer coefficient, compare with thermal conductivity  $k$  in eq. (2.4)
- $A$  is the surface area of the object from which heat is being transferred from,  $m^2$
- $T_{surface}$  is the surface temperature of the solid, K. (It is expressed as  $T_1$  in the illustration to the right)
- $T_{\infty}$  is the temperature of the surrounding fluid, K. (It is expressed as  $T_2$  in the illustration to the right)



**Figure 2.2**  
Heat transfers by convection

In this project the situation is as follows:

$A$  is known,  $T_{\infty}$  is known,  $Q$  is known in terms of electrical power in watt, and  $T_{surface}$  is the one we need to know. Then only one task remains; finding a value for the heat transfer coefficient  $h$  which, as will be shown below, is more of a complex matter.

### 2.1.3 Difficulties in Finding the Heat Transfer Coefficient for Convection

The heat transfer coefficient  $h$  depends upon physical properties of the fluid such as temperature and the *very geometry of the solid where the convection occurs*. Therefore, the coefficient must be derived or found experimentally *for every system analysed*. As the geometry gets more complex, it gets very hard to find a value for  $h$ . In fact, in reality, it is close to impossible. However if you restrict yourself to work within certain boundary conditions, there are formulas and correlations available for some typical cases. These cases are shown on the next page. They are divided into *natural* convection situations and *forced* convection situations.

## 2.1.3.1 Natural Convection Situation:

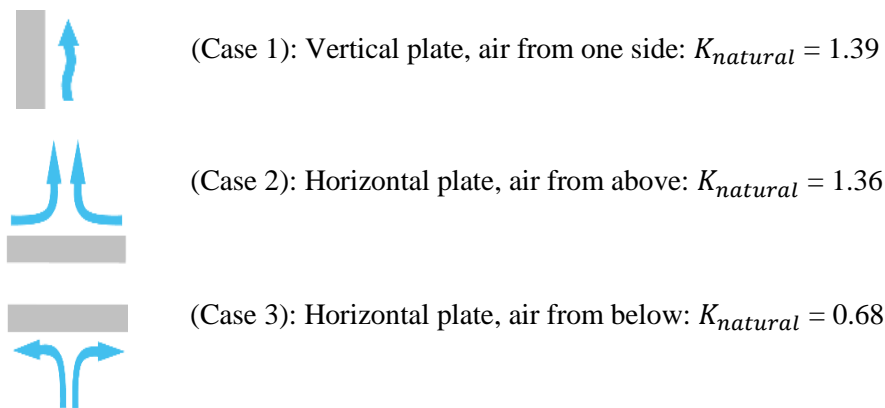
Assume the following conditions:

- $T_{surface}$ : 20-100 °C
- $T_{\infty}$ : 0-70 °C
- $L_c$ : 0.02-0.12 m (critical length, see section below)

Then  $h$  could be found with:

$$h = K_{natural} \left( \frac{T_{surface} - T_{\infty}}{L_c} \right)^{0.25} \quad (2.6)$$

where  $K_{natural}$  is a constant that depends only on the geometry. The critical length  $L_c$  is the length of the area where the convection takes place, defined in the same direction as the airstream. Below three of the most typical geometric cases are illustrated:



**Figure 2.3** The convection rate depends on the angle of the surface

As the illustration above shows, the parameter  $K_{natural}$  changes depending on how the surface is placed in relation to the air flow. In case 1 and case 2  $K_{natural}$  is relatively high, and as a result  $h$  is high as well. (See eq. 2.6) Now, according to eq. 2.5, this will result in a higher heat flux between the surface and the air flow. In practice this means that a solution where an object is cooled by natural convection from above is approximately twice as effective as one where the object is cooled from below. Of course this is of great importance when making a thermal optimization.

### 2.1.3.2 Forced Convection Situation:

In forced convection there is a chance that turbulence will occur. This is because the fluid velocity is higher in forced convection than in natural convection. Turbulent flow is in fact better than laminar flow when it comes to convection cooling. The strong, chaotic turbulent currents along the surface will efficiently help to transport heated fluid away from the surface. In practice these two equations are often used to get an approximate value of  $h$ :

$$\text{Laminar flow: } h = K_{forced} \left( \frac{U_{fluid}}{L_c} \right)^{0.5} \quad (2.7)$$

$$\text{Turbulent flow: } h = \frac{(5.63(U_{fluid}L_c)^{0.5} - 20.67)}{L_c} \quad (2.8)$$

where  $U_{fluid}$  is the fluid velocity along the surface and  $L_c$  is the critical length. The critical length here lies parallel to the fluid motion. The critical length represents the distance over which the fluid is in contact with the object.

Conclusively, with or without using the typical scenarios as a support tool, it is still a heavy task to find an accurate value for  $h$  in convection situations. A better way to do this would be to find a numerical solution to the problem, which is where FEM-analysis enters the picture.

### 2.1.4 Radiation

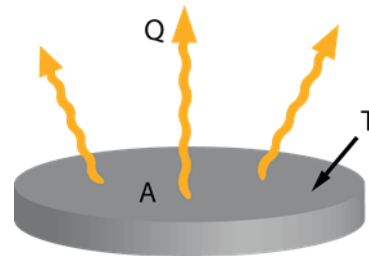
Thermal radiation is electromagnetic radiation emitted from all substances due to the inner thermal energy of the substance itself. In other words, all bodies emit heat. However, when observing two bodies, it is often only the *difference* of heat transfer between the bodies that really matters. Radiation does not need, as opposed to conduction and convection, a substance to travel through, due to its electromagnetic properties. Finally, as will be further described below, radiation in general plays a bigger role when it comes to high temperatures. In low temperatures it could often be neglected.

The heat radiation from a surface could be described with Stefan-Boltzmann's law:

$$Q = \sigma \varepsilon A T^4 \quad (2.9) \quad (\text{see figure 2.4})$$

where:

- $Q$  is the heat flux, W/s
- $\sigma$  is the Stefan-Boltzmann constant:  
 $5.67 \times 10^{-8} \text{ W/K}^2\text{m}^2$
- $\varepsilon$  is the emissivity, no unit
- $A$  is the surface area,  $\text{m}^2$
- $T$  is the surface temperature, K



**Figure 2.4** Radiation from a solid body

As can be seen in equation 2.5, the heat energy leaving the surface is proportional to the temperature raised to four. In reality this means that influence of radiation could be neglected when dealing with low temperatures, but has a huge impact when it comes to high temperatures.

An important parameter when discussing radiation is the emissivity,  $\varepsilon$ . The relative ability of a material's surface to emit heat by radiation is measured as the material's emissivity. The emissivity is a ratio between the energy generated by a particular material and the energy radiated by a black body. A black body is defined as a body with  $\varepsilon = 1$ . Thus  $\varepsilon$  in reality varies between 0 and 1. Emissivity is in other words a material property, which of course is an important factor to consider when selecting material for thermal designs.

### 2.1.5 Temperature Influence

To summarize we have three types of heat transfer, conduction, convection and radiation. All these have now been discussed and the physical relations for each and every one of them have been derived. In most real scenarios all of these three take place. It will be of interest to know how big part they play in comparison to each other. To put them in perspective to each other, the three relations are shown below:

- Conduction:  $Q = kA \frac{T_1 - T_2}{L}$
- Convection:  $Q = hA\Delta T$  (2.9.1)
- Radiation:  $Q = \sigma\varepsilon AT^4$

As could be seen from the equations, the heat transfer depends on three things:

- The material properties (k, h and  $\varepsilon$ )
- The geometry (A, L and h)
- The heat gradient ( $\Delta T$ )

In this section focus will be on the temperature influence. The question that is to be answered is:

*How does the temperature region in which the heat transfer takes place affect the relevance of conduction, convection and radiation respectively?*

In other words, how does Q depend on  $\Delta T$  in the three equations above? Keeping in mind that the parameter h in the convection equation contains  $T^{0.25}$  (see eq. 2.6), we could state the heat transfer's dependence of temperature as:

- 
- Conduction:  $Q \propto \Delta T$
  - Convection:  $Q \propto (\Delta T)^{1.25}$  (2.9.2)
  - Radiation:  $Q \propto (\Delta T)^4$

So the higher the temperature, the more important becomes radiation and the less important becomes conduction and convection. For really high temperatures, conduction and convection are completely negligible. In the same way radiation will be negligible for low temperatures. How important of a role the radiation will play in this particular thesis remains to see from the simulation results.

### 2.1.6 Thermal Resistance

Another important and handy parameter in the thermal design area is the *thermal resistance*. The understanding of this variable is very important later on when analysing the simulation results. Thus the following section is devoted to explain it in theory and in practice.

The thermal resistance is a way to describe how “hard” it is for the heat to transfer from one point to another in a certain scenario. It can also be described as the *temperature difference across a structure due to the heat that flows through it*. That is, if the thermal resistance of a body is high, the temperature will differ greatly from one side to the other when heat energy flows through the body. Thermal resistance is a good way for measuring how efficiently the heat is transported through a number of objects. For instance the heat could travel from an electronic component that generates heat, through a PCB, through a covers and out to the surrounding air. In other words, thermal resistance is the reciprocal to thermal conductance.

The relations between thermal resistance, heat flux and temperature difference is analogue to the relations in Ohm’s law:

$$I = \frac{\Delta U}{R} \quad (2.10)$$

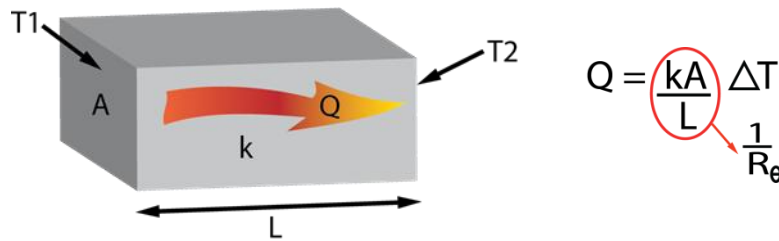
Where I is the current,  $\Delta U$  is the electrical potential and R is the electrical resistance. Now imagine that instead of electrical current that flows we have heat energy that flows, and instead of an electrical potential we have a temperature potential, that is, a temperature difference. Finally, instead of an electrical resistance we have a thermal resistance,  $R_\theta$ , and the relations between these three variables will be:

$$Q = \frac{\Delta T}{R_\theta} \quad (2.11)$$

Thus the unit for thermal resistance  $R_\theta$  is degrees Celsius per Watt [ $^\circ\text{C}/\text{W}$ ].

Observe the similarity of eq. 2.10 and eq. 2.11. This is a convenient approach for studying heat flow, as will be shown later, for thermal designs of electrical devices.

To get a better understanding of what factors the thermal resistance really depends on, study figure 2.5 below. Heat flows through a simple solid box with the cross section A. The equation to the right of the picture shows how the thermal resistance contains information about the cross section A, the critical length L and the thermal conductivity k of the body:



**Figure 2.5** Thermal resistance could be understood by studying heat through a solid body

Referring to the equation in the picture, the thermal resistance could be found as:

$$R_{\theta} = \frac{L}{Ak} \quad (2.12)$$

Equation 2.12 is intuitively easy to understand; the resistance increases with the length of the object, decreases with the area through which the heat flows, and decreases with the conductivity k. This is the thermal resistance for a *conduction situation*, but it could be found in the same way for convection and radiation.

When thermal resistances occur in series, they are *additive*. So when heat flows through two components, each with a thermal resistance of, for instance, 1 °C/W, the total resistance is 2 °C/W.

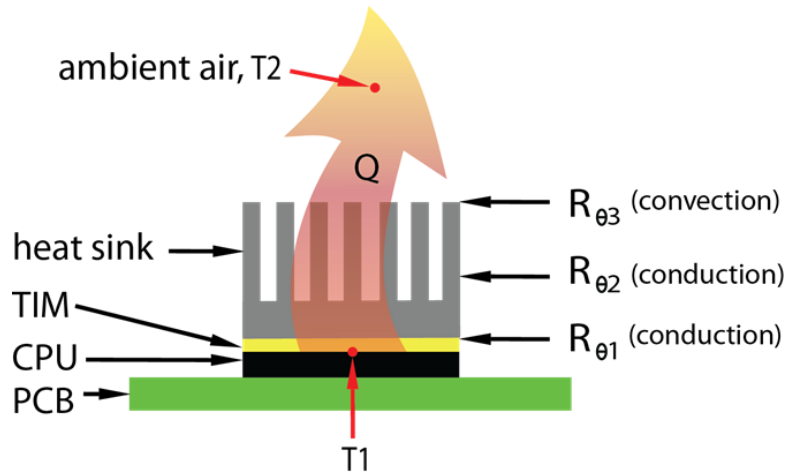
The thermal resistance could be used for finding for example the temperature of a microchip on a PCB, only with information about the room temperature and the electrical power consumption of the microchip. By knowing the conductivity k and the geometry of all the materials between the chip and the ambient air, the thermal resistance could be calculated for each step from the chip to the surroundings. The thermal resistances are then added together and from eq. 2.11 we get:

$$Q = \frac{\Delta T}{R_{\theta}} = \frac{T_{chip} - T_{ambient\ air}}{R_{\theta_1} + R_{\theta_2} + R_{\theta_3} + \dots} \quad (2.13)$$

Since Q is the known number of watt that the chip consumes,  $T_{circuit}$  can be calculated from the formula above.

As an example, study the figure below:





**Figure 2.6** Heat flows from a CPU chip, through a TIM material, through a heat sink and dissipates out to the surrounding air.

The picture shows a cross section of a PCB. On the PCB a microchip is mounted, in this case a CPU chip. On the chip a TIM is attached. TIM stands for Thermal Interface Material and is usually a thin film with relatively high thermal conductivity, placed between two objects between which you want a high thermal energy flow. On the top there is a heat sink, from which the heat then is traveling out to the surrounding air. The air temperature is assumed to be known, and thus the temperature  $T_1$  at the top of the integrated circuit can now be found with the equation:

$$Q = \frac{\Delta T}{R_{\theta}} = \frac{T_1 - T_2}{R_{\theta 1} + R_{\theta 2} + R_{\theta 3}} \quad \rightarrow \quad T_1 = Q(R_{\theta 1} + R_{\theta 2} + R_{\theta 3}) + T_2 = \dots$$

This is the typical way for, in a theoretical approach, predicting how hot the integrated circuit is going to be. It will however always be merely an approximation of the reality, since for instance the radiation is not taken into account [1].

## 2.2 Finite Element Analysis Fundamentals

*The Finite Element method is used in a lot of engineer computer software like CFXDesign and COMSOL. The software calculates the wanted value from the meshed body and the used equation feature in the software. To calculate heat flow CFXDesign is a specialized tool that can be connected to The CAD software to update changes in the design throughout the simulation. In the software a meshing grid is retrieved. The grid contains element geometries in shapes of triangles. Each triangle is made of the nodal points that are described with coordinates. From every coordinate a value is retrieved from the different relevant conditions that are established like material, temperature, heat generation or emissivity.*

When differential equations become too complicated in engineering mechanics the finite element method is a numerical method where the differential equations are solved numerical. The region where the differential equations are based on can be one, two or three dimensional. The region is divided into smaller parts where the parts being calculated one at a time. It is too rough to take for granted that the variable varies in a linear matter over the entire region. The total image of the elements is called the finite element mesh.

The different element can be divided into groups for having the same behaviour. These elements can be calculated with the same method and rules. You can simplify the calculation by assuming boundary conditions to be linear. The finite element method can be used in several different problems concerning heat conduction, torsion of elastic shafts, diffusion, water flow and elastic behaviour of bodies.

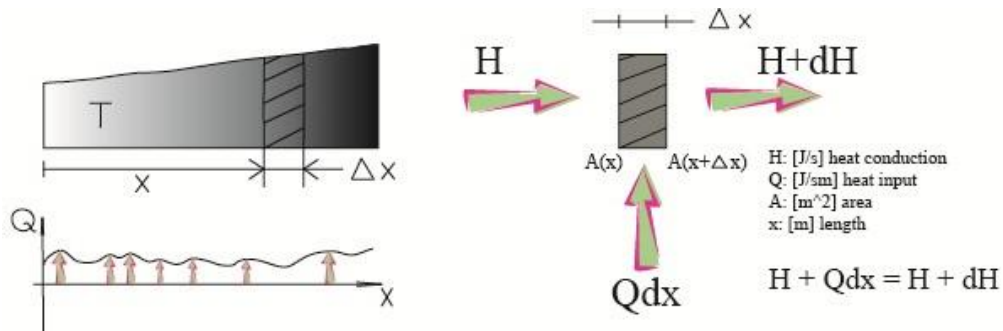
To obtain a solution the calculations starts for a few elements. The steps for the finite element method as follows:

1. Establishment of stiffness relations for each element. Material properties and equilibrium conditions for each element are used in this establishment.
2. Enforcement of compatibility, i.e. the elements are connected.
3. Enforcement of equilibrium conditions for the whole structure, in the present case for the nodal points.
4. By means of 2. and 3. The system of equations is constructed for the whole structure. This step is called assembling.
5. In order to solve the system of equations for the whole structure, the boundary conditions are enforced.
6. Solution of the system of equations.

Since FE is a numerical method the simple one dimensional equation must therefore be rewritten in equivalent form. The simple form is referred to as strong form and the equivalent as weak form.

### 2.2.1 Strong Formulation of One Dimensional Heat Flow

The object is considered with a nonlinear temperature  $T(x)$ , along the one-dimensional image. Heat,  $Q$  can be internally produced or transferred from the surroundings. The thickness is small in relations to its length. The problem are time independent in this case, therefore it is assumed that total heat flow per unit time



**Figure 2.7** Heat transfer through a body

$$\frac{dH}{dx} = Q$$

$$H(x) = A(x) \cdot q(x)$$

by definition

$q$  is the flux and is defined as the energy (J) that is transported a unit area (m<sup>2</sup>) per unit time (s),  $q$  is positive in the  $x$ -direction.

With  $H(x)$  as defined will give:

$$\frac{d}{dx}(A \cdot q) = Q$$

The relation which describes heat flow within the material  $T$  is the temperature and  $k$  the thermal conductivity of the material. Fourier's law of heat conduction is

$$q = -k \cdot \frac{dT}{dx}$$

This implies that  $q > 0$  in accordance with the fact that heat flows from hotter to cooler regions. This leads to following differential equation:

$$\frac{d}{dx}\left(A \cdot k \frac{dT}{dx}\right) + Q = 0 \quad 0 \leq x \leq L$$

If  $A \cdot k$  is constant this will become:

$$A \cdot k \cdot \frac{d^2 T}{dx^2} + Q = 0 \quad 0 \leq x \leq L$$

To solve the differential equation the boundary conditions is required at the end of the body. At the end it is assumed that either the temperature  $T$  or the flux  $q$  is given. If the object is completely insulated the value of flux will be zero. The boundary condi-

tion can also be some given value of flux ( $q$ ) at the point  $x = 0$ , while at  $x = L$  the temperature  $T$  is given.

Strong formulation of one dimensional heat flow:

$$\frac{d}{dx} \left( Ak \frac{dT}{dx} \right) + Q = 0; \quad 0 \leq x \leq L$$

$$q(x = 0) = - \left( k \frac{dT}{dx} \right)_{x=0} = h$$

$$T(x = L) = g$$

where  $h$  and  $g$  are known quantities.

### 2.2.2 Weak Formulation of One Dimensional Heat Flow

The weak formulation is a reformulation of the strong form and from this we will obtain the Finite Element Method.

The Finite Element Method is defined from a strong formulation from a simple heat transfer problem. This particular form is not possible to work with in an iterative process where the result is the temperatures in the different parts of the body. One way of define the finite element method is to rewrite the strong form to a weak form. This weak formulation is a very awkward expression at first site although it is necessary. To see the whole transformation from strong form to weak form see appendix A.

From the one dimensional case, the definition of one-dimensional definition of the temperature, the definition of  $\bar{B}$  and the former expression with the weak formulation gives

$$\left( \int_a^b \frac{dv}{dx} Ak \bar{B} dx \right) \bar{a} = -[vAq]_a^b + \int_a^b vQ dx \quad \text{The weak formulation}$$

Mainly there are three different weigh functions point collocation method (based on Dirac's delta function), the least square method and the Galerkin method. Of these three methods Galerkin and least square are the more exact. The least square always give a symmetric matrix and Galerkin does not. Since the weak formulation is used combined with the weigh function the Galerkin method will eventually give a symmetric matrix. That is why the Galerkin method is being used with its compatibility with the weak formulation.

$$v = \bar{N} \bar{c} \quad \text{The Galerkin weigh function}$$

Since  $v$  is a scalar the expression can be rewritten as

$$v = \bar{c}^T \bar{N}^T$$

This implies that

$$\frac{dv}{dx} = \bar{c}^T \bar{B}^T \quad \text{where} \quad \bar{B}^T = \frac{d\bar{N}^T}{dx}$$

Inserting the rewritten Galerkin expression and the following two in the weak formulation will give (using the fact that  $\bar{c}^T$  is independent of  $x$ )

$$\bar{c}^T \left[ \left( \int_a^b \bar{B}^T Ak\bar{B} dx \right) \bar{a} + [\bar{N}^T Aq]_a^b - \int_a^b \bar{N}^T Q dx \right] = 0$$

As this expression should hold for arbitrary  $\bar{c}^T$ -matrices, it is concluded that

$$\left( \int_a^b \bar{B}^T Ak\bar{B} dx \right) \bar{a} + [\bar{N}^T Aq]_a^b - \int_a^b \bar{N}^T Q dx = 0 \quad \text{The FE formulation}$$

The FE-formulation can be written in a more compact version, the following matrices is defined

$$\bar{K} = \int_a^b \bar{B}^T Ak\bar{B} dx$$

$$f_b = -[N^T Aq]_a^b$$

$$f_l = \int_a^b N^T Q dx$$

$\bar{K}$  is called the stiffness matrix and it is a square  $n \times n$  matrix.  $f_b$  is the boundary vector and  $f_l$  is the load vector. These vectors have the dimensions  $n \times 1$ . The vectors for boundary conditions ( $f_b$ ) and load ( $f_l$ ) can be defined as the force vector  $f$ .

$$\bar{K}\bar{a} = \bar{f} \quad \text{The compact FE formulation}$$

When the equations are numerically solved  $\bar{a}$  will then be known. By the previous mentioned equation  $T = \bar{N}\bar{a}$  the temperature will be obtained in the different nodal points.

The stiffness matrix  $\bar{K}$  comes from the definition of it and the definition of  $\bar{B}$ , which was mentioned earlier. The components are described below.

$$\bar{K} = \begin{bmatrix} \iint_a^b \frac{dN_1}{dx} Ak \frac{dN_1}{dx} dx & \iint_a^b \frac{dN_1}{dx} Ak \frac{dN_2}{dx} dx & \dots & \iint_a^b \frac{dN_1}{dx} Ak \frac{dN_n}{dx} dx \\ \iint_a^b \frac{dN_2}{dx} Ak \frac{dN_1}{dx} dx & \iint_a^b \frac{dN_2}{dx} Ak \frac{dN_2}{dx} dx & \dots & \iint_a^b \frac{dN_2}{dx} Ak \frac{dN_n}{dx} dx \\ \dots & \dots & \dots & \dots \\ \iint_a^b \frac{dN_n}{dx} Ak \frac{dN_1}{dx} dx & \iint_a^b \frac{dN_n}{dx} Ak \frac{dN_2}{dx} dx & \dots & \iint_a^b \frac{dN_n}{dx} Ak \frac{dN_n}{dx} dx \end{bmatrix}$$

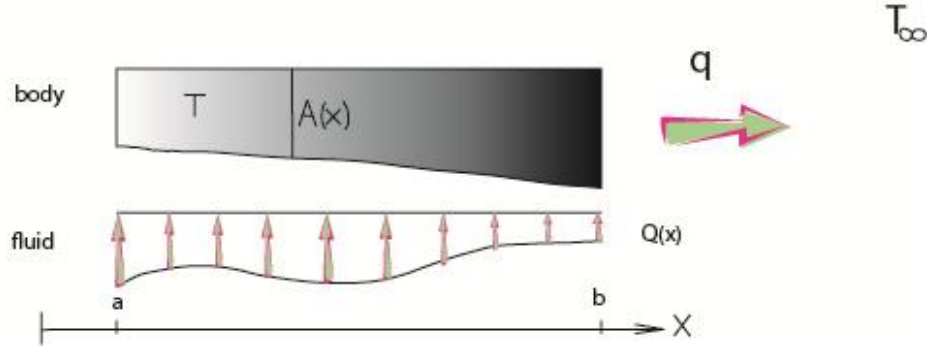
Likewise is the boundary vector and load vector definition below.

$$\bar{f}_b = \begin{bmatrix} [N_1 A q]_a^b \\ [N_2 A q]_a^b \\ \dots \\ [N_n A q]_a^b \end{bmatrix}; \quad \bar{f}_l = \begin{bmatrix} \iint_a^b N_1 Q \, dx \\ \iint_a^b N_2 Q \, dx \\ \dots \\ \iint_a^b N_n Q \, dx \end{bmatrix}$$

### 2.2.3 Heat Flow with Convection

Convection is heat that is transported through fluid motion around a body see section 2.1.2. The faraway temperature around the body is assumed to be uniform. The temperature at the surface of the body is given by  $T$ . The difference of the surrounding temperature and  $T$  controls the heat flow between the body and the fluid. To calculate this “the Newton’s convection boundary condition” is used.

$$q_n = \alpha(T - T_\infty)$$



**Figure 2.8** Convection through a body where  $q$  is the flux

$q_n$  is the flux through the boundary with the outer unit vector  $\mathbf{n}$ .  $\alpha$  is the parameter that is dependent of the type of fluid, surface conditions and fluid velocity, it is called “the convection coefficient” with the dimension  $[\frac{J}{m^2 s^\circ C}]$ .  $\alpha$  is a positive quantity, implying that when the temperature difference  $T - T_\infty$  is positive, then the flux becomes positive.

To demonstrate an example a thin body is used with convection at the end of the body.

$$q_n = \alpha(T - T_\infty)$$

The boundary vector  $f_b$  in the FE formulation can be written as:

$$f_b = -[N^T A q]_a^b = -(N^T A q)_{x=b} + (N^T A q)_{x=a}$$

The convection occurs at the end of the body, then  $q_n = -q(x = a)$ . In general the approximation is  $T = \bar{N}\bar{a}$  and that makes the temperature at  $b$  as  $T_{x=b} = \bar{N}_{x=b}\bar{a}$ .

This leads to the flux at the right hand of the body

$$q_{x=b} = \alpha \bar{N}_{x=b} \bar{a} - \alpha T_\infty$$

The boundary vector  $\bar{f}_b$  can hereby be written as

$$\bar{f}_b = -\alpha (A\bar{N}^T\bar{N})_{x=b} \bar{a} + \alpha T_\infty (A\bar{N}^T)_{x=b}$$

According to the previous FE formulation the expression can be written like this in consideration of convection

$$(\bar{K} + \bar{K}_c) \bar{a} = \alpha T_\infty (A\bar{N}^T)_{x=b} + (N^T A q)_{x=a} + \bar{f}_1$$

$$\text{where } \bar{K}_c = \alpha (A\bar{N}^T\bar{N})_{x=b}$$

The difference from where the original stiffness matrix is  $\bar{K}$ , to convection criteria stiffness matrix  $\bar{K} + \bar{K}_c$  is the singularity. The original matrix is singular but not the special case with convection. A conclusion have to be drawn from this, the heat flow goes only in the perpendicular direction of the x-axis. To solve the stiffness some criteria must be fulfilled. The heat Q is positive when it is supplied to the body. It is necessary to assume that the temperature difference is much larger in the x-direction of the fin compared to the temperature difference perpendicular to the x-axis. Otherwise the flow will not be one-dimensional as the approximation [2].





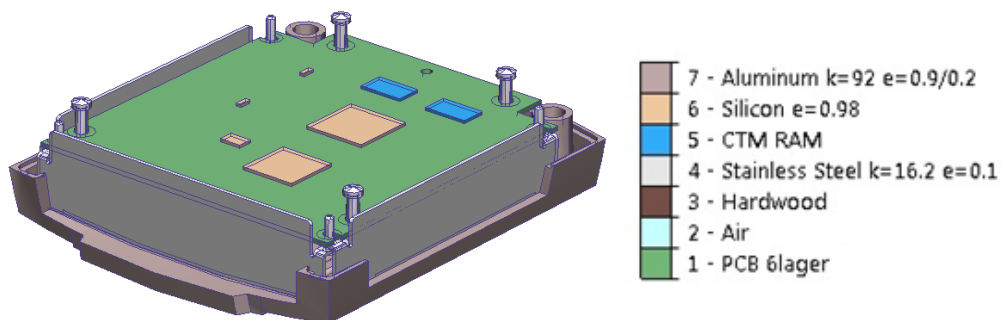
### 3 CFDesign – A Brief Introduction

*The simulation tool used in this project is called CFDesign, an application used specifically to simulate heat and fluid dynamics. For better understanding of the simulation chapter later on, a brief introduction of the interface of the software will be given below.*

The basic idea is to launch an already complete CAD-model into CFDesign. Once inside the software, materials and boundary conditions can be defined by the user. CFDesign will then generate a mesh to the model, separating it into smaller elements which are then used for the finite element method analysis. A more detailed description of this process will follow down below.

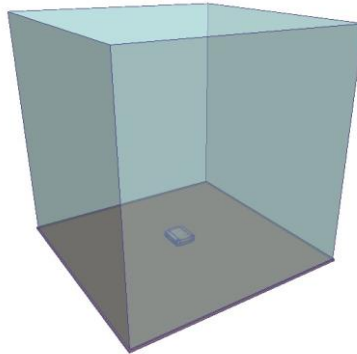
#### 3.1 Applying Materials

Materials are applied for each and every part of the model according to the real scenario, together with the material parameters needed by the software to simulate a specific scenario such as heat conductivity and emissivity. (See chapter 2) The figure below illustrates an example of a simulation model once it is inside CFDesign, where different colours represent different materials; see the material legend to the right.



**Figure 3.1** Materials applied to the model

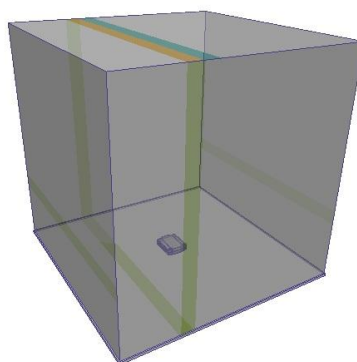
The air surrounding the model is usually simulated as a large cube of air with the model placed inside of it. The sides of the cube are set to be about ten times the length of the model. The model is here placed on a wooden board in the bottom of the cube. By simulating the air around the model the convective air flow around it can also be studied. The picture below shows the model inside the air cube:



**Figure 3.2** The model inside the air cube

### 3.2 Boundary Conditions

Boundary conditions are then applied. Boundary conditions are necessary information for solving the finite element analysis. This could for example be the ambient air temperature, the ambient air pressure or how much heat the electric components are generating. Depending on what scenario that is set up, the number of boundary conditions varies. Sometimes a solution could be found even if you leave some boundary conditions out, but in general you receive a better result the more information you can provide about the reality. More about boundary conditions will be described later on in the study. In CFDdesign the boundary conditions are applied on surfaces or on volumes, represented with stripes in different colours for different types of boundary conditions. This is illustrated in the picture below:



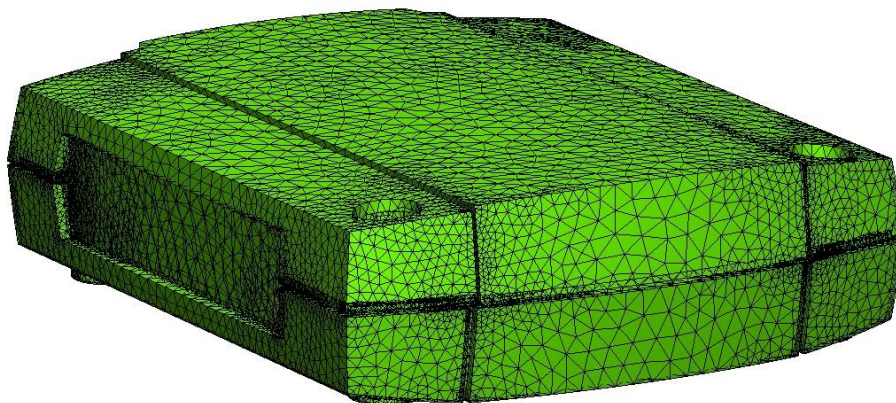
**Figure 3.3** The coloured stripes represent the boundary conditions in the simulation

### 3.3 The Mesh

CFDesign will now generate the mesh, that is, the network system of nodes covering all surfaces of the model. The nodes will form the matrix of mathematical coordinates needed for the finite element analysis. Each and every node will after the simulation is solved contain information such as temperature, fluid motion direction and pressure.

A finer mesh will generally result in more accurate results. However, a finer mesh will also demand more processor capacity during the solving process and thus take longer time to solve. Of course there is always a limit for how much accuracy that is needed, so a balance between fine and coarse has to be found for each mesh. A common way for finding an appropriate concentration on the mesh is first to estimate a mesh and then do a simulation. After this the concentration is raised, after which a new simulation is done. If the results between the two simulations do not differ significantly, this means that an even finer mesh would be unnecessary. If they do in fact differ a lot, a new, finer, mesh should be tried out.

In areas where bigger geometrical and temperature gradients occur, that is, where the geometry is relatively complex or the temperature varies a lot, the mesh need to be finer. Otherwise these important gradients will not be “captured” in an appropriate way. Think about it as a photo with for instance a white background and a flower in the middle. If one was to choose in what area the highest picture resolution would be, it would be better to have a high resolution on the flower since the colours varies a lot there. On the background on the other hand, it does not really matter if the resolution is low since it is all white anyway. Thus the mesh should, analogue to the picture with the flower, be applied with different concentration for different areas, to avoid wasting processor power on having a fine mesh on surfaces where it is not really needed. Below is a picture of the model where the mesh is showed. Observe how the mesh is finer around the more complex geometries.

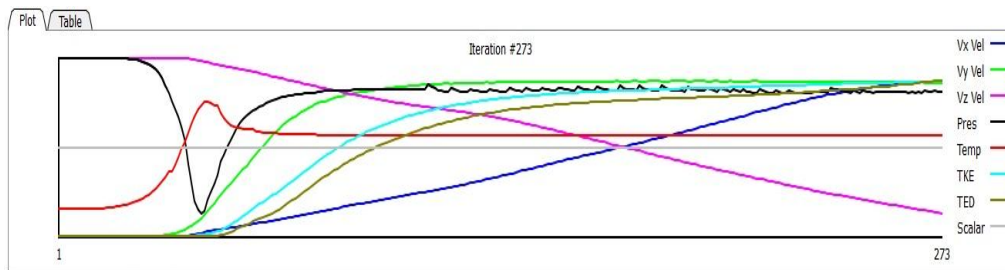


**Figure 3.4** Mesh applied to the model.

### 3.4 Solving the Scenario

Once the mesh is applied the analysis can be initiated. The calculation time will differ greatly depending on mesh concentration, geometry complexity and boundary conditions. Once a converged solution for the simulated scenario has been found, a selection of tools in CFDesign is used to analyse the result. The application will now provide information about areas like temperatures, heat flux and how the fluid is moving due to convection.

As the solving process is advancing, a convergence plot appears at the bottom of the screen, see the illustration below. Here the user can follow the solving process by interpreting the information that the graphs provide.

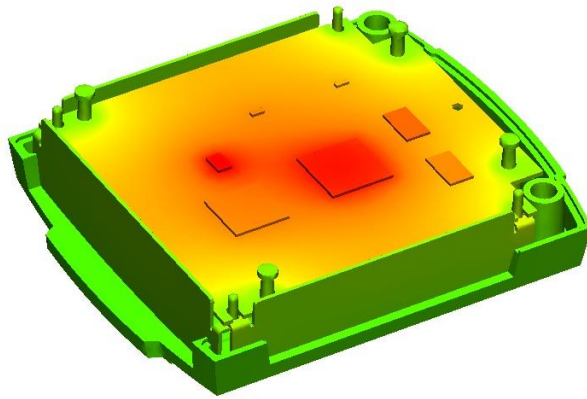


**Figure 3.5** The plots show how important quantities vary during the solving process

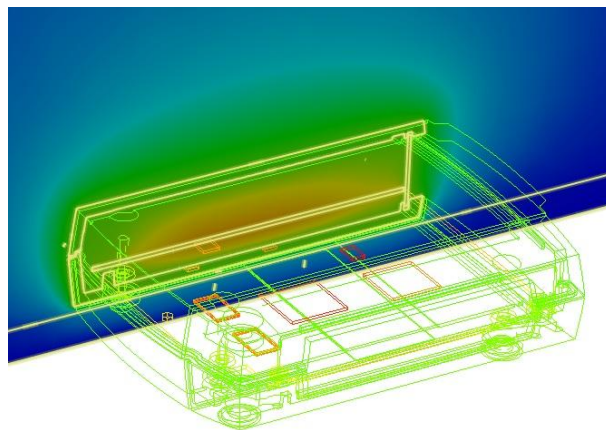
Every graph in the convergence plot represents an average value of an important quantity in the simulation. The most relevant of these are fluid velocity, pressure, temperature and kinetic energy. The y-axis in the convergence plot represents the magnitude of the quantity, the x-axis could be seen as time, although what it really represents is the number of iterations that the solver has done so far.

The ultimate goal for a FEM problem is that all the magnitudes will *converge*, that is, their values *stabilise* and do not iterate back and forth. In the plot this can be seen when the graphs stop alternating up and down and become constant with the x-axis. However the main goal of the simulations in *this* study will be to find certain temperatures. As a result it is in this case only the temperature graph that really has to converge (the red graph in the convergence plot). Thus it will sometimes be a good decision to abort the solving process before the all the graphs have converged, as long as the temperature graph seems stable. This is not a rule of thumb though and will depend on the situation. It will take training and experience to interpret the convergence plot correctly; it is an extensive area and will not be discussed further in this study.

The illustrations below are some examples of what the result in CFDesign could look like.



**Figure 3.6** The colours represent the surface temperatures of a device where red are the hottest and green are the coolest



**Figure 3.7** A cross section shows how the air temperature varies inside a device

### 3.5 Monitor Points

Sometimes it can be favourable to keep an extra track of certain points in the scenario. These points could then be declared as monitor points. As a simulation is running the same quantities as could be seen in average for the whole scenario can also be seen for only the monitor points. This is helpful if the user wish to locate convergence problems or just for some reason wish to study a specific quantity in a specific point. [3]



## 4 The Test Product

*In order to validate a simulation some kind of reference values are needed that represents the reality that is to be simulated. By comparing these reference values to the simulation results it can be found out how close to reality the simulation software manages to simulate. Thus a specific AXIS product was chosen to act as a test object throughout the validation process. In this chapter the reasons for choosing this specific test product for this study will be discussed, together with the function as well as the geometries of the products.*

### 4.1 Choice of Test Product

A video encoder was chosen as test product. The encoder only consists out of one PCB enclosed in a boxlike aluminium cover. Its simple geometry allows easy modifications which is why it became an appropriate choice for a test product. To choose one of the much more complex camera products would result in bigger sources of error due to their complexity. Minimizing sources of error is really important during the validation process, since the sources of error that occur during the validation will remain through all the other simulations in the study.

The video encoder that was chosen was also a particularly simple one, instead of the more common type with four CPU:s this encoder only had one. The reason for choosing the smaller one was to minimize the sources of error during the heat tests; With four CPU:s the error would be four times as big since there always will be some inaccuracy when measuring the temperature of a CPU.

Below is a photo of the product. The cover is made of aluminium. The interiors consist of a single PCB.



**Figure 4.1** The video encoder

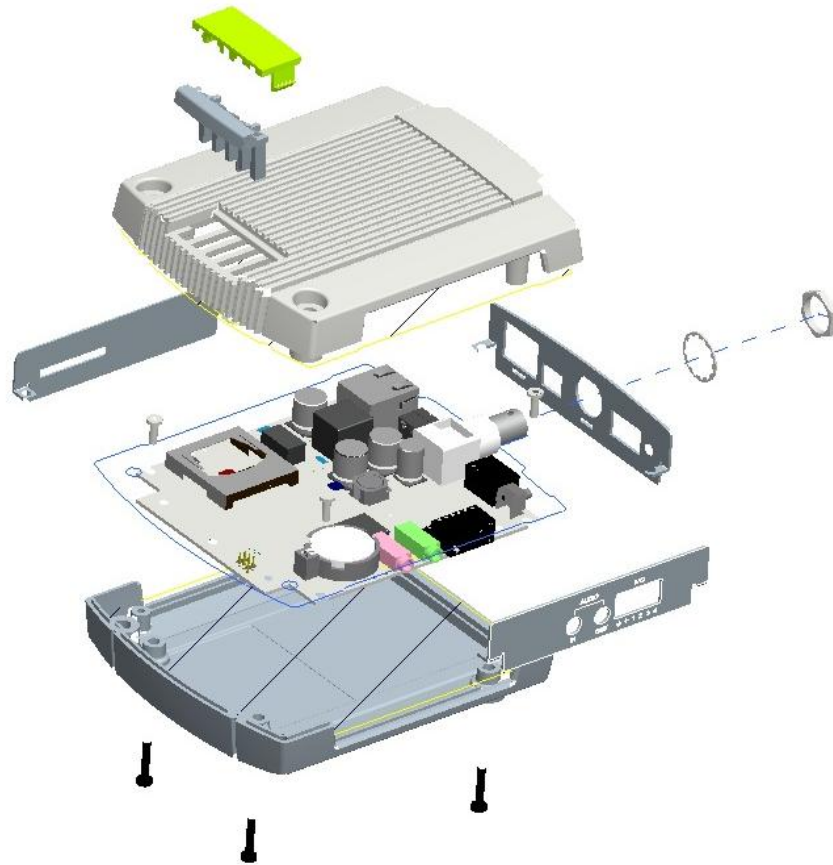


## 4.2 Function and Usage

What the video encoder does is to transform analogue data into digital data. Many companies still use analogue surveillance cameras and have no intentions to swap over to a digital system since the old system works just fine. However, they are interested in using AXIS software to analyse, store and send the information from their cameras. To do this, the information must be transformed into digital signals, which is where the encoder enters the picture.

## 4.3 Geometry

In the figure below an exploded view of the device is shown. It contains of two aluminium cover parts, three steel side panels, one horizontally placed PCB and eight steel screws. The aluminium parts, from here on referred to as the cover, has the approximate dimensions 100x100x30 mm. The green part at the top is a transparent plastic piece that covers a number of led lights on the top of the product. On the PCB in the middle a number of electric components are attached.



**Figure 4.2** Exploded view of the encoder

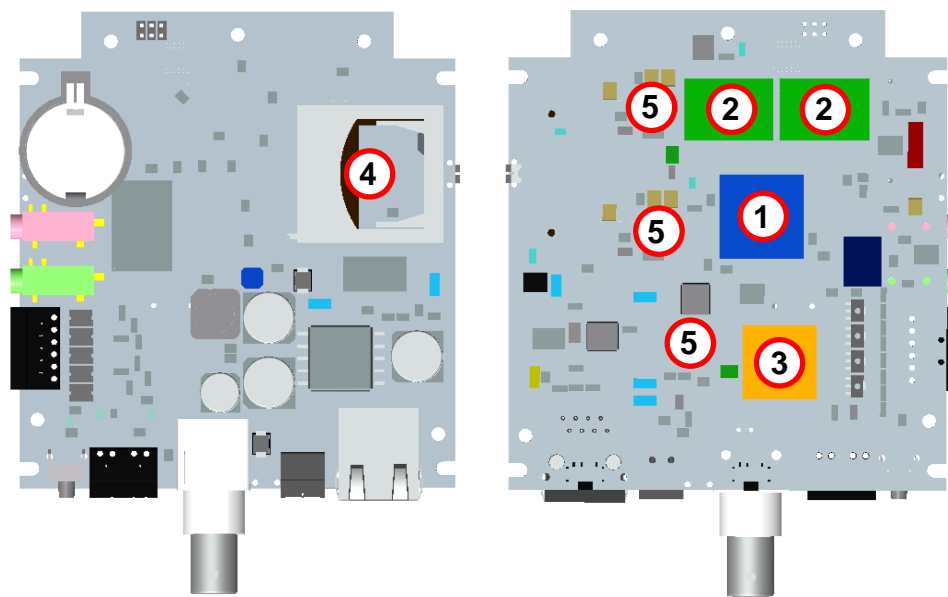


#### 4.4 Interiors

All the parts in the test product were not used in the simulation. In this project only active components that consume a considerable amount of power were of interest, since these components represent almost all the heat generation. The heat generation of the other components will be approximated as equally spread out over the PCB, and thus these will not need to be simulated. To represent these other components later on in the simulation, the whole PCB will be set to generate their combined power generation.

It is important for the reader to understand that no energy leaves the encoder in any form but heat, and thus the power consumption of each and every active component is directly proportional to that components heat generation.

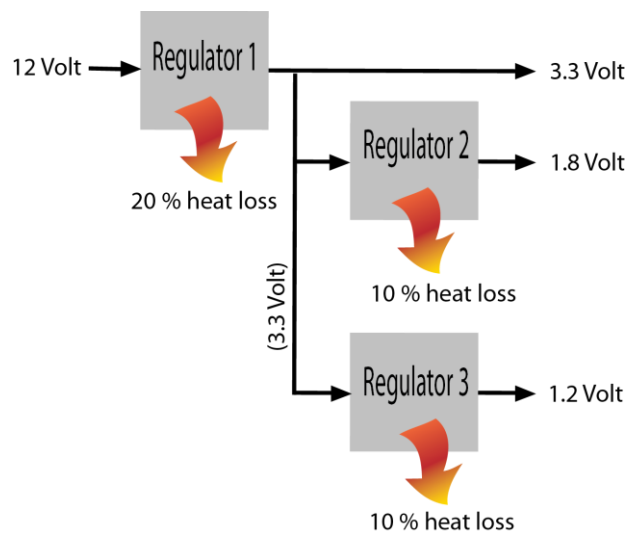
Below is a picture of a CAD-model of the PCB. The numbers in the illustration represents the important components, which are explained in the list at the next page.



**Figure 4.3** The PCB from above (left) and from below (right)

Listed below is a brief description over the components that are taken into account during the simulation. Although the very role that these play is of no direct importance for our simulation, it is still good to have some understanding of them. The numbers in this list below represents the numbers in the figure on the last page.

1. CPU – The main processor of the device. The CPU represents over 40 percent of the total power consumption, and will thus have the highest heat generation by far.
2. Memory – Working memory.
3. Video chip – This is where the actual transformation from analogue to digital signals takes place.
4. Ethernet – In this integrated circuit the incoming Ethernet information are dealt with, and its power consumption and thus heat generation will therefore strongly depend on the amount of activity there is between the encoder and the Ethernet.
5. Electrical regulators – The incoming voltage to the encoder lies somewhere between 8 and 20 Volt. Since this voltage is too high for the internal components, it must be modified into three smaller ones in order to supply every component in the encoder with the voltage it needs to operate. A wiring diagram for how this is done can be seen below.



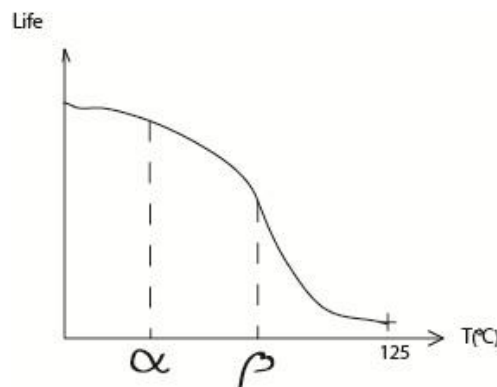
**Figure 4.4** Wiring diagram for the regulators on the PCB

As figure 4.4 indicates, the three resulting voltages are 3.3, 1.8 and 1.2 volt. The process of regulating voltage is not done without significant losses, and these can be expressed in percent of the incoming power. As the incoming voltage for regulator two and three is relatively small, their heat generation will not have significant effect on the total picture, whilst regulator one with its high incoming voltage and 20 percent loss will have a great impact. All of them will however be considered to be active components. They will from now on be referred to as regulator one, two and three.

After choosing a test product the validation and the heat testing were initiated. Since there is a chance that the products take damage during the heat tests a number of video encoders were dedicated for the tests.

#### 4.5 Critical Temperature Values

This section will describe how the components are affected when operating in critical temperatures. Even if a component does not break, high operating temperatures will cause the components lifetime to drop. The CPU chip will be used as an example in the figure below, where the relation between lifetime and operating temperature is shown.



**Figure 4.5** Life for the CPU depending of operating temperature

The CPU in the encoder is made for withstand up to 125 °C before it breaks. Between the temperature  $\alpha$  and  $\beta$  the lifetime suddenly drops. These temperatures are always difficult to know for a certain chip since the lifecycle of a chip spans over many years. For the CPU however, a good measure would be that if the operating temperature exceeds approximately 70 °C further thermal optimization has to be done.



## 5 Validation

*This chapter contains the validation process where it was decided whether the simulations in CFDesign was able to reflect the reality with sufficient accuracy or not. The chapter is divided into three parts. The first part describes a number of heat tests that were performed on the test product where temperatures were measured at strategic locations. The second part explains what preparations that has to be done before running a simulation in CFDesign. In the third and final part the exact same scenario as took place during the heat tests are simulated in the software. The simulation results are then compared to the heat test results. If they match, the simulation can be stated as validated. If not, troubleshooting and correction will be necessary.*

*Of the three parts only the second part, the simulation preparations, is necessary for running a simulation in CFDesign. The other two are done only in this study to validate. Validations like this will of course not be possible if simulating hypothetical, non-existent products.*

### 5.1 Heat Testing

The heat test setup, the test procedure and the test results will now be presented. Finally a thermal imager was used to get further information about the thermal situation of the PCB.

#### 5.1.1 Test Setup

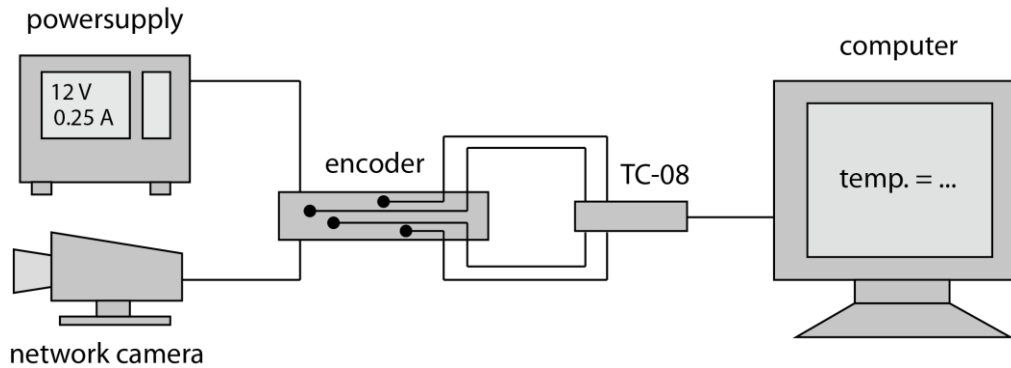
Eight temperature sensitive probes were attached on various places of the encoder. In order to receive a good overview of the thermal activities in the product, the probes should be placed both at critical hot spots and in places representing the environment. Environmental spots in this case were the ambient air temperature inside and outside the covers. Critical spots were on top of active components and hot spots on the PCB. The probes were attached with heat conducting paste and isolating tape. The conducting paste improves the thermal contact between the component and the probe, letting the probe register close to the exact temperature of the surface where it is attached. The isolating tape keeps the probe in place and its isolating properties keep the tape from transferring too much heat away from the spot.

The eight probes were then connected to a TC-08, a small device which provides a computer with the temperature information via USB. In the computer the information was displayed using the application Picolog Recorder, where the temperatures of the probes were sampled continuously and recorded every second.

## 5 Validation

An analogue camera was connected to the encoder, with the only purpose to provide the encoder with something to work with. After converting the information to digital signals, the encoder then sent this information to the computer, which displayed the camera view.

The illustration below explains how the test was set up:



**Figure 5.1** Wiring diagram for the heat test

Below is a photo shown, taken from the laboratory. The blue device to the left is the TC-08, the test product is placed in the middle and to the right is the computer used for temperature sampling.



**Figure 5.2** Setup for the heat test

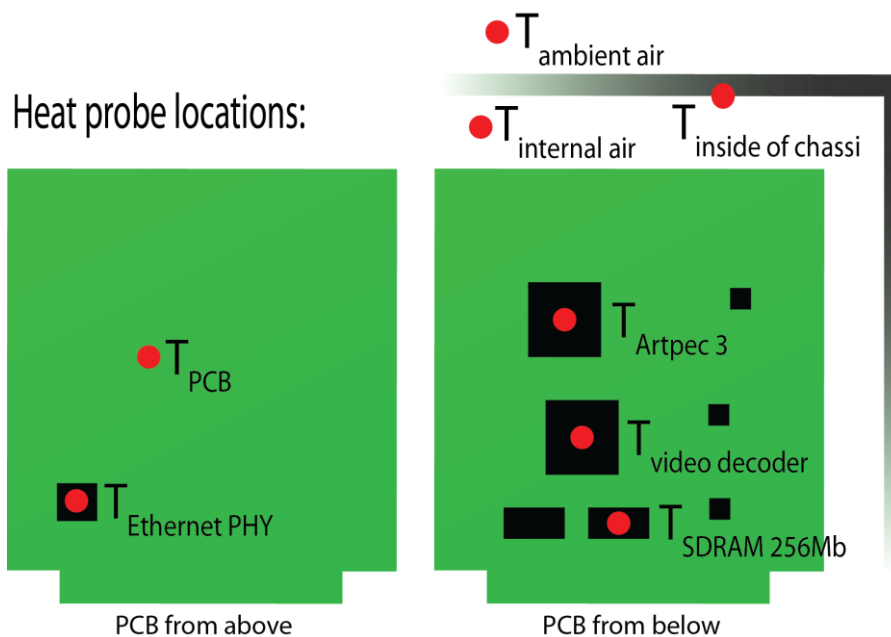
### 5.1.2 Running the Test

After the initiated temperatures were registered, the encoder was powered up with an adjustable power supply so that the exact input voltage could be controlled. As soon as the encoder started to operate the temperatures started to rise, and after approximately one hour steady state occurred and the temperatures kept a constant value.

To receive even more information about how the geometry affects the temperatures, the top cover was then removed from the encoder in the end of the test, and when steady state once again occurred the temperatures noticed.

The incoming voltage during the test was set to 12 Volt, and the current was noted as 0,25 Ampere. These numbers was used later on for finding the power consumption for the active components. Observe that the power consumption for each and every component could not be measured during the heat test; solely the total power consumption for the product can be measured.

A number of heat tests as described above were performed. In this report only the results from some of them are shown, since these results will be sufficient to verify that our simulation was accurate. The probe placements for these results are shown below:



**Figure 5.3** Locations of heat probes on test product

### 5.1.3 Results

In the result table shown below the temperatures from the four most relevant moments are shown. Those moments are:

- **The initiative temperature, when the decoder is unpowered.**  
These temperatures can be good reference temperatures during the analyses later on in the study.
- **After 30 minutes, when temperatures are closing in on steady state.**  
These values give a hint of how fast the temperatures close in on a steady state condition
- **After 60 minutes, when steady state appears.**  
These are the most important values; they represent the temperatures when the product is at full operation.
- **After the top cover has been removed and steady state has appeared again.**  
These values provide extra information; with these an extra validation simulation can be made if necessary, where the cover is removed.

**Table 5.1** The measured temperatures from the heat test in the laboratory

Measured temperatures	Temp. unpowered	Temp. after 30 min [°C]	Temp. after 60 min [°C]	Temp without top covers [°C]
<b>1 CPU</b>	23,9	57,0	<b>57,7</b>	55,6
<b>2 Video chip</b>	23,9	35,5	<b>37,0</b>	32,7
<b>3 Memory</b>	23,9	41,5	<b>42,5</b>	41,8
<b>4 Ethernet</b>	23,8	39,1	<b>40,0</b>	37,0
<b>5 PCB</b>	23,9	40,3	<b>42,3</b>	40,4
<b>6 Ambient internal air</b>	24,0	36,9	<b>38,2</b>	28,6
<b>7 Inside covers surface</b>	23,0	29,8	<b>31,0</b>	24,5
<b>8 Ambient air</b>	23,0	23,3	<b>22,9</b>	23,0

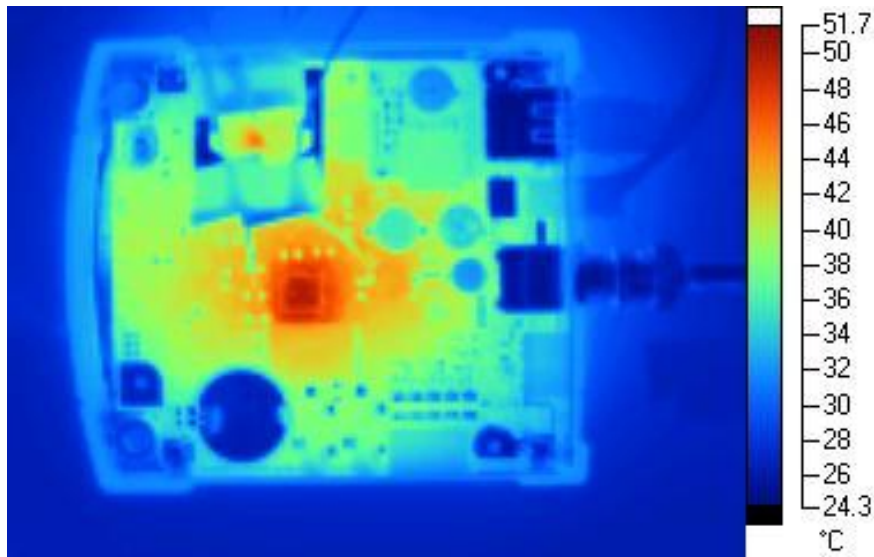
This chart will be the reference later on in the validation process. In this study only the values in the chart that are marked in bold were needed in the validation.



#### 5.1.4 Thermal Imager

A thermal imager was also used to better be able to locate eventual hotspots, and to get a better picture of the temperature gradients over the PCB. The thermal images give a good hint of what the thermal situation looks like inside the product, and conclusions can be drawn about the temperature variations. Two pictures on the PCB will be shown here; one from above and one from below.

Below the photo from above is shown. After the encoder was powered up and the temperatures had stabilized, the top cover was removed and the picture was taken. This had to be done quickly, since the temperatures start to change as soon as the cover is removed.



**Figure 5.4** Thermal image picture of the PCB from above

Considering the red area in the middle one may think that an active component is placed here. This is not the case however, since what is seen is the heat coming from the CPU on the other side of the PCB. The red area above the middle of the picture on the other hand indicates the placement of the Ethernet microchip.

## 5 Validation

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When the temperatures once again were stable, the PCB was removed from the bottom cover, turned upside down and a new picture was taken. This as well was of course done as quickly as possible. It should be mentioned that since this second picture represents a state when the top cover is removed, the temperatures here are somewhat lower than usual. The big red area in the middle represents the CPU chip. The red area to the right of the CPU represents the video decoder chip. A close look also reveals the memory chip to the left of the CPU, and regulator 3 below the video decoder chip.



**Figure 5.5** Thermal image picture of the PCB from below

It should be pointed out that the images taken with the thermal imager are not hundred percent accurate. One reason is that the different parts of the PCB above have different emissivity. The camera however, does not know this since it only receive information about the radiation. It will assume the same emissivity for the whole PCB. As a result the glossier surfaces (like the metal battery down to the left in figure 5.4) tend to get a little too blue. In the same way the surfaces with high emissivity, the matt surfaces, tend to get a little to red.

## 5.2 Simulation Preparations

Before running a thermal simulation in CFDesign three main tasks has to be performed: Finding values for the components power generation, preparing the CAD-model and setting up the simulation in CFDesign. The three steps will be thoroughly described in this section.

### 5.2.1 Finding Values for the Components Power Consumption

In order to do a heat simulation it is necessary to get information about how much power the components in the device consume. This information could, in this case, be obtained from AXIS's data base.

The power consumption values, together with the heat test results, provide information about the relation between the power consumption and the temperatures in the device, which in fact is the same thing as the relation between the heat generation and the temperatures in the device. This information will in other words be our reference frame for what reality looks like; these are the relations we hoped to obtain in our simulation software as well.

The idea once the power consumption had been found was then to compare the simulated temperatures with the ones from the heat tests. If these turned out to be the same, it had been verified that the simulation had been set up correctly. If not, adjustments in CFDesign were to be made until the temperatures from the test and the simulation were the same. Information about the components power consumption was specified in the components data sheets. However, as described in chapter 4, there are three different voltages that supply the components, and some components even use more than one voltage to operate. Thus some calculations had to be done before receiving the correct values. The voltages that the different components need to operate are illustrated in the chart below.

**Table 5.2** The different currents in the components

Components	$I_{3.3V}$ [mA]	$I_{1.8V}$ [mA]	$I_{1.2V}$ [mA]
<b>CPU</b>	150	300	1000
<b>Memory (2st)</b>		230	
<b>Video chip</b>	83	153	
<b>Ethernet</b>	100		
<b>Others</b>	126		
<b>Total [mA]</b>	<b>459</b>	<b>683</b>	<b>1000</b>

The last row in the chart (others), represents all the remaining heat generating components, such as includes LED:s, drivers, audio functions and the Flash chip.

To explain the system in the chart above, consider for instance the CPU row: The CPU is using power from all the three supplying currents and its summarized power consumption is received by adding the resulting power consumption for each current:

$$P_{CPU} = 150 \cdot 3.3 + 300 \cdot 1.8 + 1000 \cdot 1.2 = 2.2 \text{ W}$$

In this way we can calculate the power consumption for every component, except for the regulators. Since the heat loss for the regulators depend on the total power consumption of a certain current, we have to decide the power consumption for these as well. With the wiring scheme for the regulators in mind, we get the following chart:

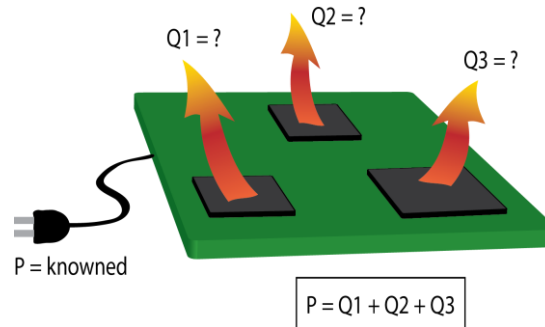
**Table 5.3** The summarized currents in the components and their power consumption

Components	$P_{3.3V}$ [W]	$P_{1.8V}$ [W]	$P_{1.2V}$ [W]	$P_{12V}$ [W]	$P_{\text{All currents}}$ [W]
<b>CPU</b>	0,495	0,540	1,200		2,235
<b>Memory</b>		0,414			0,414
<b>Video chip</b>	0,274	0,276			0,550
<b>Ethernet</b>	0,330				0,330
<b>Others</b>	0,416				0,416
<b>Total</b>	<b>1,515</b>	<b>1,230</b>	<b>1,200</b>		<b>3,945</b>
<b>Reg. 1(3.3 to 1.2V) 10%</b>			0,133		0,133
<b>Reg. 2(3.3 to 1.8V) 10%</b>		0,137			0,137
<b>Total</b>	<b>1,581</b>	<b>1,367</b>	<b>1,333</b>		<b>4,215</b>
<b>Reg. 3(8-20 to 3.3V) 20%</b>				1,070	1,070
<b>Total</b>					<b>5,285</b>

Since regulator 3 depends on all three currents, a column especially for this component has been added, the one that is named  $P_{12V}$ .

It seemed now as if the power consumption values that were needed for simulating the scenario were obtained. However, these theoretical values are too high, since all values taken from component specification charts represents a scenario where the device is in full operation, which could be read from the chart above to be at 5,285 Watt. Despite efforts to get as close as possible to this value during the heat test by using heavier software functions and so forth, the encoder was only operating at 2,88 Watt. Thus the theoretical values in the chart above had to be modified to fit the scenario from the heat test. These modifications will now be described.

The total power consumption from the heat tests was known since before, see the figure below.



**Figure 5.6** Total power consumption from the heat tests was known since before.

Now by simply using the ratio between the total power consumption from the heat test and the total theoretical power consumption a power ratio could be found:

$$\text{Power ratio} = \frac{2.88}{5.28} = 0.54$$

In other words, the power consumption we were looking for are only 54 percent of the theoretical ones. By multiplying with the power ratio the correct power consumption values were obtained:

**Table 5.4** The adjusted power consumption values

Components	theoretical	heat test	fraction
	$P_{\text{total}}$ [W]	$P_{\text{total}}$ [W]	[%]
<b>CPU</b>	2,235	1,207	42
<b>Memory</b>	0,414	0,224	8
<b>Video chip</b>	0,550	0,297	10
<b>Ethernet</b>	0,330	0,178	6
<b>Others</b>	0,416	0,224	8
<b>Total</b>	<b>3,945</b>	<b>2,13</b>	<b>74</b>
<b>Reg. 1(3.3 till 1.2V) 10%</b>	0,133	0,072	3
<b>Reg. 2(3.3 till 1.8V) 10%</b>	0,137	0,074	3
<b>Reg. 3(12.0 till 3.3V) 20%</b>	1,070	0,578	20
<b>Total</b>	<b>5,285</b>	<b>2,844</b>	<b>100</b>

The power consumption of the active components during the heat test was now finally obtained.

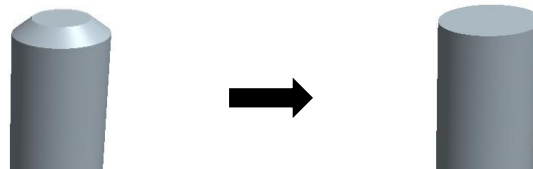
For better overview in table 5.4 a column is added to the left where the power consumption is expressed in percent of the total power consumption. It could for example be seen that 26 percent of the power consumption consists of the regulators, that is, only for modifying the voltage in the device. Furthermore it could be noted that the CPU alone represents 42 percent of the total power consumption of the encoder.

### 5.2.2 Preparing the CAD Model for CFDesign

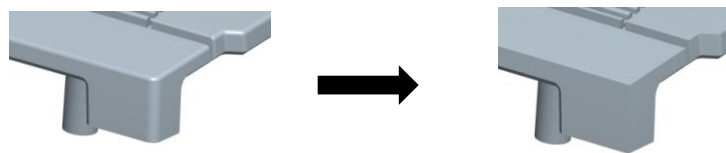
A finer mesh will demand more processor capacity. However, the more complex of a model you launch into CFDesign, the finer the mesh has to be in order to “capture” all the surfaces, corners and so forth. In other words it is always plausible to keep the model as simple as possible, although it still has to include enough vital information for the simulation software to provide realistic results.

AXIS creates CAD models for all their products, so instead of creating the test product from scratch, AXIS’ complete model was used. Since this model was way more complex than it needed to be, the model was reduced. Some examples of what features that were removed follows below.

Since a round or a chamfer in the CAD model will not affect the heat transfer to any extent that matters, these will be removed.

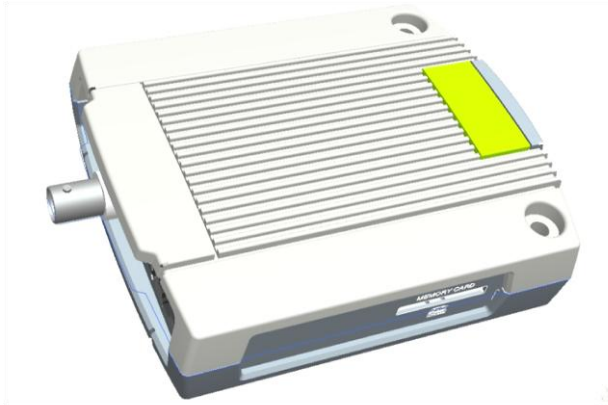


**Figure 5.7** Chamfer features being removed



**Figure 5.8** Round feature being removed

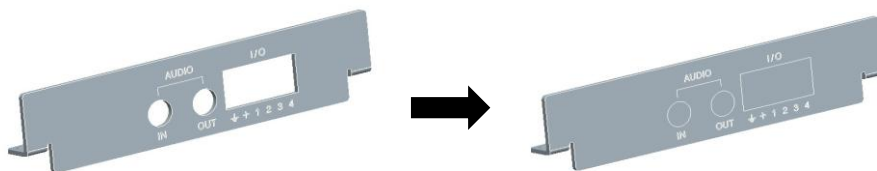
The pattern of the top of the encoder, see illustration below, looks indeed like it is meant for cooling the product. However the pattern has been added solely for design purpose and will not have any relevant influence on the heat dissipation. Thus it will be removed as well.



**Figure 5.9** Geometrical pattern on the top exists only as a design feature

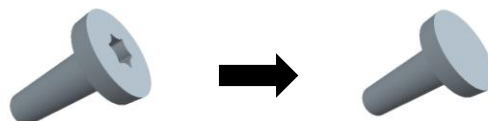
The removal of the pattern is the most important feature to remove from the product since it contains such complex geometry features.

The side panels in the original model have been equipped with a number of holes for the outer connections to the product. Since these holes were covered with components on the inside, no air was allowed to pass through the holes. However, when these components were removed from the PCB, the holes in the side panels had to be removed as well. Otherwise the simplified model would have air leakage that the original model would not.



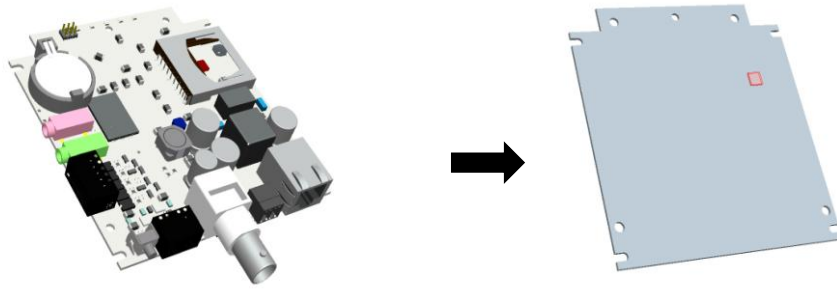
**Figure 5.10** Holes in side panels being removed

Some final details were removed in the end like split lines, mould features and screw extrusions, see illustration below.

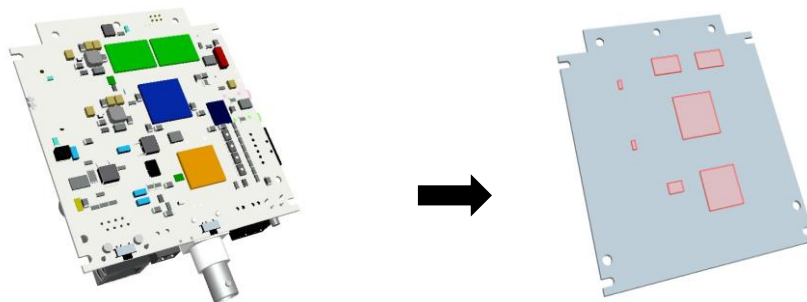


**Figure 5.11** Screw extrusions being removed

Another part that is unnecessarily complex is the PCB. Instead of using the PCB from AXIS's database, a new PCB was created from scratch. This contained only the relevant heat producing components; CPU, working memory, video chip and Ethernet chip, which were listed on page 36. The pictures below illustrate the simplification.

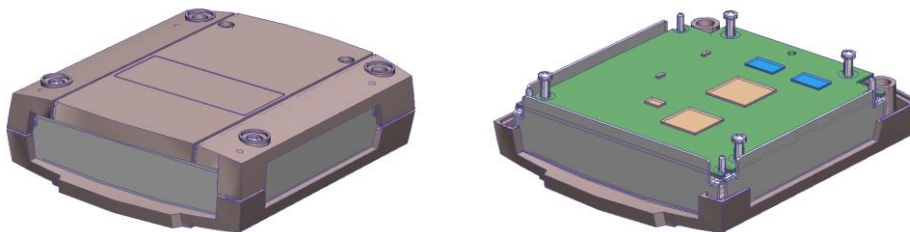


**Figure 5.12** PCB (seen from above) being modified



**Figure 5.13** PCB (seen from below) being modified

Apart from the fact of simplifying the geometry of the parts, interfering materials between the parts has to be removed before the CAD-model can be transferred to CFDDesign. This since the CAD application can allow interference while CFDDesign cannot. The figure below illustrates the new model, further referred to as *reduced model*.



**Figure 5.14** The reduced model. Closed view (left) and open view (right)



### 5.2.3 Setting Up the Simulation in CFDesign

Having the heat tests and component's power consumption documented and the CAD model ready, all was set to create a scenario for the first simulation. This ingoing section describes the complete process of setting up the simulation in CFDesign.

#### 5.2.3.1 Applying Materials

The first step was to apply materials to the model. CFDesign provides the user with a number of default materials with a complete set of properties like density, heat conduction, wall roughness, and emissivity. However, this default mode is often changed to fit a specific scenario. The different parts and materials for this specific study are displayed in the chart below, together with the material properties needed for the simulation.

**Table 5.5** The conductivity and emissivity for the material the encoder was made of

Part	Material	Conductivity, k [W/mK]	Emissivity, e
<b>Cover</b>	ADC 12 (Al. die cast)	92.0	0.9
<b>PCB</b>	FR-4 (Plastics and Cu)	60.3	0.6
<b>Panels</b>	SUS 304 (Stainless steel)	16.2	0.9
<b>Screws</b>	Steel 8.8 (Stainless steel)	15.0	0.1

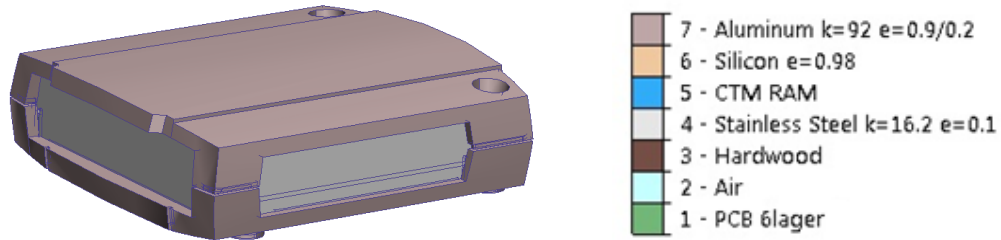
The cover is made of an aluminium die cast with a relatively low heat conductivity of 92.0 W/mK, as most aluminium materials have conductivity at about 200 W/mK. (See appendix B for more information). The cover surface has a surface finish of powder based paint which gives it a high emissivity of about 0.9.

The conductivity of the PCB depends on how many layers the PCB contains and the copper content in these layers. This information was found and entered in CFDesign, which estimated the conductivity to 60.3 W/mK.

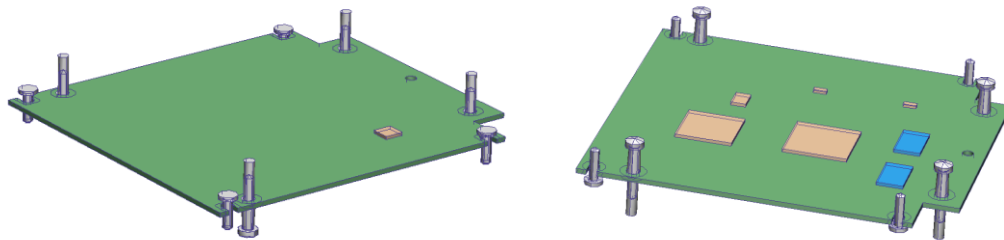
The panels are made of a common type of stainless steel, with the characteristic low conductivity of 16.2 W/mK. This is of course one of the reasons why AXIS has chosen not to design the main parts of the cover in stainless steel. The panels have the same finish as the cover parts, giving them an emissivity of 0.9 as well.

The screws are also made in steel, with a conductivity of 15 W/mk. Their emissivity is not of great importance since they do not have any comparably big surfaces.

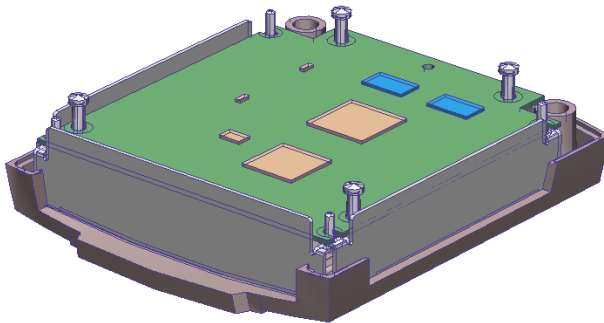
The figures below illustrates how the different parts were applied with materials, see the colour scheme in figure 5.15.



**Figure 5.15** The cover of the encoder with applied materials.



**Figure 5.16** The PCB seen from above (left), and from below (right). The beige and blue rectangles are the active components.



**Figure 5.17** The complete product without the bottom cover is shown to the left.

When to choose materials for the active components the process became more difficult. All components in this project exist as integrated circuits, or microchip, which of course do not consist of a single material. Although somehow an approximation had to be made since it would be unnecessarily complex to simulate the integrated circuits with all their involved parts. A short description of the interior design of an integrated circuit is given in appendix C. If ambiguities occur during the following sections it is recommended to go through this appendix.

When simulating an integrated circuit in CFDesign the microchips are represented as small boxes on the PCB as showed earlier. Two main alternatives were available for making them behave thermally correct:

1. Using a special function in CFDesign with which the application transforms the box to a *virtual microchip*. This demands however that the user knows the thermal resistance, both between the junction and the top side of the case (defined as  $R_{\theta \text{ junction to case}}$ ), plus the thermal resistance between the junction and the PCB (defined as  $R_{\theta \text{ junction to board}}$ ).
2. Choosing a material for the whole box whose thermal properties approximately matches the thermal properties of the whole integrated circuit.

By using alternative one, that is, by providing the application with the exact thermal resistances upwards towards the case roof, and downwards towards the PCB, the application will be able to “send” the right amount of heat energy upwards and downwards.

In alternative two this is not possible. However the equilibrium energy dynamics that arise around the microchip will make the software ration out close to the correct amounts anyway. (If for instance all the heat energy is sent upwards, the temperature above the centre of the microchip will be higher than under the centre. This will cause the software to send more heat downwards, since it is always aiming for a thermal equilibrium).

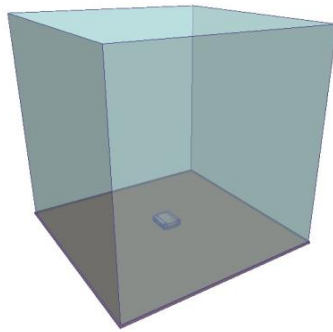
But despite this alternative one is the preferable one since it is a little more accurate. Thus an extensive search on AXIS for the thermal resistances for all the active components was made. It resulted in that only the thermal resistances for the working memories were found:

- $R_{\theta \text{ junction to case}} = 3.1 \text{ K/W}$
- $R_{\theta \text{ junction to board}} = 21.3 \text{ K/W}$

It was decided to try alternative one for the working memory components, and alternative two for the rest of the components, since the working memories were the only ones of which the thermal resistances could be found. The material for the other components was set to be silicon, since this is a proven appropriate material for simulating microchips [4]. The choice of component material in CFDesign can be seen if the reader once more study figure 5.15, where the legend to the right describes that the beige boxes are set to be silicon and the blue boxes, the working memories, are made of CTM, which means that they are fictive microchips.

In the same way as described in chapter 3, CFDesign – A Brief Introduction, the whole encoder was then placed in a box with about ten times the dimensions as the

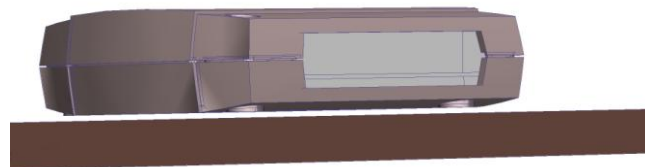
product itself. This box was set to be air, see the illustration below. Under the box a wooden board was placed to illustrate the table the product was placed on during the heat test. This is set to be wooden, which in practice means that it has a negligible thermal conductivity.



**Figure 5.18** The model inside the air cube, placed on a wooden board

In reality, two solid objects that are pressed against each other do in fact only really make contact on a fraction of the total contact surface. This will of course result in some kind of thermal resistance. CFDesign however does not take this into account, and will treat to solids in contact with each other as having a hundred percent contact. This is because the application cannot possibly guess how many percent of the contact surface that actually makes contact; this depends on the pressure between the solids, their emissivity and their surface finish. Thus, if it is known that for some specific solids there will be very low heat flux, one could place the solids with a tiny gap between them to simulate the negligible heat transfer.

An example of this is between the bottom of the encoder and the wooden board it is placed on. Since the board is made out of wood, plus that there is no real pressure between the encoder and the board except for the encoders own weight, the heat transfer here will be negligible. In other words, since there was no heat transfer between these surfaces in reality there must not be any heat transfer in the simulation either. Thus the encoder was placed hovering two millimetres above the board surface, see the figure at the next page.

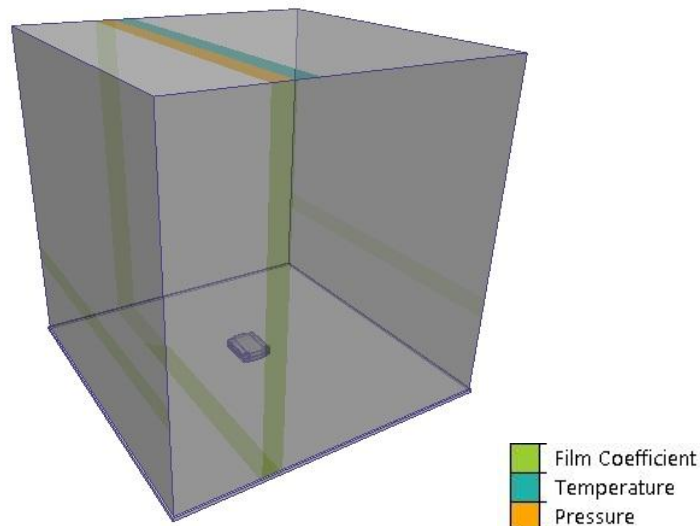


**Figure 5.19** The model is placed 2 mm above the board

One may wonder why then a board is necessary in the simulation at all, but it will still play an important part in affecting the convection air streams. Without it, the cold air at the sides of the product would just fall downwards instead of being forced inwards against the encoder as a result of the depression that is created when the heated air above the encoder is moving upwards.

### 5.2.3.2 Applying Boundary Conditions

The boundary conditions are, as mentioned in chapter 3, the mathematical conditions that define how the computer should treat the borders between meshed volume and volume outside the simulated scenario. In our case these borders are found along the air cube surfaces and along the bottom surface of the wooden board. In the illustration below the air cube with the encoder in the middle are displayed. The coloured stripes along the walls represent the boundary conditions; see the legend to the right.

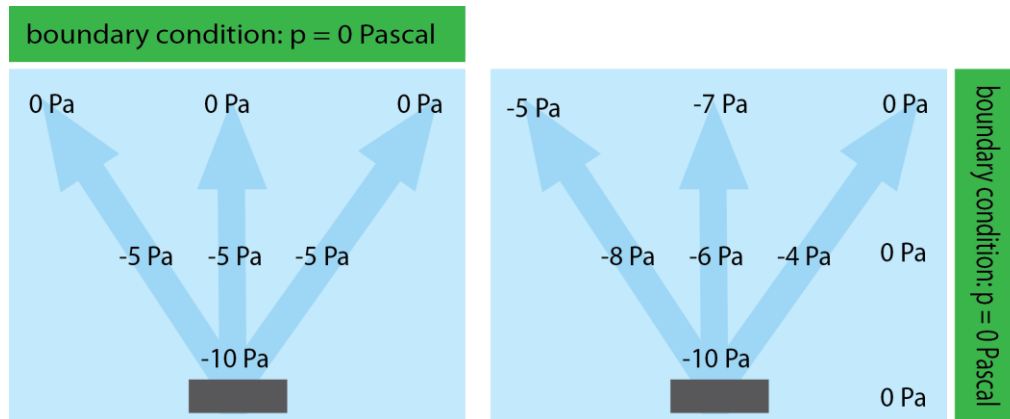


**Figure 5.20** The outer boundary conditions

Temperature conditions were applied on the top of the cube, at 23 °C, since this was the ambient temperature during the heat tests. This means that no matter what happens during the solution process, this surface will always be kept on a temperature of 23 °C. By providing the software with this kind of certain information, it will be easier for the software to solve the problem. To be able to place boundary conditions however, one must of course be sure of that the condition is properly presumed. In this case we could consider it to be correct, since the heat generated from the product at the bottom of the cube could not, in any relevant amount, affect the temperature of the air that far from the product.

Even a pressure boundary condition is applied on the top of the cube. This is set to have a gage pressure of 0 Pascal, or in other words, 1 atm. This boundary condition

will act as the pressure reference point for the application when simulating the convection streams. What the boundary condition does is to hold a constant pressure of 0 Pascal over the whole surface where it is applied. It needs to be applied horizontally in order for CFDesign to simulate the air streams correctly. The illustration below, which shows the air cube with the encoder in the middle, shows why this is so important. Observe that the values in this illustration are not absolute; they are purely there to show the *relations* between hypothetical pressures at different spots in the air cube.



**Figure 5.21** The importance of placing the pressure boundary condition horizontally

In the figure to the left the pressure condition has been placed horizontally, keeping the pressure on the top at 0 Pascal. As the heated air above the encoder rises it leaves a depression behind it. As the air is moving upwards due to the change of density, the pressure will increase gradually to finally meet up with the boundary condition at zero Pascal at the top. This will reflect the reality.

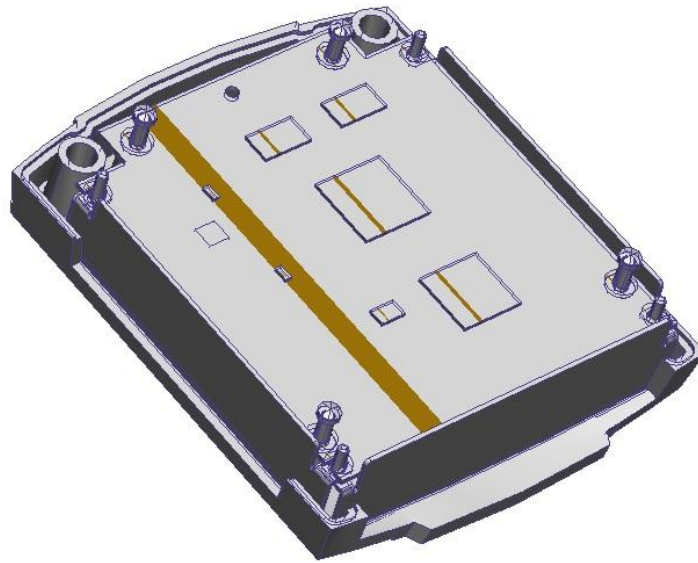
In the figure to the right the pressure condition has been placed vertically on one of the walls. This will result in unbalanced airstreams as they will be simulated on different terms depending on if they are moving towards the wall with the boundary condition or towards another wall. This is of course not what the reality looks like, and is thus not a proper setup.

The last task for the cube is to apply some form of control over the heat flux through the walls and through the wooden board. This is done by applying a *film coefficient*, also known as a convection coefficient. This parameter will decide how much heat energy per unit area and temperature difference that are allowed to flow through the wall. In other words the film coefficients will try to simulate that the air cube is in fact surrounded by real air.

The film coefficient applied on the walls and the wooden board was set to  $5 \text{ W/Km}^2$ , which is known to be a good value for air when working in the temperature range that could be read from the heat test results in this project [4].

Boundary conditions also needed to be applied around the heat generating components, as it is these boundary conditions that will tell the application that these volumes should in fact generate heat. Thus all the active components were provided with

a heat generating boundary condition. The amount of heat that every component should generate is simply equal to the power that it consumes, namely the power consumption that was found and modified in section 5.2.1. The power consumption for the “other components” was spread out equally over the whole PCB. This approximation was considered plausible since the power consumption for these components are so small. The illustration below shows how the heat generating boundary conditions were applied to the components. Like for the others, a coloured stripe signifies the boundary condition.



**Figure 5.22** Heat generating conditions (brown stripes) are applied

To summarize, all boundary conditions are viewed in the table below, where location, type of boundary condition and magnitude plus unit can be seen.

**Table 5.6** The boundary conditions for the simulation

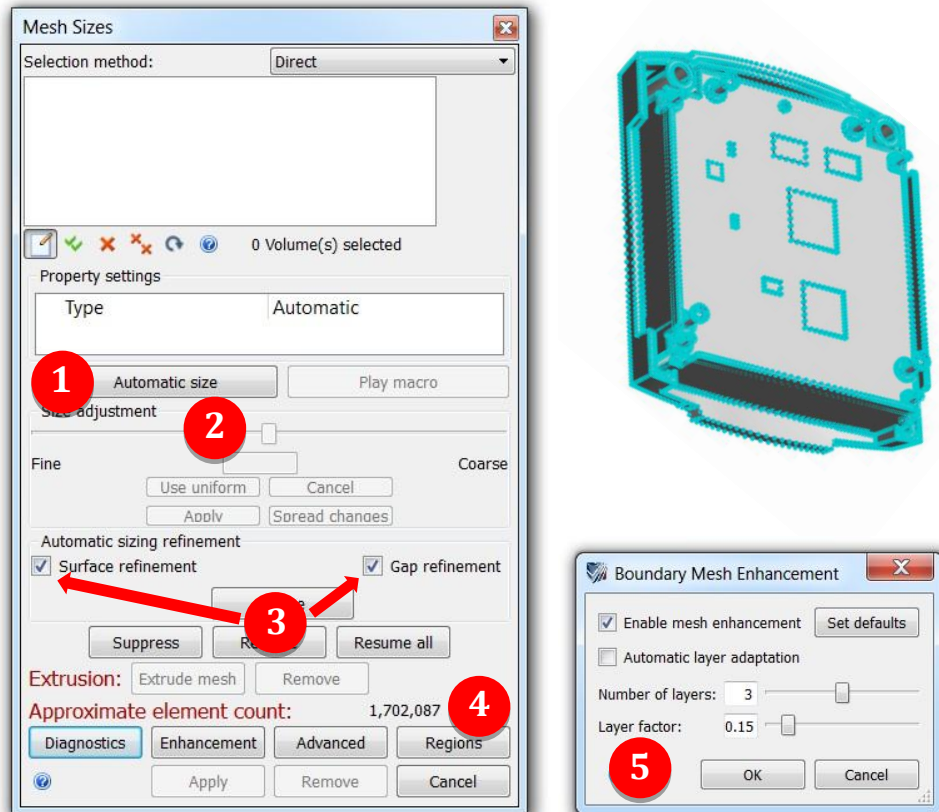
Location	Boundary condition	Magnitude
<b>Air cube roof</b>	Temperature	23°C
	Pressure	1 atm
<b>Air cube walls</b>	Film coefficient	5 W/Km <sup>2</sup>
<b>Wooden board</b>	Film coefficient	5 W/Km <sup>2</sup>
<b>Active components</b>	Heat generation	See table 5.4

### 5.2.3.3 Applying the Mesh

As mentioned in chapter 3 the properties of the mesh will affect the results greatly, since it contains information of the very coordinates that will lay as fundament for the FEM analysis. Most often, the mesh has to be tried out a couple of times before it is considered to be appropriate for a specific simulation. Since the generating process is a relatively time consuming process (a number of hours) CFDesign has the ability to do a pre-generated mesh, a guess of how the mesh will be once it is generated. This pre-generation is done in a couple of minutes, and by pre-generating a couple of times until the mesh properties seems appropriate instead of using the real generating function a lot of time can be saved.

Study the illustration at the next page. To the right the very model is shown. The blue dots which can be seen along the edges of the model gives, after some experience, a hint of what the mesh is going to look like after the real mesh generation. Dots packed tightly together indicate a fine mesh around that area, spread out dots indicates a coarse mesh. The two windows, which are explained in the text section at the next page, contain settings for the mesh and are displayed in this study to provide a better understanding for the software functions.





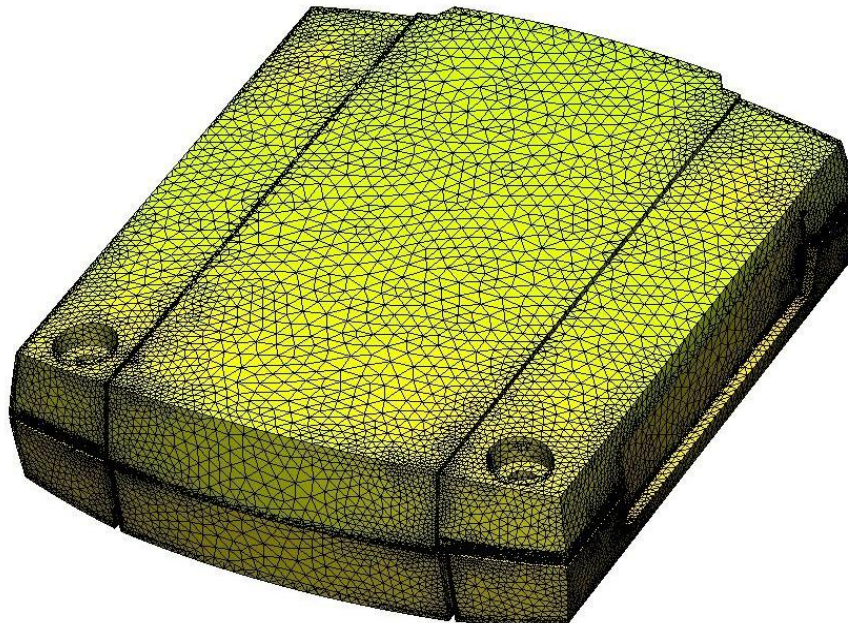
**Figure 5.23** Mesh settings in CFDDesign, explained step by step

Now study the window to the left in the illustration. The window on the top contains the basic settings of the mesh. The first step will be to auto-generate a primary mesh (1). Here the application will make a first guess of how the mesh should look like. It will take into account that more complex geometry areas will demand a finer mesh and thus make the mesh finer over these areas. The slide below (2) can be used to make the mesh *in general* finer or coarser. This was however not considered to be needed this time and the slide was left to be centred. The two functions surface refinement and gap refinement (3) were checked as this will refine the mesh further in areas where the application considers this to be needed. Further down the window a guess of how many elements the mesh will contain is displayed (4). This gives a hint of how demanding the upcoming simulation will be for the computer, and is therefore important to keep an eye on while modifying the mesh. The elements are held together by so called nodes, and as a rule of thumb the mesh should not contain more than half a million nodes [4]. Of course this depends on what accuracy the user wishes to receive, but usually other sources of error are so great that a finer mesh will not really provide a more accurate result.

Now an attempt to generate a real mesh could be done. The mesh generation however is a complex process. To be able to cope with fluid surface phenomena like turbulence a special type of elements are generated along the interface between solid and fluid surfaces. These elements are shaped as prisms, with six corners. Small gaps in the geometry can however result in that these layers of prisms collide with each other, which will in turn result in that the mesh generation fails. One way of avoiding this problem is to decrease the *mesh enhancement layer factor* (5), since this will decrease the thickness of the prisms, decreasing the risk of collision between them.

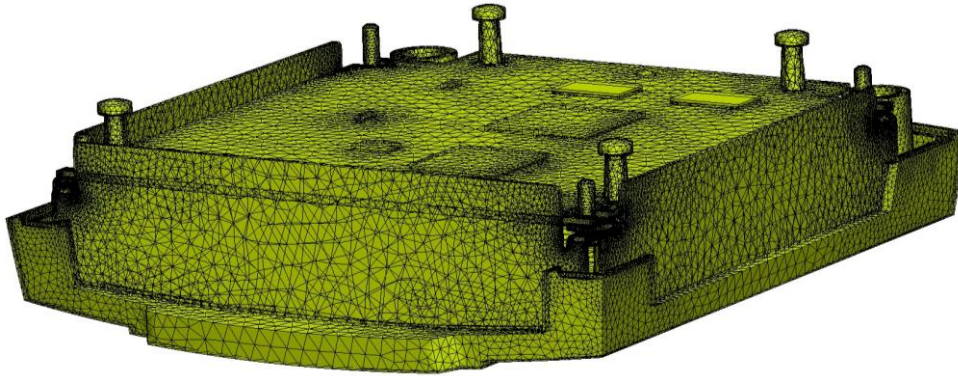
It should also be mentioned that if the very solving of the simulation later on will not converge, the so called *refinement length* for the mesh can also be modified to facilitate a solution. What this really does is to change the acceptance of how long the minimum distance between two nodes in the mesh is allowed to be. Thus an increase of this will result in that the finest areas of the mesh will be somewhat coarser, making it somewhat easier to solve the problem.

After a number of iterations with the pre-generating method just described, a real mesh was created on the model. The final mesh is showed in the illustrations below.



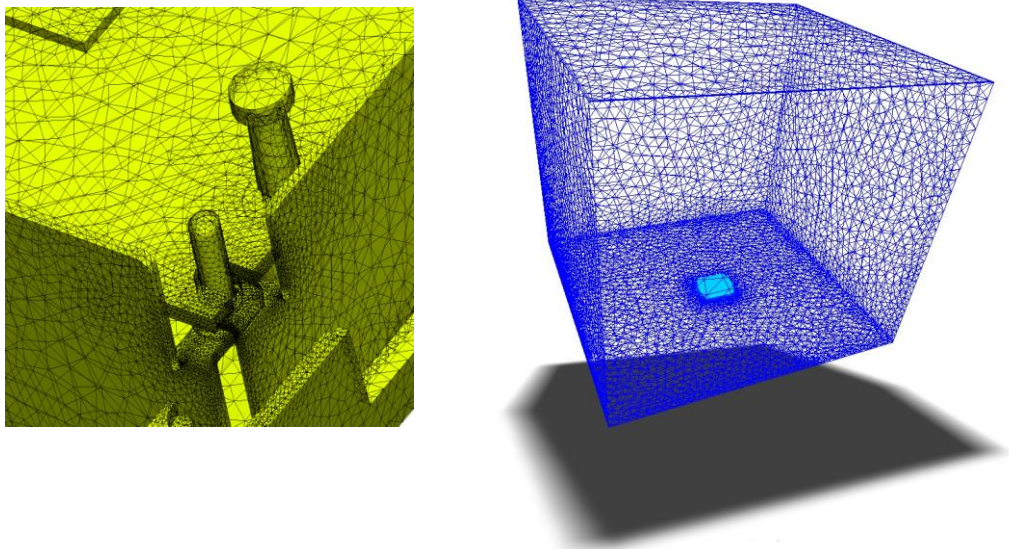
**Figure 5.24** The finished mesh

In the figure below the top cover has been removed to give a better view of how the interiors are meshed. Observe how the two microchips at the rear, the memory chips, are not meshed since they have been defined according to the special “microchip-model” in CFDesign. (This was described at page 47.)



**Figure 5.25** The mesh seen when the top cover is removed

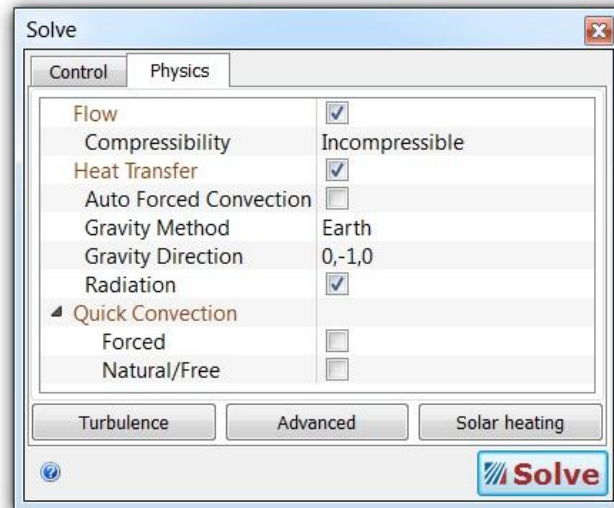
Also observe how the mesh is finer around the screws in the corners due to the more complex geometry. This could be seen even better in figure 5.26 to the left. Below to the right the whole air cube is showed in meshed state, just to give the reader a picture of the size of the air elements as well.



**Figure 5.26** To the left: A close up of one of the corners. To the right: The mesh for the air cube. The model itself could be seen as the small light blue box in the middle.

### 5.2.3.4 Solver Settings

Before the solving process could be initiated some final settings had to be made, see figure below.



**Figure 5.27** The solver settings window in CFDesign

In this window the user can decide what fundamental phenomena the application will take into account when simulating. As could be seen in the figure, phenomena as heat transfer, gravity direction and radiation can be switched on and off, depending on how accurate (and time consuming) the simulation should be.

Flow, heat transfer and radiation were checked plus gravity settings that correspond to the surface of the earth. Now everything was set for the first simulation.

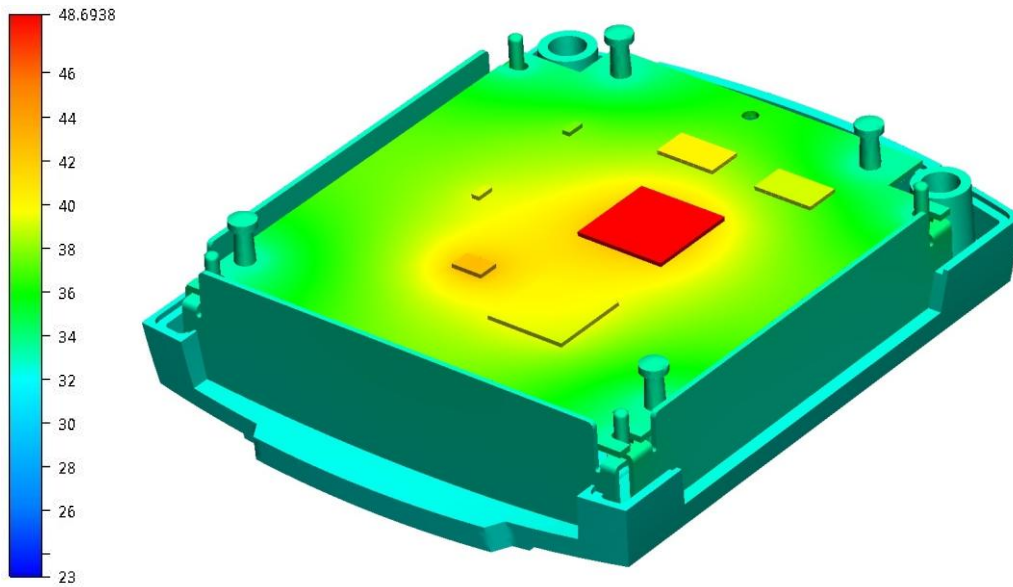
## 5.3 Validation of Simulation

*This section contains the very validation. After a number of hours the software reached a solution, the results were analysed. Some adjustments were made to match the results from the heat tests after which the simulation was solved once more. After repeating this procedure a couple of times the simulation was considered validated, that is, sufficiently in line with the heat test results.*

There are basically two main quantities that were studied in the results; temperature and velocity. Temperature and velocity are graphically illustrated in CFDesign in colours, where blue represents low temperatures/velocities and red represents high temperatures/velocities. A great deal could be said about the thermal situation by being able to study these two quantities in any point.



The results of the primary simulation are displayed below. The illustration shows the model covered in colours representing temperatures. The legend to the left shows what temperatures the colours represent. The temperatures in the legend are expressed in degrees Celsius.



**Figure 5.28** Temperature results for the first simulation

Before going into any extensive analyses it should first of all be stated that the temperature result looks plausible; the microchips are red and orange, the cover is blue and the PCB is somewhere in between. The values seem to be accurate as well; the light blue cover lies obviously somewhere around 32 °C, the PCB around 36 °C and the components between 40 °C and 50 °C. Furthermore the PCB areas around the screws in the corners are somewhat colder than the rest of the PCB. This indicates that the screws have a cooling effect on the PCB, and that heat energy flows from the PCB down through the screws. This statement is not surprising but was nevertheless not certain, since the screws have a very low conductivity. A fast comparison to the thermal imager pictures from section 5.1.4 was also made, which also verified that the temperature spread seemed proper.

Now the temperatures were compared to the heat test temperatures. By checking the simulated temperatures on the exact same spots as the probes were attached a systematic comparison was made. This is illustrated in the table at the next page.

**Table 5.7** The compared values between laboratory tests and simulation

Location	Simulation results (°C)	Lab test results(°C)	Deviation (%)
CPU	48.7	57.7	16
Video chip	40.3	37.0	9
Memory	44.4	42.5	5
Ethernet	40.3	40.0	1
PCB	40.1	42.3	5
Ambient internal air	38.7	38.2	1
Inside cover surface	32.9	31.0	6
Ambient air	23.0	23.0	0

As can be seen from the table the values are relatively close but not identical. In most of the spots the temperature differs by a couple of degrees, in some spots it differs a lot more. So what could be expected? Is this good or bad?

One should expect at least an accuracy of 90 %, that is, the simulation results should not deviate more than 10 % from the heat test results. A good result does not deviate more than 5 %, after this it starts to get unnecessarily accurate. Of course it is always good to be as close as possible, but since it will always be a simulated reality, with approximations and assumptions involved, there is no meaning of chasing these last few percent since no proof of that kind of accuracy can be stated anyway. [4]

Considering the values in the table once more with the arguments above in mind, it seems to be relatively good results overall. However it is clear that there is something wrong with the CPU temperature. This great deviation was not surprising since the CPU was indeed simulated as a silicon box, without containing information about the thermal resistance upwards and downwards from the centre of the chip. This was, mentioned the case for all the chips except for the SDRAM chips, but for some reason it seemed to work out quite well for the other chips. A reason for this could be that the power consumption for the other chips is so small in comparison to the power consumption for the CPU that the error due to the latter shows more. It could also depend on the simple fact that  $R_{\theta \text{ junction to case}}$  and  $R_{\theta \text{ junction to board}}$  were very different from each other when it came to the CPU but more similar when it came to the other chips. If  $R_{\theta \text{ junction to case}}$  and  $R_{\theta \text{ junction to board}}$  are of similar magnitude in reality, the silicon box method namely works quite well. If that is not the case however, the silicon box, sending an equal amount of heat in every direction, will not be a good choice.

After some further discussion it was believed that the last hypothesis above was correct: The thermal resistance between the CPU and the PCB should be modified. Considering that the chip was about 9 °C to colder in the simulation than in reality, it seemed plausible that the thermal resistance between the chip and the PCB should be raised. Another sign that supported this theory was that the video encoder chip was somewhat hotter in the simulation. If the thermal resistance below the CPU would be increased, this would to some extent prevent the CPU from heating the video encoder chip, which would perhaps result in a closer result.

To solve the problem, a fictive contact resistance was placed between the chip and the PCB. The next question was how high the resistance should be. To come up with a good guess, some rough calculations were made. The question in other words is: *How big must the contact resistance between the CPU and the PCB be to raise the CPU temperature with 9 °C?*

Temperature difference due to the contact resistance

$$\Delta T = 9 \text{ °C}$$

Heat energy that flows through the contact surface every second:

$$Q = 1.2 \text{ W (The power consumption of the CPU chip)}$$

It was here assumed that no heat transfers from the chip out to the surrounding air which is not completely true. However it was considered a reasonable approximation in this situation, since not much convection should take place in such a tightly packed cover.

According to eq. 2.11 in the theory chapter, the thermal resistance, in this case a contact resistance could be written as:

$$R_{\theta \text{ contact}} = \frac{\Delta T}{Q} = \frac{9}{1.2} = 7.5 \text{ °C/W}$$

Since the contact area in this case is fixed, the thermal resistance will be modified to be expressed in units of area as well:

The contact area between the CPU and the PCB was, according to the CAD-model:

$$A_{\text{contact}} = 0.018^2 = 0.000324 \text{ m}^2$$

The contact resistance could then be expressed as:

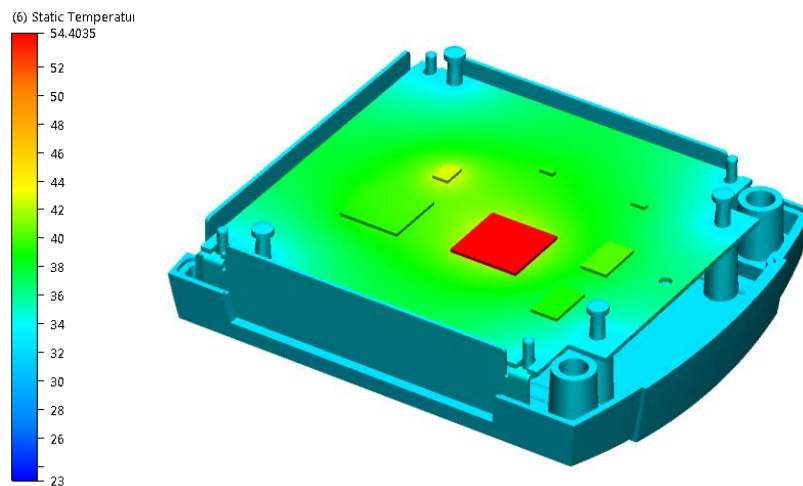
$$R_{\theta \text{ contact}} = 7.5 \text{ °C} \times \frac{0.000324 \text{ m}^2}{\text{W}} = 0.00243 \text{ °Cm}^2/\text{W}$$

In other words:  $R_{\theta \text{ contact}} = 0.00243 \text{ °Cm}^2/\text{W}$  is what was applied to the contact surface between the CPU and the PCB in CFDesign. Another simulation was executed and the temperatures were once again compared to the heat test results. This time they were much closer, however a couple more iterations were made before the result was considered to be satisfactory. This final result is showed in the table at the next page.

**Table 5.8** Laboratory and simulation values compared after adding contact resistance

Location	Simulation results (°C)	Lab test results(°C)	Deviation (%)
CPU	54.4	57.7	6
Video chip	39.1	37.0	6
Memory	40.5	42.5	5
Ethernet	38.6	40.0	3
PCB	40.0	42.3	5
Ambient internal air	38.0	38.2	0
Inside cover surface	32.3	31.0	4
Ambient air	23.0	23.0	0

From the table it could be seen that the values now has improved; it only deviates with three degrees for the CPU chip. All the other temperatures are still within the range of what is considered an approved accuracy [4]. Consequently this simulation was accepted as the final, validated simulation. That is, this simulation will act as the base for all the varied simulations in chapter 6. However before starting to modify the scenario, some more results for this simulation will be shown.

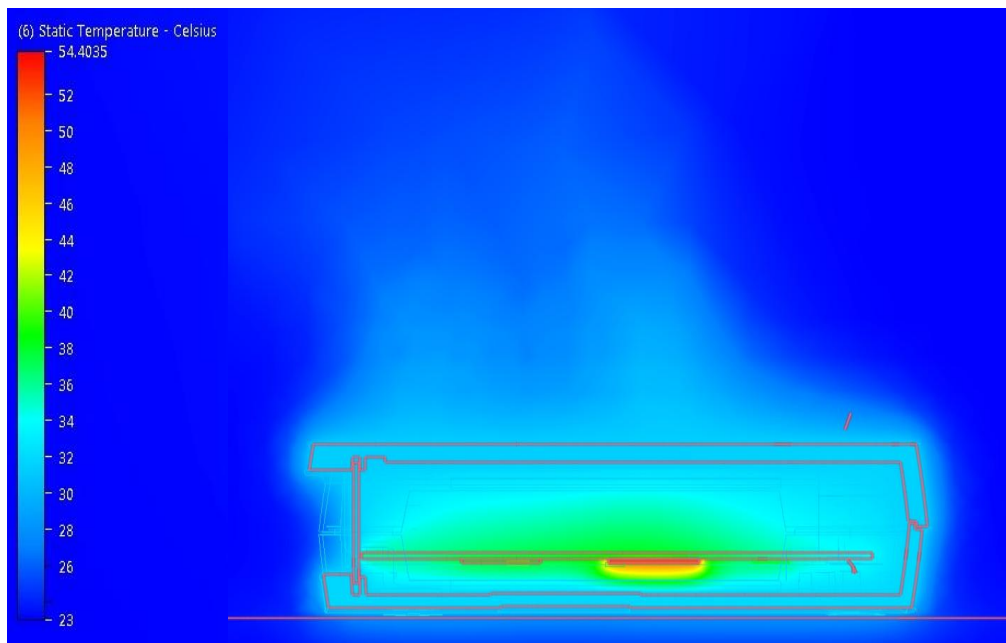
**Figure 5.29** Temperature results for the modified simulation.

Above the temperature results for the model are shown. The values are similar to the results from the simulation *without* the contact resistance, apart from the fact that the CPU temperature is lower. However the CPU is still the greatest heat source, with regulator 3 as number second, (The little yellow box above the CPU).

The air in the simulation is not visible in this figure since this would cover the very model. The legend to the left indicates indeed that there is some kind of substance that has a temperature of 23 °C. This could be expected to be the parts of the surrounding air which, as mentioned, had a set starting temperature of 23 °C.



When analysing these kinds of pictures from a thermal design point of view it is important to *locate the dominant temperature gradients*. This means finding the areas where the temperature is changing the most. The temperature in the figure 5.29 obviously goes from 23 °C up to 54 °C. Ideally everything would have the ambient temperature of 23 °C, that is, no temperature gradients. Consequently, it is not the areas with low temperature gradients (the one-coloured areas) that cause problems. It is the areas with high temperature gradients (the multi coloured areas) that causes the temperature to rise. Thus it is primarily those areas that have to be dealt with when doing thermal improvements on the real product. In figure 5.29 a typical critical temperature gradient occurs between the CPU and the PCB; a better conductance here would result in a decreased CPU temperature. In an analogue way, replacing the side panels with a more conductive material would not help to decrease any temperature since these obviously does not contain any temperature gradients. Areas where the temperature gradients are very high can be referred to as “bottlenecks”, as they tend to “strangle” the heat flow.



**Figure 5.30** Temperature results seen from a cross section

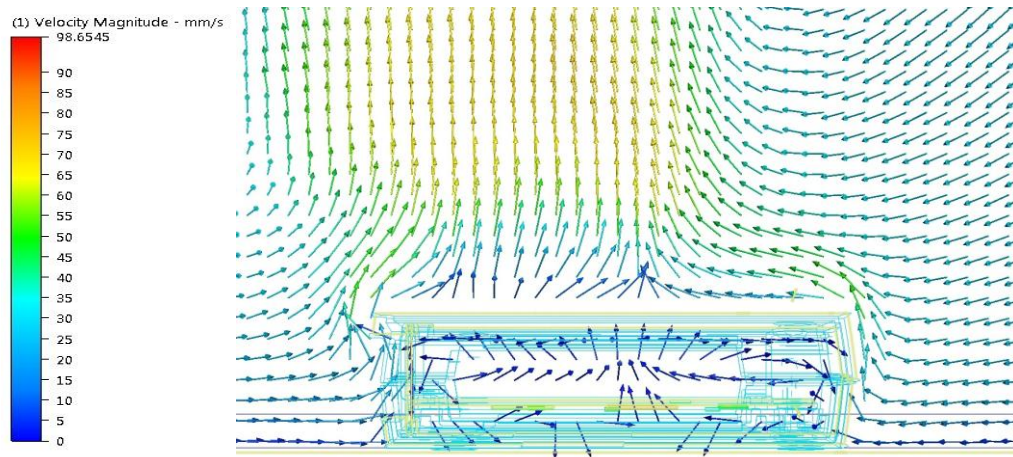
Above is the air temperatures shown from a cross section. The red area in the middle of the picture represents the CPU chip, the green area shows the heat focused around all the PCB components. In the edges of the picture the dark blue areas represent the ambient air temperature at 23 °C. As it gets closer to the model, the temperature increases up to light blue (around 35 °C).

Above the top cover the hot air could be seen streaming up from the model due to the convection. This gives a hint of how tightly the product could be placed under another object before start losing convective cooling effect. Say for example that another encoder was placed in a rack two encoder-heights above this one; this would not af-

fect the air streams noticeably since here are mostly dark blue areas. On the other hand, placing another encoder half an encoder-height above this one would strongly affect the air streams in a negative way.

High temperature gradients can be found in figure 5.30 in the interface between the cover and the surrounding air. This is usually the case since the heat, travelling by conduction in the cover, suddenly has to take a leap and transfer into the air. Since the air in itself is a very bad conductor, it has to move away and make place for colder air to be able to get rid of the heat. If this does not happen fast enough, a temperature gradient will appear between the solid and the fluid. This is what happens in this case.

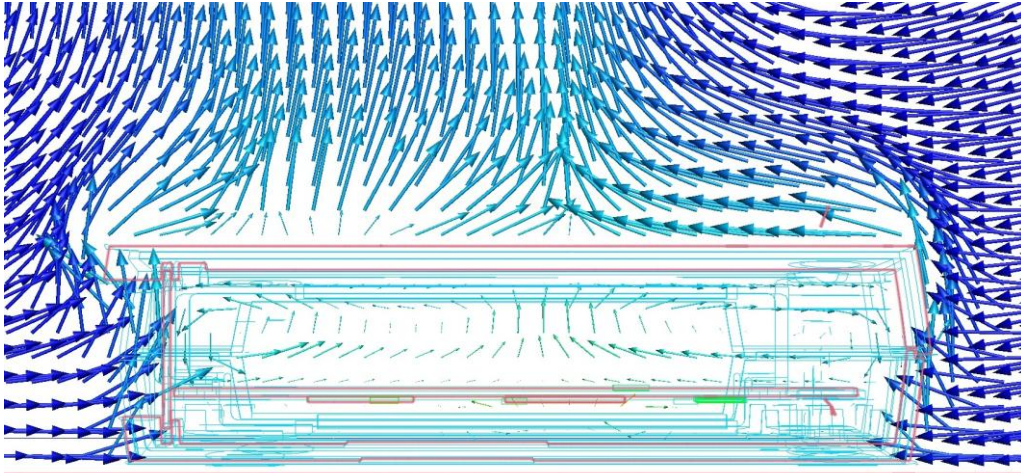
Next illustration shows the air velocity situation. The magnitude of the velocity is represented in colours. Additionally, the movement direction in every point is illustrated with a small arrow, giving the viewer a picture of the convection streams that appear inside and around the object.



**Figure 5.31** Air velocities shown as vectors from a cross section view.

Around the cover the typical convective pattern for a heat source appears. That is, vertical currents above the model, bringing the heated air upwards. The horizontal currents at the side of the model are bringing the cold air inwards and caress the cover walls while receiving heat energy from the cover. Looking at the dark blue arrows inside the casing and at the legend in the figure above it could be stated that the velocities here are lower than 5 mm/s. This implies that the convection does not play a huge role inside the cover. (See appendix B.1.3)

Inside the cover it is actually hard to see what is happening, which is why a close up is showed below. In this close up the magnitude of the velocity is even represented with the length of the arrows. This makes it easier to see how much smaller the velocities are inside the cover than outside the cover.



**Figure 5.32** The close up shows how much smaller the velocities are inside the cover



## 6 Simulations

*This chapter contains the very simulation section in this project. Here 15 scenarios were planned deviates from reality. They will be referred to as Fictive Scenarios. These scenarios were simulated in CFDesign and the results were analysed. The final step was then to combine some of these scenarios to study their combined effect on the product, and investigate how they affect each other.*

*To be able to compare results from different simulations without taking into account that they differ in geometry, the same product was used in all the simulations.*

In the fictive scenarios parameters as material thickness, cover size, component placement and so forth were changed. The purpose of this was to see what would have happened if these were to be changed in reality. This part, together with its conclusions, is the main part of this project. In this way a better understanding of which parameters that have great influence on the temperature and which ones that have less is achieved, and one will thus be able to choose the more efficient solutions in similar upcoming projects.

With the broad range of analysing tools in CFDesign it was furthermore possible to study the fluid movements due to the convection that takes place inside the test product. The influence of convection compared to the influence of radiation and conduction are also studied.

### 6.1 Planning and Choosing the Fictive Scenarios

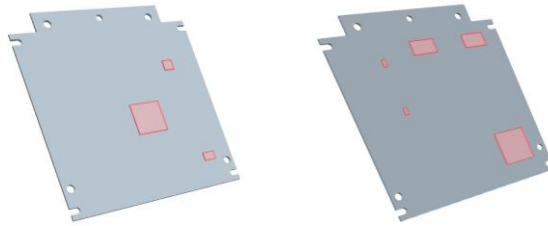
Below is a list of the 15 fictive scenarios and a motivation to why these were chosen.

- **Increase the surrounding air temperature with 10 °C**  
Motivation: To see the effect from increasing the surrounding temperature in according to the chip and cover temperatures.
- **Decrease the surrounding air temperature with 10 °C**  
Motivation: To see the effect from decreasing the surrounding temperature in according to the chip and cover temperatures. Also compare the increased and decreased temperature and see if there is a difference in amount.

- **Increase the overall power consumption with 10 %**  
Motivation: To see what leverage the change in heat generation has on the final temperatures. By increasing the chips' power consumption the change in temperature can be compared.
- **Decrease the overall power consumption with 10 %**  
Motivation: To see what leverage the change in heat generation has on the final temperatures. By decreasing the power consumption for the chips the change in temperature can be compared.
- **Increase the cover conductivity from 95 W/mK to 200 W/mK**  
Motivation: Exploring the need of using a better heat conductor as cover or if the conductivity already transfers the heat in an optimal way.
- **Decrease the cover emissivity from  $e = 0.95$  to  $e = 0.05$**   
Motivation: To study the emissivity's influence. By decreasing the emissivity a temperature decrease will appear. The question is how critical this decrease really is.
- **Replace the eight steel screws with silver screws**  
Motivation: It is not clear whether a significant amount of heat is going down through the eight screws. To get a better picture of this, the 8 screws will be replaced with screws that transfer heat much better. If this should result in considerably lower temperatures, the screws could be considered as "bottle-necks".
- **Replace the aluminium cover with a plastic cover**  
Motivation: Plastic is relatively cheap and a profitable material for producing complex shapes like for instance these covers. If it would turn out that the temperatures would not differ much this would be valuable information, not only for this product but also for similar ones.
- **Run the simulation without taking the heat radiation into account**  
Motivation: To find out how much heat that travels through radiation from the heat sources.
- **Remove the top cover**  
Motivation: Since this scenario also was run as a heat test it is a secondary way to verify the validity of the simulation. It is also interesting to see what impact the increased natural convection will have on the temperatures.

- **Place the heat sources spread out on the PCB**

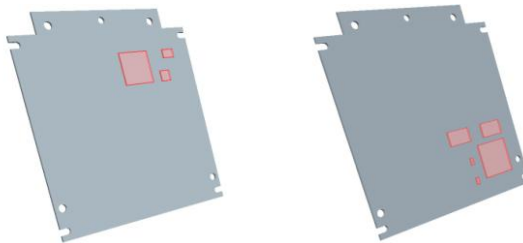
Motivation: If the components are rearranged on the PCB this could change the heat dissipation. Components on the PCB are placed away from each other and near the screws. Then they will not heat each other and the heat would be transferred through the screws to a greater extent.



**Figure 6.1** Image of the PCB with components wide apart

- **Place the heat sources tightly packed together on the PCB**

Motivation: To study the worst positioning possible from a thermal point of view; all components at one location. The influence from component positioning is always important to understand when designing new products.



**Figure 6.2** Image of the PCB with components tight together

- **Place an aluminium block between the CPU chip and the top cover**

Motivation: Since the CPU chip is the most heat generating chip, this is a proper place to put a high conductive material. An aluminium block will be placed on top of the chip to transport the heat directly from the CPU to the cover.

- **Decrease the cover thickness and change the material to zinc**

Motivation: Zinc transports heat a little better than the type of aluminium used in this product. Since zinc is easier to mould and is more expensive than aluminium the zinc cover should be somewhat thinner than the one of aluminium.

- **Increase the enclosed air volume inside the casing**

Motivation: This is very interesting from a cooling perspective of view; How much colder does it get when the air volume inside the cover is for instance tripled?

The first nine scenarios above were now simulated and the results are presented and analysed in next section. The remaining six scenarios were geometrically more complex, and demanded a further simplification of the model before they could be executed. Those last scenarios will be presented separately.

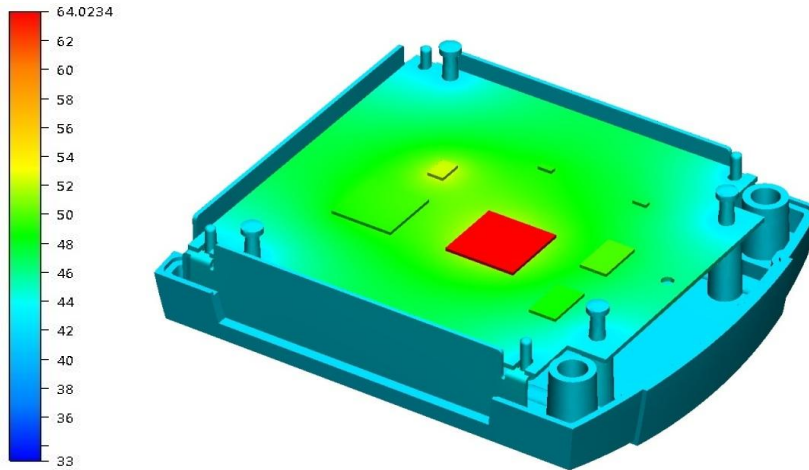
### **6.2 Analysing the Results of the First 9 Fictive Scenarios**

In this section follow the results of the 15 scenarios. When a scenario is presented there will be a temperature image that show how the different components were affected. Since the components in these simulations were simulated as silicon blocks the difference between the junction temperature and the components surface temperature is negligible. Consequently the components' junction temperature is represented by the colours seen in these pictures.

A legend to the left shows what temperatures the colours represent. The legends are set after the smallest and highest temperature measured in a specific scenario. For every simulation there will also be a table that shows how the critical temperatures have changed compared to the original simulation. In some cases additional images will also be shown.



### 6.2.1 Increase the Surrounding Air Temperature with 10 °C



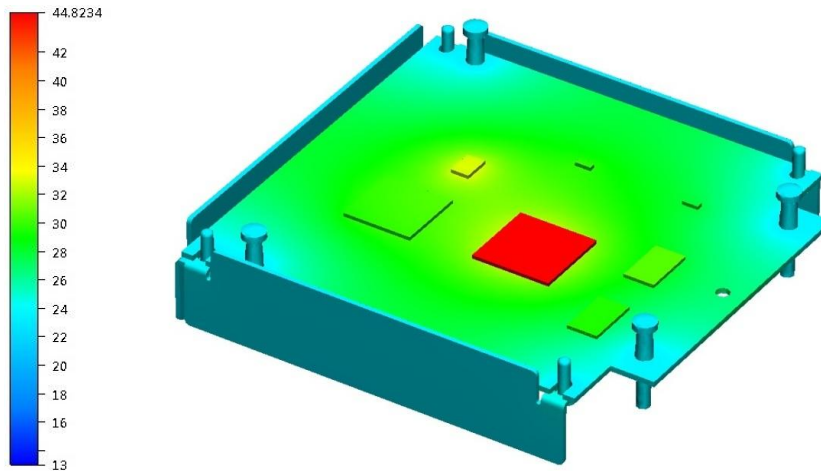
**Figure 6.3** Reduced model with ambient temperature 13 °C

As could be expected, all temperatures were increased by approximately 10 °C. Since many properties, like conductivity and emissivity, are directly temperature dependent properties this result was not a certain fact. (See chapter 2)

**Table 6.1** Temperature comparison for the decreased ambient temperature

REDUCED			
Component	original [°C]	10°C+	10°C+
			rise [°C(%)]
<b>CPU</b>	54.4	64.2	9.8(18.0%)
<b>Memory</b>	40.5	49.8	9.3(23.0%)
<b>Video chip</b>	39.1	49.3	10.2(26.1%)
<b>Ethernet</b>	38.6	48.1	9.5(24.6%)
<b>PCB/Others</b>	40.0	48.8	8.8(22.0%)
<b>Bottom cover</b>	32.3	42.5	10.2(31.6%)
<b>Average</b>	-	-	<b>9.6(24.2%)</b>

## 6.2.2 Decrease the Surrounding Air Temperature with 10 °C



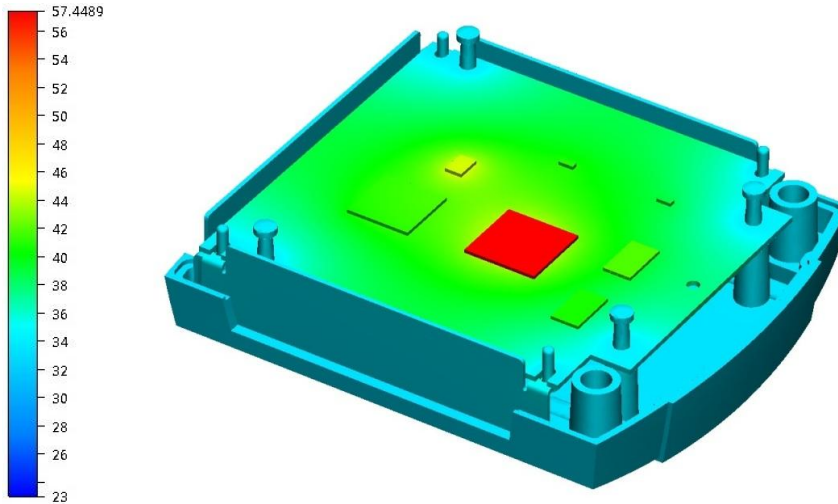
**Figure 6.4** Reduced model with ambient temperature 33 °C

All temperatures were decreased by about 10 °C. The effect from increasing and decreasing the ambient temperature seems to be *linear* to the temperatures inside the product. With this conclusion drawn, no more scenarios where the ambient temperature is changed are considered to be needed. If the linear relation is valid beyond the temperature range of 13 to 33 degrees is of course not for certain before further simulations with ambient temperature changes are made.

**Table 6.2** Temperature comparison for the increased ambient temperature

REDUCED			
Component	original [°C]	10°C-	10°C-
			rise [°C(%)]
<b>CPU</b>	54.4	44.8	-9.6(-17.6%)
<b>Memory</b>	40.5	30.5	-10.0(-24.7%)
<b>Video chip</b>	39.1	30.1	-9.0(-23.0%)
<b>Ethernet</b>	38.6	28.1	-10.5(-27.2%)
<b>PCB/Others</b>	40.0	29.5	-10.5(26.3%)
<b>Bottom cover</b>	32.3	22.8	-9.5(-29.4%)
<b>Average</b>	-	-	<b>-9.9(-24.7%)</b>

### 6.2.3 Increase the Overall Power Consumption with 10 %



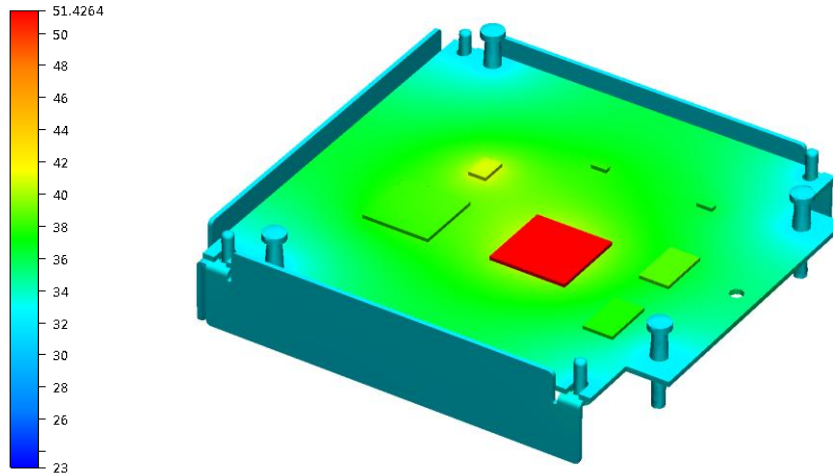
**Figure 6.5** Reduced model where the power consumption is increased by 10 %

Since the power consumption was raised by a factor and not by a set number of Watts, the components with high power consumption were the ones that suffered the biggest temperature raise. The CPU-chip temperature increased by 3 °C, the video chip and the RAM chips increased by 2 °C. It appears also as this type of modification will affect areas that lay close to the heat sources in the "heat chain" more than other areas. This differs from the scenarios with modified ambient temperature where all areas were affected equally. Heat chain means the different steps or medium for the heat to pass between being generated in a component and dissipating in the surrounding air. One of the heat chains or this case could for instance be: Microchip to the PCB to a screw to the cover to the ambient air. Another could be: Microchip to the internal air to the cover to the ambient air.

**Table 6.3** Temperature comparison with 10 % increased power consumption

REDUCED			
Component	original [°C]	W110%	W110%
			rise [°C(%)]
<b>CPU</b>	54.4	57.4	3.0(5.5%)
<b>Memory</b>	40.5	41.8	1.3(3.2%)
<b>Video chip</b>	39.1	41.2	2.1(5.4%)
<b>Ethernet</b>	38.6	39.1	0.5(1.3%)
<b>PCB/Others</b>	40.0	40.8	0.8(2.0%)
<b>Bottom cover</b>	32.3	33.2	0.9(2.8%)
<b>Average</b>	-	-	<b>1.4(3.4%)</b>

## 6.2.4 Decrease the Overall Power Consumption with 10 %



**Figure 6.6** Reduced model where the power consumption is decreased by 10%

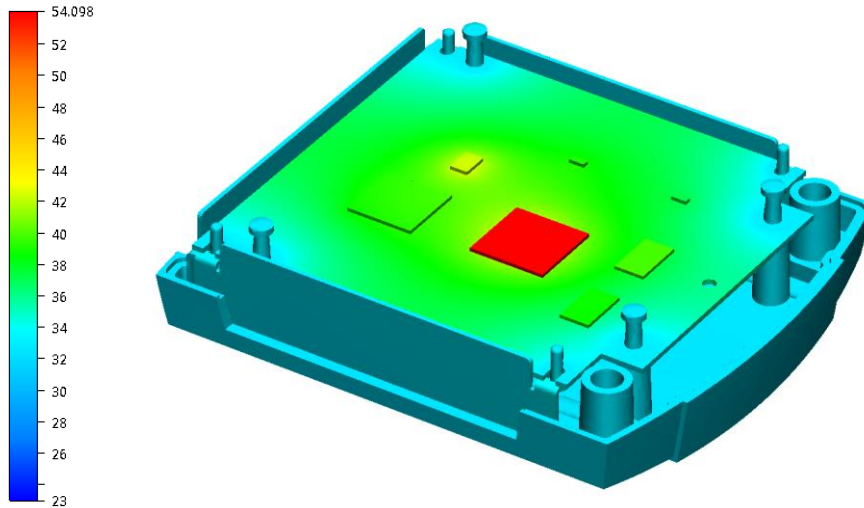
Not surprisingly the results look similar to the previous scenario with the exception that they decrease instead of increase. This simulation was still motivated since it states that the relation between the power consumption and temperature in this type of construction are more or less linear. (The temperatures decreased here as much as they increased in the previous scenario). With only two references (the original scenario and the previous scenario), this would have been impossible to be certain of.

It should be mentioned that the linear behaviour does not need to exist outside the power consumption range that has been tried out in these simulations.

**Table 6.4** Temperature comparison with 10 % decreased power consumption

REDUCED			
Component	original [°C]	W90%	W90%
			rise [°C(%)]
<b>CPU</b>	54.4	51.4	-3.0(-5.5%)
<b>Memory</b>	40.5	38.6	-1.9(-4.7%)
<b>Video chip</b>	39.1	38.1	-1.0(-2.6%)
<b>Ethernet</b>	38.6	37.0	-1.6(-4.1%)
<b>PCB/Others</b>	40.0	38.5	-1.5(-3.8%)
<b>Bottom cover</b>	32.3	31.6	-0.7(-2.2%)
<b>Average</b>	-	-	<b>-1.6(-3.8%)</b>

### 6.2.5 Increase the Cover Conductivity from 95 W/mK to 200 W/mK



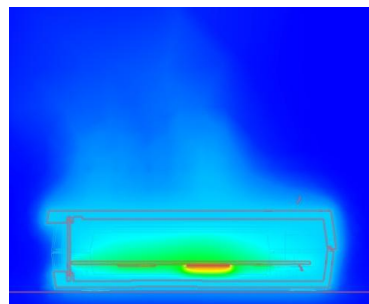
**Figure 6.7** Reduced model with the conductivity  $k = 200 \text{ W/mK}$

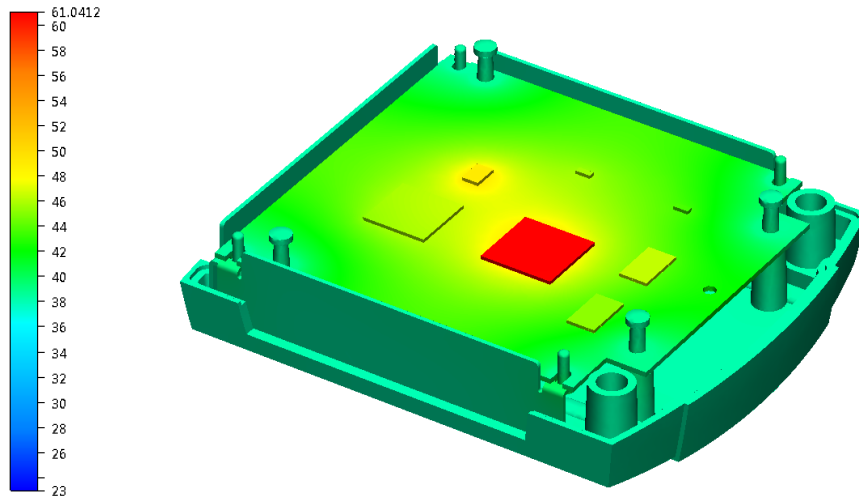
Doubling the conductivity of the cover might seem to be a good thermal improvement. The result shows however that the temperatures are almost the same as before. The reason why can be explained by studying figure 6.8 below, which displays the *original* model showed in a cross section perspective. The reason for increasing the conductivity in a material would be to get rid of eventual temperature gradients. Since there are no big temperature gradients within the cover in the picture (the whole cover is in the same colour in the figure), it is already "as good as it can be". In other words: Raising the conductivity in a material without big temperature gradients is unnecessary. However, between the cover and surrounding air a huge gradient can be seen. If this interface somehow could be affected that would be of bigger interest. One of the parameters that have influence over the heat exchange here is the emissivity, which was simulated in the next scenario.

**Table 6.5** Temperature comparison for  $k=200$

REDUCED			
Component	original [°C]	k=200	k=200
			rise [°C(%)]
<b>CPU</b>	54.4	54.0	-0.4 (-0.7%)
<b>Memory</b>	40.5	39.8	-0.7 (-1.7%)
<b>Video chip</b>	39.1	39.4	0.3 (0.8%)
<b>Ethernet</b>	38.6	38.1	-0.5 (-1.3%)
<b>PCB/Others</b>	40.0	38.6	-1.4 (-3.5%)
<b>Bottom cover</b>	32.3	32.5	0.2 (0.6%)
<b>Average</b>	-	-	<b>-0.4 (-1.0%)</b>

**Figure 6.8** Cross section



6.2.6 Decrease the Cover Emissivity from  $e = 0.95$  to  $e = 0.05$ 

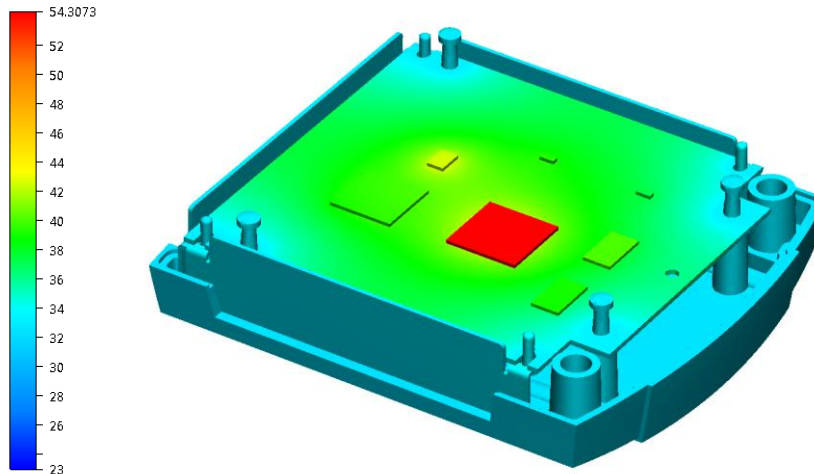
**Figure 6.9** Cover emissivity decreased from  $e = 0.95$  to  $0.05$

This simulation was done to study the exact influence of a drastic emissivity decrease on the covers outer surface. The new emissivity of 0.05, which for instance could symbolize a polished aluminium surface, resulted in a great rise of all the critical temperatures. This shows the importance of not only choosing materials with good conductivity but also with an appropriate emissivity. It should be mentioned that since the radiated heat in our case consists of infrared radiation; it will not be affected by choice of the surface *colour*. As a result it will never matter what colour that is chosen for the cover; merely the *surface finish* is of importance. However if the product will be exposed to sunlight the choice of colour once again becomes important, since the energy in sunlight lies mainly within the visible light spectra.

**Table 6.6** Temperature comparison for the decreased emissivity

REDUCED			
Component	original [°C]	e=0.05	e=0.05
			rise [°C(%)]
<b>CPU</b>	54.4	61.5	7.1(13.1%)
<b>Memory</b>	40.5	46.3	5.8(14.3%)
<b>Video chip</b>	39.1	46.0	6.9(17.6%)
<b>Ethernet</b>	38.6	44.6	6.0(15.5%)
<b>PCB/Others</b>	40.0	45.6	5.6(14.0%)
<b>Bottom cover</b>	32.3	38.0	5.7(17.6%)
<b>Average</b>	-	-	<b>6.2(15.4%)</b>

### 6.2.7 Replace the 8 Steel Screws with Silver Screws



**Figure 6.10** Reduced model with 8 silver screws instead of steel screws

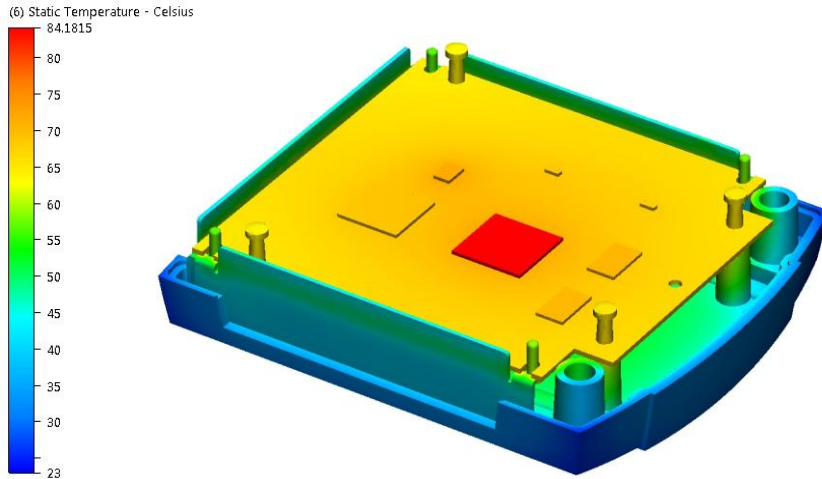
Replacing the steel screws with silver screws will greatly decrease the thermal resistance through the screws. This was done to find out if the screws themselves acted as a bottleneck for the heat flow between the PCB and the cover. It turned out though that they did not; the temperatures are pretty much the same as before. The conclusion that could be drawn here is that the screws, despite their low conductivity and small cross sections, are not where the heat confronts the real resistance. The real bottleneck, as could be seen in the figure above, is between the CPU and the PCB (huge colour difference). The second biggest resistance is the PCB itself. Compared to these huge resistances the screws actually transport heat quit well, and thus have no real need of being replaced. However, if the other two bottlenecks were somehow drastically decreased, then it could be a good idea to once again considering improving the screw properties.

**Table 6.7** Temperature comparison for the improved conductivity on the screws

REDUCED			
Component	original [°C]	Silver screws	Silver screws
			rise [°C(%)]
<b>CPU</b>	54.4	54.3	-0.1(-0.2)
<b>Memory</b>	40.5	40.0	-0.5(-1.2%)
<b>Video chip</b>	39.1	39.7	-0.6(-1.5%)
<b>Ethernet</b>	38.6	38.3	-0.3(-0.8%)
<b>PCB/Others</b>	40.0	38.6	-1.4(-3.5%)
<b>Bottom cover</b>	32.3	32.4	-0.1(-0.3%)
<b>Average</b>	-	-	<b>-0.3(-0.6%)</b>



### 6.2.8 Replace the Aluminium Cover with a Plastic Cover



**Figure 6.11** Reduced model with a plastic cover

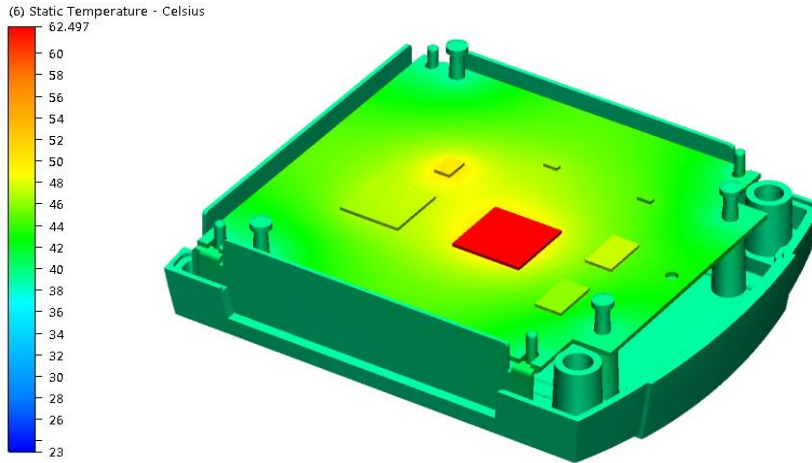
First of all, the huge thermal resistance in the cover can easily be observed from the picture above by looking at the great colour differences over the material. The plastic material can obviously not provide the necessary heat spread for cooling this product efficiently. The corners of the cover appear in dark blue which is not even higher than the ambient temperature around the product. This will of course result in a cooling effect of zero between these parts of the cover and the surroundings which is clearly not desirable. It could also be seen in the picture that now when the heat is having a hard time going through the screws and down through the cover due to the covers low conductivity, more heat will go through the side panels. This could be seen by looking at the green horizontal stripe across the nearest side panel; the heat from the PCB is heating the panel, making it about 5 degrees hotter along this stripe. In the previous simulations no such temperature difference could be seen on the panels.

**Table 6.8** Temperature comparison for the exchanged cover material

REDUCED			
Component	original [°C]	Plastic cover	Plastic cover
			rise [°C(%)]
<b>CPU</b>	54.4	84.2	29.8(54.8%)
<b>Memory</b>	40.5	70.5	30.0(74.1%)
<b>Video chip</b>	39.1	69.0	29.9(76.5%)
<b>Ethernet</b>	38.6	68.3	29.7(76.9%)
<b>PCB/Others</b>	40.0	68.9	28.9(72.3%)
<b>Bottom cover</b>	32.3	59.4	27.1(83.9%)
<b>Average</b>	-	-	<b>29.2(73.1%)</b>



### 6.2.9 Do the Simulation without Taking the Heat Radiation into Account



**Figure 6.12** The simulated values without radiation

In CFDesign the user are able to choose whether the application should take the radiation into account or not; in this modulation the function was excluded. Not surprisingly the results are similar to those of the case with decreased emissivity.

So apparently the CPU temperature would be about *seven* degrees higher if the phenomena radiation would not exist. It is, however, important to mention that the bigger the thermal resistance is in the other two paths (conduction and convection), the bigger relative influence the radiation will have. A drastic decrease of the PCB conductivity for example would also drastically raise this number of seven degrees.

**Table 6.9** Temperature comparison without radiation

REDUCED			
Component	original [°C]	No radiation	No radiation
			rise [°C(%)]
<b>CPU</b>	54.4	62.5	8.1(14.9%)
<b>Memory</b>	40.5	47.4	6.9(17.0%)
<b>Video chip</b>	39.1	47.1	8.0(20.5%)
<b>Ethernet</b>	38.6	45.6	7.0(18.1%)
<b>PCB/Others</b>	40.0	46.3	6.3(15.8%)
<b>Bottom cover</b>	32.3	38.8	6.5(20.1%)
<b>Average</b>	-	-	<b>7.1(17.7%)</b>

### 6.3 Simplifying the Model Further

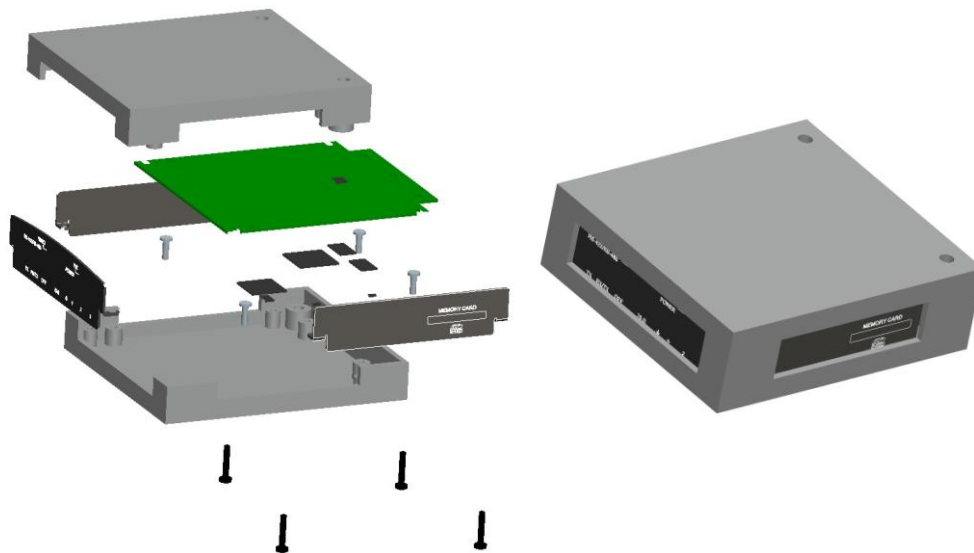
The remaining six fictive scenarios contained more complex geometry changes than the first nine scenarios. Since the CAD-model's cover was considered difficult to modify according to these geometry changes, a new, very simple cover was design in Pro/Engineer. Before it could be used it had to be verified that a simulation with this cover did not deviate too much from the Reduced Model's cover. Thus a new validation had to be made. The model with this new simplified cover will be referred to as the Simplified Model.

The same simulation set up will be performed with this simplified model. This result will be compared with both the laboratory tests and the Reduced Model simulation results.

Creating the simplified model also had another important purpose; since it was created from scratch it would prove that thermal simulations can also be done on a very simple geometry, just like it would have in a development process of a new product.

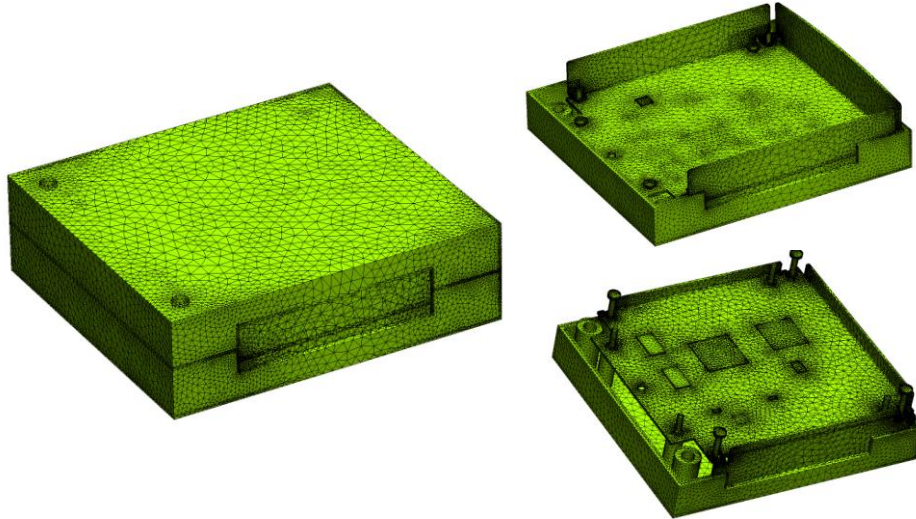
#### 6.3.1 Creating the Simplified Model and Setting it up in CFXDesign

The PCB was placed in a simple box, consisting of a bottom and a top cover. The side plates were the same in this model, since they are simple parts already. The measurements were taken directly from the original model, like height, width and depth. To arrange the same conditions the screw bosses was modelled as in the original model. Below is a figure of the simplified model in exploded and in closed view.



**Figure 6.13** The simplified model of the encoder in exploded and closed view

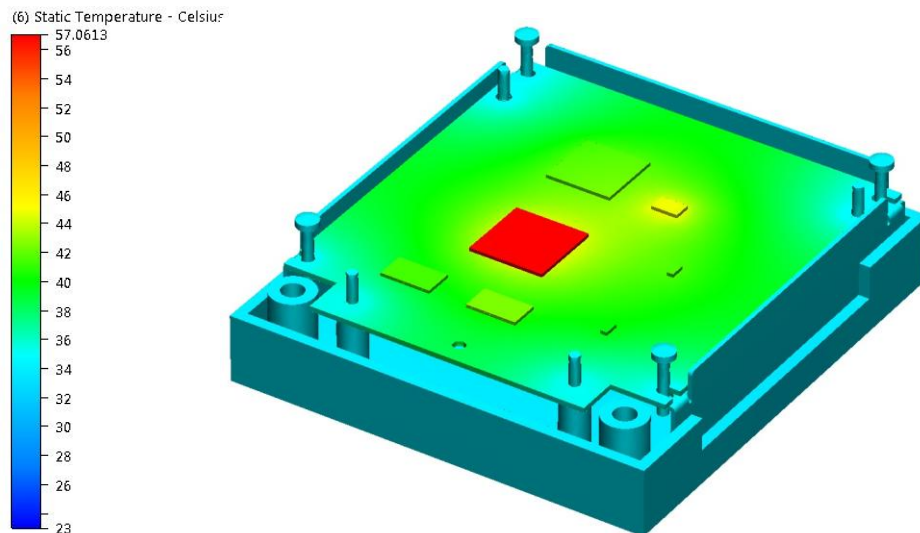
The analysis in CFDesign was set up exactly in the same way as the reduced model. Then the encoder was meshed like previously except from the fact that the element count was much lower since the geometry was less complex; approximately half the amount of elements. Below is a figure of the mesh for the simplified model.



**Figure 6.14** The mesh of the simplified model

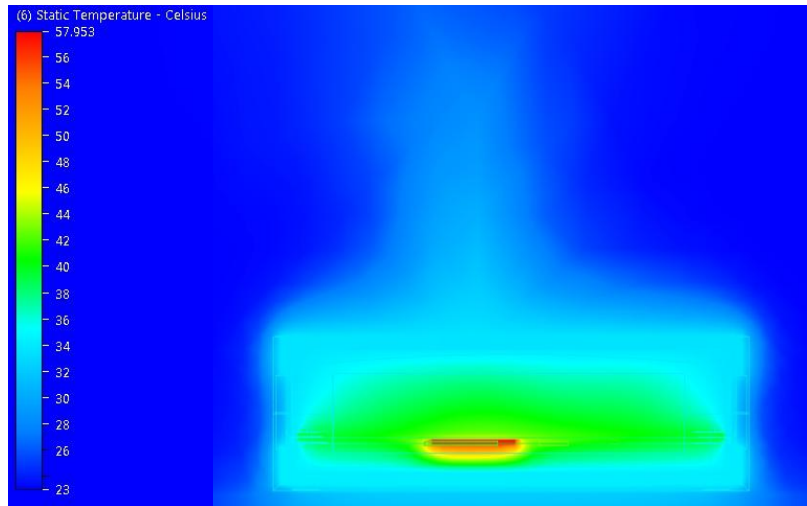
### 6.3.2 Analysing the Results of the Simplified Model

The simplified model was simulated and compared to the reduced model. Below follows a number of pictures from the result to verify that the model does not deviate considerably from the reduced model. The first picture shows the temperature results.



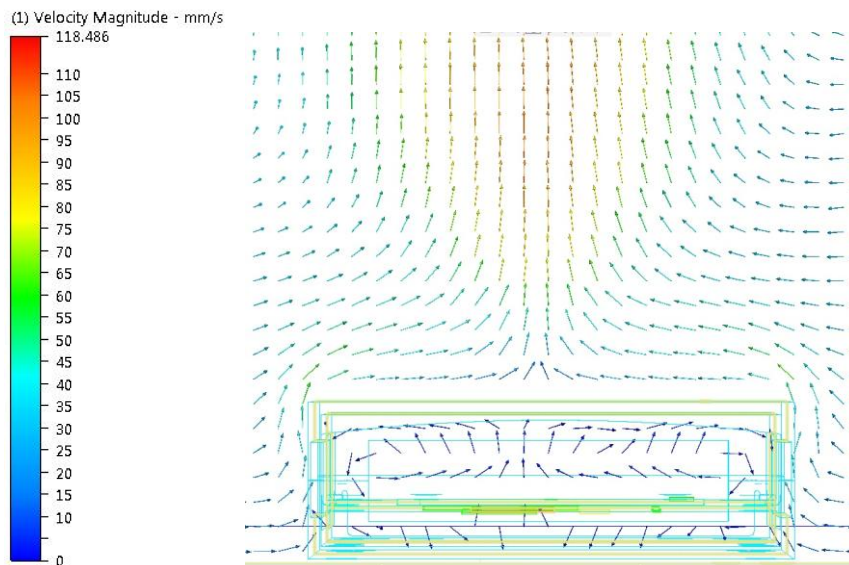
**Figure 6.15** The temperatures on the simplified model

The figure below shows a cross section of the simplified model.



**Figure 6.16** A cross section show the temperatures inside the simplified model

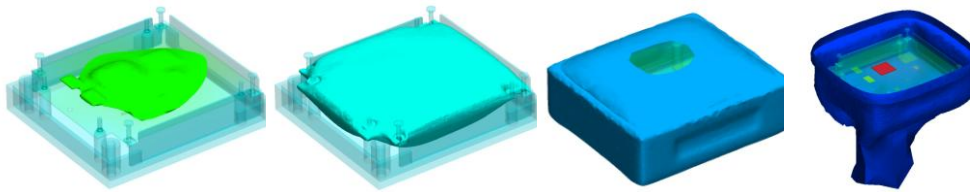
The vector image below show how the air moves inside and outside the encoder.



**Figure 6.17** A vector image of the air inside and outside the encoder

The results so far did not indicate any significant deviations from the results of the reduced model. To substantiate this statement an *iso curve analysis* was also made. This is done by choosing a fix temperature. The iso curve then shows *only* the substance with this fixed temperature.

See the iso curve figure below. The iso curve (the first from left) at 40 degrees shows that the higher temperature is concentrated around the chips and that the heat dissipates from here to the other parts of the encoder. The PCB holds entirely 35 degrees and it can be noticed that heat is transferred through the screws. Since they have less volume they have less ability to spread the heat, even if they have good conductive abilities. The cover holds 30 degrees. The iso curve is even and shows that the heat travels smoothly through the high conductive cover. The last picture below shows how the convection affects the encoder. The air below holds 25 degrees Celsius. Since air is a bad heat transfer fluid the temperature only manage to increase by 2 degrees compared to the surrounding temperature.



**Figure 6.18** Iso curves on the encoder from left at 40, 35, 30 and 25 degrees Celsius

Even the iso curves indicate that the heat generation and the heat dissipation corresponds to a real scenario. The temperatures of the simplified model were now taken from the results and compared to the temperatures of the reduced model.

### 6.3.3 Comparison between the Simplified Model and the Reduced Model

The table below shows the temperatures of the simplified model and the reduced model.

**Table 6.10** The temperatures results of the simplified model and the reduced model

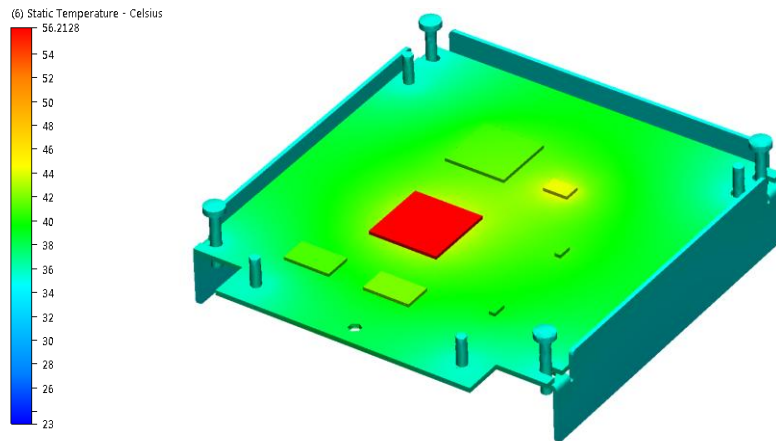
Location	Temperatures, reduced model [°C]	Temperatures, simplified model [°C]	Deviation from reduced model [%]
CPU	54.4	56.3	5
Memory	40.5	42.5	10
Video chip	39.1	41.8	-7
Ethernet	38.6	40.6	5
PCB	40	39.9	-3
Cover	32.3	33.5	4
Ambient air	23	23	0

The same type of comparison was now made as in the validation section 5.3, where it was declared that a 10 % deviation was acceptable and a 5 % deviation was very good [4]. Since no temperature deviated more than 10 % the simplified model was considered validated for further simulating.

## 6.4 Analysing Results of the Remaining 6 Fictive Scenarios

In the following section the remaining six of the fictive scenarios are run with this new simplified model. The analysis will follow the same pattern as the analysis for the reduced model.

### 6.4.1 Remove the Top Cover



**Figure 6.19** Top cover removed

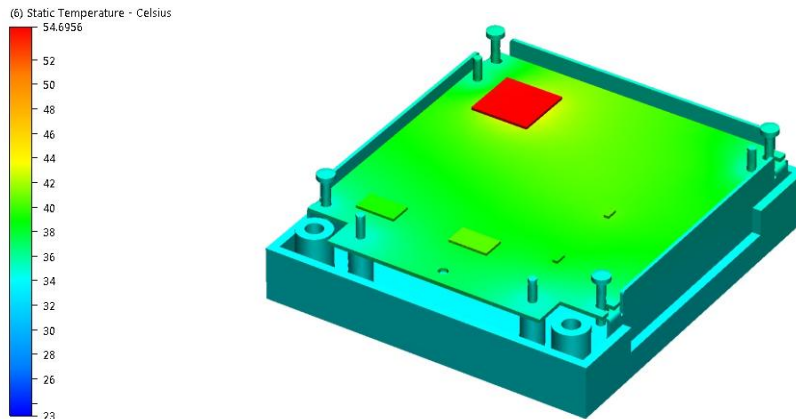
Here the top cover was removed. The cooling effect was however not as big as expected (the temperature values in the legend below are almost identical.) Observe though that almost all the heat generating components are placed under the PCB, facing the bottom cover. Therefore, even when the top cover is removed, those components will still be trapped between the PCB and the bottom cover, which is probably why removing the top cover does not result in any significant improvements. Furthermore, removing the top cover will result in a decreased aluminium volume. The cover therefore contained less material that has good heat transfer abilities than before.

**Table 6.11** Temperature comparison in the simulation with no cover

SIMPLIFIED MODEL			
Component	original(°C)	No cover	No cover
			rise [°C(%)]
<b>CPU</b>	57.1	56.2	-0.9(-1.6%)
<b>Memory</b>	42.5	41.2	-1.3(-3.1%)
<b>Video chip</b>	42.0	41.8	-0.2(-0.5%)
<b>Ethernet</b>	40.6	39.8	0.8(-2.0%)
<b>PCB/Others</b>	41.7	41.3	-0.4(-1.0%)
<b>Bottom cover</b>	34.3	34.1	-0.2(-0.6%)
<b>Average</b>	-		<b>-0.6(-1.4%)</b>



### 6.4.2 Compose the Components Wide Apart on the PCB



**Figure 6.20** Components spread out over the PCB

This simulation and the next simulation were done to study the influence of component placement on the PCB. Here the components has been spread out, and furthermore been placed as closed to the cooling screw bosses as were considered possible. The most critical component, the CPU, has been placed far from the rest for optimized cooling effect.

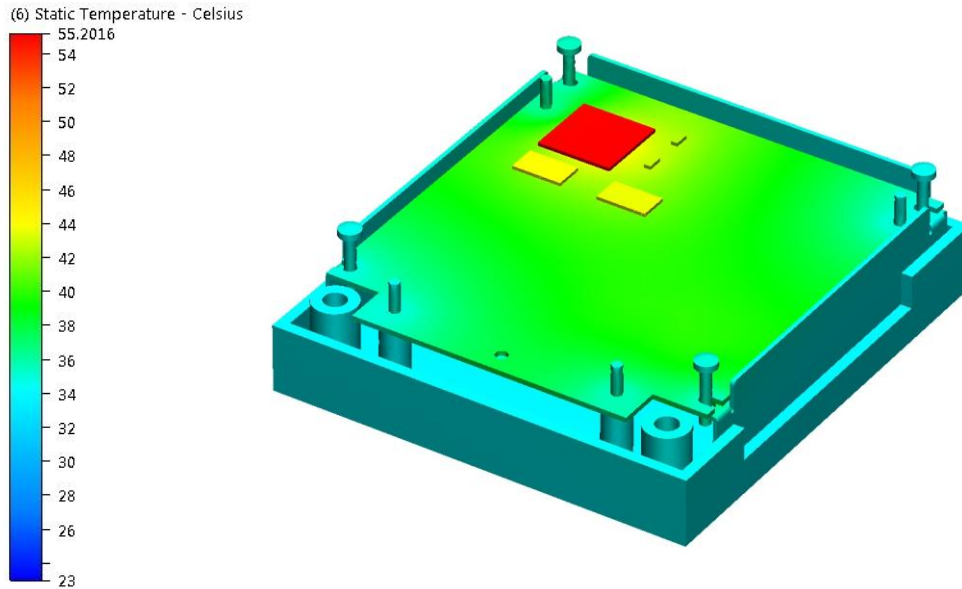
The results show a CPU temperature decrease of about 2.5 degrees Celsius. It is clearly an improvement, but in relation to the sacrifice it could not be considered enough. In reality, these types of component movements are in general not possible. Smaller movements would probably be possible, but since the scenario above is considered to be one of the most thermally optimized, smaller movements would only provide smaller improvements. Since these improvements are not bigger than one or two degrees, further movement optimization on this PCB is considered unnecessary.

It is thereby not stated that component placement is unimportant during thermal optimization; one has to keep in mind that the components were quit spread out before the movements that were done in this simulation.

**Table 6.12** Temperature comparison for spread components on the PCB

SIMPLIFIED MODEL			
Component	original(°C)	Spread comp	Spread comp rise [°C(%)]
<b>CPU</b>	57.1	54.7	-2.4(-4.2%)
<b>Memory</b>	42.5	40.1	-2.4(-5.6%)
<b>Video chip</b>	42.0	40.6	-1.4(-3.3%)
<b>Ethernet</b>	40.6	39.3	-1.3(-3.2%)
<b>PCB/Others</b>	41.7	40.3	-1.4(-3.4%)
<b>Bottom cover</b>	34.3	34.4	0.1(0.3%)
<b>Average</b>	-		<b>-1.5(-3.2%)</b>

### 6.4.3 Compose the Components Tightly Together on the PCB



**Figure 6.21** Components tightly packed together on the PCB

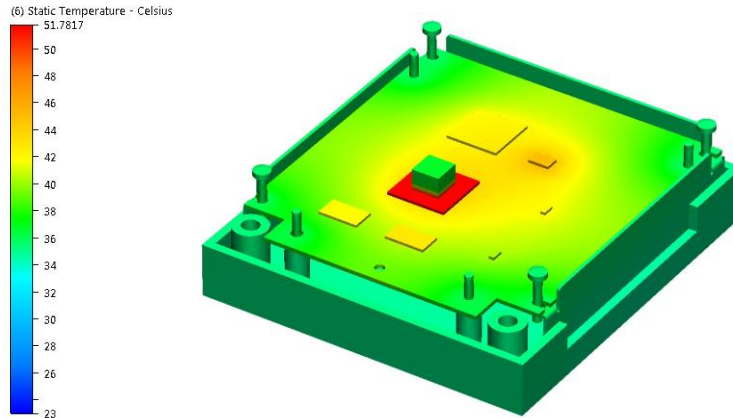
Here the components were packed together and placed in a corner of the PCB. An interesting effect here was that all temperatures were not raised as one maybe would guess; the CPU and the PCB average temperature was actually significantly lower. The reason is that the CPU, the dominant heat generator, now was placed close to one of the obvious heat channels, the screws. This is despite of the fact that the chip is surrounded by all the other heat generating components. As a conclusion, at least for this type of geometries, it seems more important to place the components closer to eventual heat channels than spreading them far from each other. Of course this depends strongly on the specific geometry of a product.

**Table 6.13** Temperature comparison for placing the components close together

SIMPLIFIED MODEL			
Component	original(°C)	Comp close	Comp close
			rise [°C(%)]
<b>CPU</b>	57.1	55.2	-1.9(-3.3%)
<b>Memory</b>	42.5	43.5	1.0(2.4%)
<b>Video chip</b>	42.0	40.1	-1.9(-4.5%)
<b>Ethernet</b>	40.6	41.2	0.6(1.5%)
<b>PCB/Others</b>	41.7	39.5	-2.2(-5.3%)
<b>Bottom cover</b>	34.3	34.4	0.1(0.3%)
<b>Average</b>	-		<b>-0.7(-1.5)</b>



#### 6.4.4 Place an Aluminium Block Between the CPU and the Bottom Cover



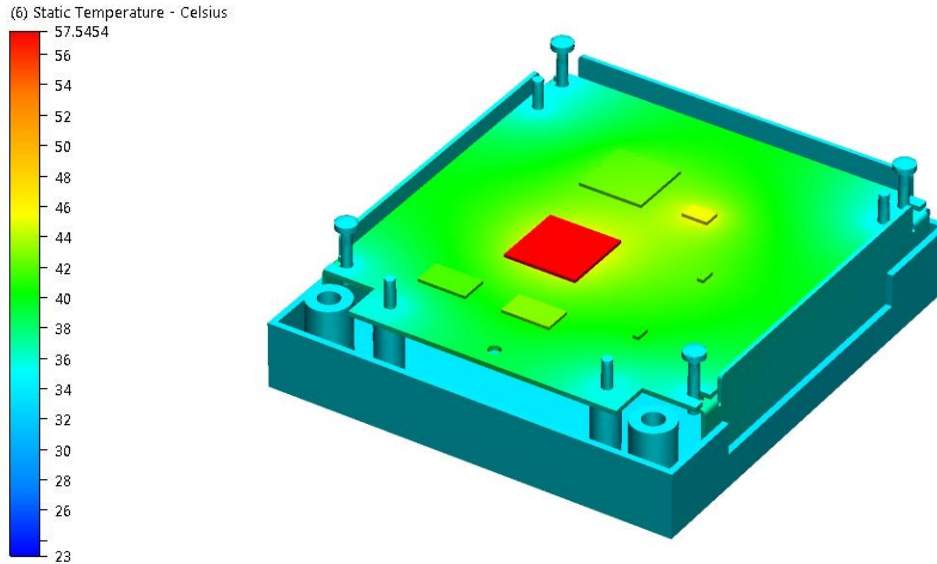
**Figure 6.22** Aluminium block placed between the CPU and the bottom cover

An 8x8x4 mm aluminium block was here placed in between the CPU and the bottom cover. As a result, a great deal of the heat was transferred directly from the CPU to the bottom cover. The improvements were considerable; The CPU temperature dropped from 57.1 down to 51.8 degrees Celsius. The cover temperature were as a consequence raised a couple of degrees, otherwise no bigger temperature changes occurred. Needless to say this is a proper method to use from a thermal point of view. From an economic and a production point of view it is considered a possible solution; the aluminium block could possibly be part of the bottom cover, moulded together as one part. Of course this would demand high tolerances between the chip and the aluminium block, but in some situations it still could be worth it. Since perfect tolerances never occur it is recommended to place a TIM material between the aluminium block and the chip. Here a detailed consideration has to be done though; higher tolerances will cost more but on the other hand the gap between the chip and the box will decrease and the TIM will be thinner. This will decrease the thermal resistance and make the solution more efficient, since the biggest thermal resistance in a solution like this exists in the TIM material.

**Table 6.14** Temperature comparison with the aluminium block

SIMPLIFIED MODEL			
Component	original(°C)	Al-block	Al-block
			rise [°C(%)]
<b>CPU</b>	57.1	51.8	-5.3(-9.3%)
<b>Memory</b>	42.5	42.7	0.2(0.5%)
<b>Video chip</b>	42.0	42.2	0.2(0.5%)
<b>Ethernet</b>	40.6	41.1	0.5(1.2%)
<b>PCB/Others</b>	41.7	41.8	0.1(0.2%)
<b>Bottom cover</b>	34.3	36	1.7(5.0%)
<b>Average</b>	-		<b>-0.4(-0.3%)</b>

## 6.4.5 Cover Exchanged to Zinc and Cover Thickness Decreased by 0.5 mm



**Figure 6.23** The cover material is changed to zinc

The current aluminium used for the cover has a conductivity of 95 W/mK. Zinc has a conductivity of 135 W/mK why this was tried out as an alternative cover material. To make the scenario more realistic the cover thickness was also decreased from 2.5 mm to 2mm since this would be a more proper choice for a zinc cover.

The results show that the temperatures are about the same as before. Since zinc is more expensive than aluminium, both per weight and for processing, this turned out to be a bad choice. A better choice would in that case be to replace the aluminium with a different alloy with higher conductivity. As this was tried out in a previous simulation without any bigger improvements, the cover material choice could be considered good as it is.

**Table 6.15** Temperature comparison with a thinner cover

SIMPLIFIED MODEL			
Component	original(°C)	Thin cover (zinc)	Thin cover (zinc)
			rise [°C(%)]
<b>CPU</b>	57.1	57.5	0.4(0.7%)
<b>Memory</b>	42.5	42.9	0.4(0.9%)
<b>Video chip</b>	42.0	42.4	0.4(1.0%)
<b>Ethernet</b>	40.6	41.1	0.5(1.2%)
<b>PCB/Others</b>	41.7	42.1	0.4(1.0%)
<b>Bottom cover</b>	34.3	34.6	0.3(0.9%)
<b>Average</b>	-		<b>0.4(0.9%)</b>

6.4.6 Increase the Cover Air Volume by 200 %

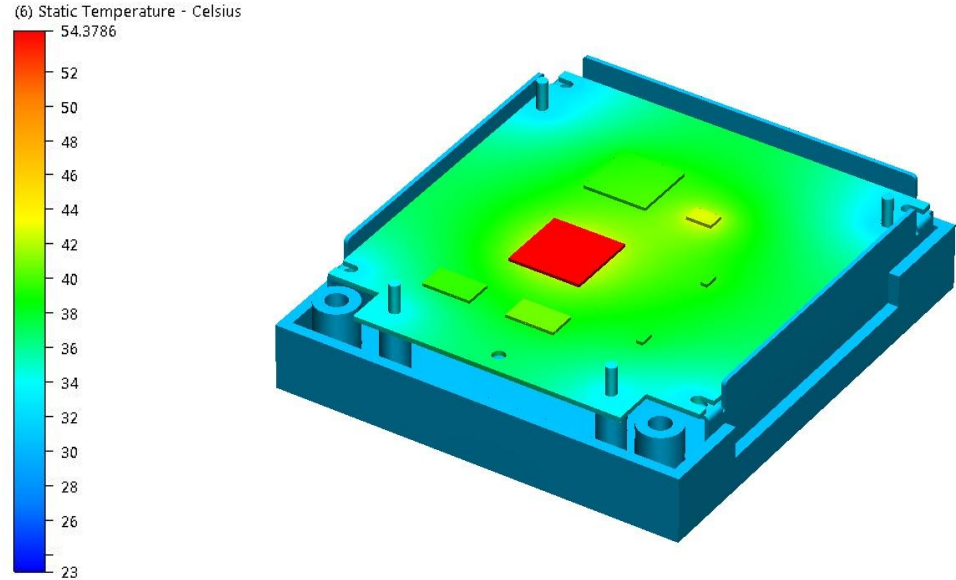


Figure 6.24 Cover volume increased

Since the space between the PCB and the bottom cover is too small for efficiently cooling convectional currents can arise this scenario was tried out. Here the bottom cover was decreased so that the total air volume inside the product was increased by about 200 %, see the figure below.

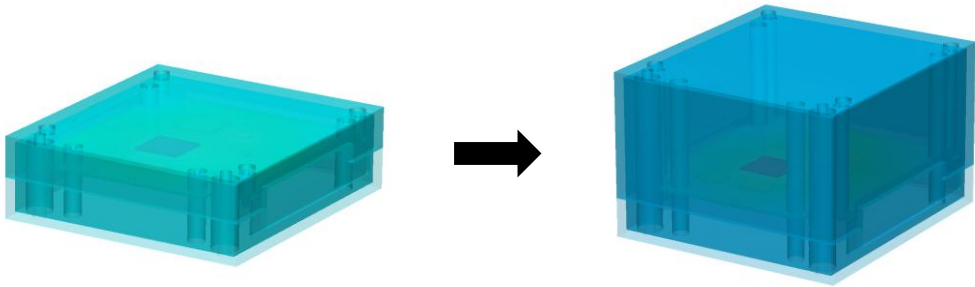
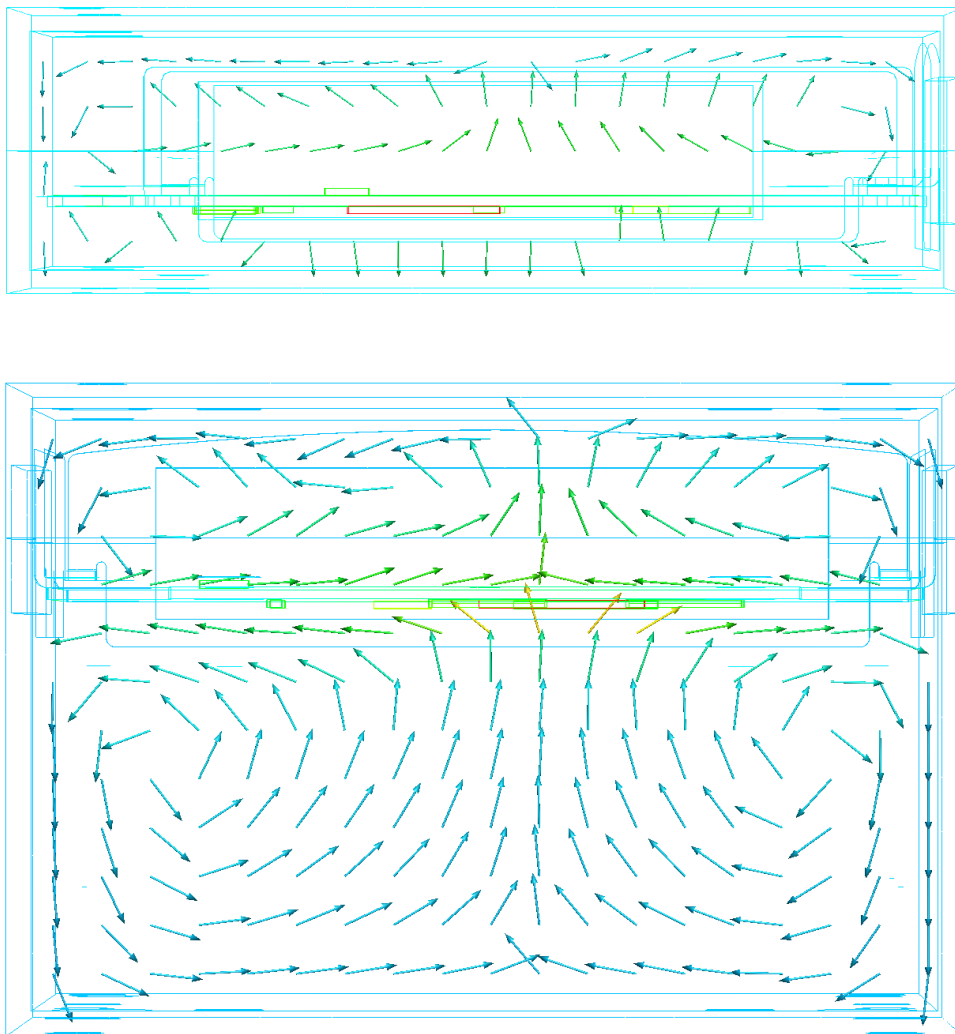


Figure 6.25 Cover volume was increased by 200 %. Observe that the product is upside down in this picture

The next figure shows the velocity vectors for the air moving inside the product. The upper figure is the old cover, below is the new cover. The green horizontal plate in the middle of the figures is the PCB. See how the typical circular currents arise in the new cover. Heated air is being pressed to the sides because of the colder air in the middle. When hitting the walls of the cover the air will be cooled down. Since this air will be colder than the air in the middle of the product this will fall down to the bottom, forcing the air in the middle upwards and so on. The cooling effect would of course be stronger if the hot components were placed at the bottom and the heated air was allowed to travel upwards. It is never the less interesting to see that the phenomena occur even when the hot components are placed in the top.



**Figure 6.26** Convectional circular currents arise when the cover is increased

The result legend below however shows that the temperature drop is marginal; only 3 degrees Celsius for the CPU chip. This is valuable information since it states that these kinds of modifications are not as effective as one may think. On the other hand these results also support the earlier statements in the simulation where the top cover was removed completely. Here it was pointed out that no cooling effect is achieved when increasing the air volume on the wrong side of the PCB. Since it in this simulation was increased *below* the PCB, at least *some* cooling effect can be seen. (Compare the results below and the results from the simulation above where the top cover was removed.)

**Table 6.16** Temperature comparison with a deepened cover

SIMPLIFIED MODEL			
Component	original(°C)	Deepened	Deepened
			rise [°C(%)]
<b>CPU</b>	57.1	54.4	-2.7(-4.7)
<b>Memory</b>	42.5	40.3	-2.2(-5.2%)
<b>Video chip</b>	42.0	39.3	-2.7(-6.4%)
<b>Ethernet</b>	40.6	38.3	-2.3(-5.7%)
<b>PCB/Others</b>	41.7	39.1	-2.6(-6.2%)
<b>Bottom cover</b>	34.3	30.7	-3.6(-10.5%)
<b>Average</b>	-		<b>-2.7(-6.5%)</b>

### 6.5 Planning and Choosing the Combined Scenarios

When doing thermal optimization a lot of different parameters are changed, just as in the previous row of simulations. So say for instance that increasing the volume would result in a temperature drop of 3 degrees Celsius, and putting in silver screws would result in a temperature drop of 2 degrees. Would *both* increased cover volume and silver screws then result in a 5 degrees drop? Or perhaps just in 3 degrees? Or somewhere in between? These are of course important relations to understand which is why a number of *combined scenarios* were made as well.

To obtain a better overview of which combinations that was possible the matrix below was set up. The X- and Y-axis in the matrix contain the fictive scenarios, and by choosing one scenario from every axis a combination box appears somewhere in the matrix. The numbers (1-52) describes the scenarios and the numbers (1-16) in the parenthesis is the chosen combined simulated scenarios.

Matrix	10 C+	W+10%	k=200	plastic	silver	no cover	packed	spread	Albox	thin	high
10 C+											
W+10%	1(1)										
k=200	2	3(2)									
plastic	4	5									
silver	6	7(3)	8(4)	9							
no cover	10	11(5)	12	13(6)	14						
packed	15	16(7)	17	18	19(8)	20					
spread	21	22(9)	23	24	25(10)	26					
Albox	27	28(11)	29(12)	30(13)	31	32	33(14)	34(15)			
thin	35	36	37		38	39	40	41	42		
high	43	44(16)	45	46	47	48	49	50	51	52	

Figure 6.27 Combination matrix

With this matrix as reference all the combinations were discussed. All the grey fields in the matrix are combinations that were not possible. This could be if one combination appears two times on the matrix, or if the scenarios simply cannot be combined. The white areas represent combinations that were considered unnecessary to simulate. The yellow areas represent combinations that are interesting and worth simulating. The green areas represent high priority combinations that really need to be simulated.

To better understand the shortages in the combination matrix, these are explained in the legend below:

**Table 6.17** Description of shortages in figure 6.27, the combination matrix

<b>Shortage:</b>	<b>Description:</b>
<b>10C<sup>o</sup> +</b>	The ambient temperature is increased by 10 degrees Celsius; this is the surrounding temperature of the encoder inside the air cube.
<b>W+10%</b>	The power consumption is increased by 10% on the different components.
<b>k=200</b>	The conductivity on aluminium is increased to 200 W/mK, its original value is 95 W/mK.
<b>plastic</b>	The covers is made out of plastic instead of aluminium.
<b>silver</b>	The eight screws that encoder is assembled with is made out of silver.
<b>no cover</b>	The top cover is removed during the simulation.
<b>packed</b>	The components on the PCB are rearranged with focus on placing them tight together.
<b>spread</b>	The components on the PCB are rearranged with focus on spreading them.
<b>aluminium block</b>	An aluminium block is extruded from the bottom covers along with a TIM (Thermal Interface Material) on the CPU chip, which is the most heat producing circuit.
<b>thin</b>	The covers is made of zinc instead of aluminium and also made thinner, since zinc allows this.
<b>high</b>	The volume of the encoder is extended. The bottom cover is deepened with a factor three.

It should be noted that not all the 15 fictive scenarios are included in the combination matrix. This was considered unnecessary since some of them appear in pairs. For instance raising the ambient temperatures with 10 °C, and decreasing the ambient temperature with 10 °C. If a combination including one of these was simulated, it would not be necessary to do one with the other as well since the combined effect would have already appeared.

For every combination (that is not grey) a motivation was made for why, or why not, a specific combination was picked out. All these motivations follow down below, one for each of the 52 combinations:

1. **(1) The combination between raising the ambient temperature and increasing the power consumption by 10 %.**

As seen in the earlier simulations separately these adjustments made a slight increase in temperature. Will the total temperature change be analogue to the two simulations total change?

2. **The combination between increasing the conductivity on aluminium to 200 W/mK and raising the ambient temperature.**

Since the simulation of rising the conductivity did not show more than a slight difference in temperature. The convectional current limits the heat transfer to the air. An increase in temperature will show almost the same result that only the increase of ambient. This is the reason why this simulation is not particularly interesting.

3. **(2) The combination between increasing the conductivity and increasing the power consumption by 10 %.**

This simulation is interesting to run. Perhaps the simulation could show if there is some connection between increased power consumption and the improved heat transfer properties in the metal.

4. **The combination between a plastic cover and an increase in the ambient temperature with 10 degrees Celsius.**

With a plastic cover the heat does not travel efficiently through the cover, to increase the ambient temperature more give no more information.

5. **The combination between a plastic cover and increasing the power consumption by 10 %.**

With the same argument from simulation 4 the result will only show extremely high temperatures and that is why this simulation is uninteresting.

6. **The combination between using silver screws and increase the ambient temperature with 10 °C.**

The result from simulating the ambient temperature seemed to be more or less linear. Assuming there will be slight difference in the simulation with increased ambient temperature this scenario will not be worth while to run.

7. **(3) The combination between using high conductive screws and increasing the power consumption by 10 %.**

This simulation was interesting in case the screws could transport more heat away if the increased power consumption causes the temperature to rise.



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**8. (4) The combination between using silver screws and increasing the conductivity on the cover to  $k = 200 \text{ W/mK}$ .**

If the use of high conductive screws would give any effect it might be a good idea to increase the conductivity on the aluminium cover.

**9. The combination between using silver screws and replacing the aluminium cover with a plastic cover.**

The earlier results showed an extreme temperature rise with a plastic cover. Since the plastic cover do not transfer heat very good, high conductive screws will not do any difference. This since even if the screws transfer heat away from the PCB the plastic cover will have a high temperature gradient.

**10. The combination between removing the cover and increasing the ambient temperature with  $10 \text{ }^\circ\text{C}$ .**

Even if the removal of the cover increased the conductivity to air from the PCB this will not be enough to match the increase of the ambient temperature. And like previous result this simulation with increased ambient temperature will not show any surprising results.

**11. (5) The combination between removing the cover and increasing the power consumption by  $10 \%$ .**

The increase of the power consumption is affecting the temperature inside the cover. If the cover is separated from each other and only the bottom cover remains this could give some interesting results.

**12. The combination between removing the cover and increasing the conductivity on the aluminium cover to  $k = 200$ .**

If this amount decreases smaller amount of aluminium could transfer the heat away. The convection to the air is not even close to match the ability to absorb the heat when the cover is removed. Since the aluminium already has a low temperature gradient the improvement will not show according to the previous results.

**13. (6) The combination between removing the cover and replacing the aluminium cover with a plastic cover.**

This simulation should be of interest to see how much the temperature does rise and if the convection will increase among the increase of temperature difference between the air and the cover.

**14. The combination between removing the cover and using silver screws.**

This simulation will not give more answers. The previous results showed a slight increase with no cover and a slight decrease with high conductive screws. These separate simulations have to little amount of change to draw any conclusion of except that they do not matter as much.

**15. The combination between placing the components on the PCB close together and increasing the ambient temperature with  $10 \text{ }^\circ\text{C}$ .**

To combine with increasing the ambient temperature is not interesting according to previous results.

**16. (7) The combination between placing the components on the PCB close together and increasing the power consumption by 10 %.**

There is a point to run this simulation. When the power consumption is increasing will the placement of the components matter more or less is the question. The temperature rises with the increased power consumption. The combination will eventually show if the placement or the increased power consumption do matter most.

**17. The combination between placing the components on the PCB close together and increasing the conductivity on the aluminium cover to  $k = 200$ .**

Previous result has shown a low temperature gradient if the power consumption is the same on the aluminium cover. To improve the conductivity even more will not do any difference to this combination either.

**18. The combination between placing the components on the PCB close together and replacing the aluminium cover with a plastic cover.**

Since the components were placed near screw bosses the essence of this placement will be useless in a simulation with plastic. Plastic is a bad heat transfer material.

**19. (8) The combination between placing the components on the PCB close together and using silver screws.**

The simulation was interesting since the heat sources are concentrated near the screws. There could be some increase of conductive ability through the screws when the heat travels shorter distance in the PCB.

**20. The combination between placing the components on the PCB close together and removing the cover.**

The strength in the simulation with close components was to let the heat travel a shorter distance out to the cover. Removing the cover would lead to loss of usefulness of the other simulation combination.

**21. The combination between placing the components on the PCB wide apart and increasing the ambient temperature with 10 °C.**

As already mentioned the simulation result from previous single simulation showed a nearly linear behaviour with increased ambient temperature. To run this simulation further is no meaning because of this.

**22. (9) The combination between placing the components on the PCB wide apart and increasing the power consumption by 10 %.**

Analogue to the combination number 16 the result is interesting if the placement of the components play the big role in the combination.

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**23. The combination between placing the components on the PCB wide apart and increasing the conductivity on the aluminium to  $k = 200$ .**

The previous simulation results showed little effect of increasing the conductivity. This combination will give almost the same result as only placing the components close.

**24. The combination between placing the components on the PCB wide apart and replacing the aluminium cover with a plastic cover.**

The shift of cover material causes extreme temperature rise. The slight decrease of temperature in the simulation with components wide apart will then be negligible.

**25. (10) The combination between placing the components on the PCB wide apart and using silver screws.**

The components that are placed wide apart are close to the screws. This simulation will show if the high conductivity on the screws will play a greater role.

**26. The combination between placing the components on the PCB wide apart and removing the cover.**

When the components were placed closer to the cover it is a bad idea to remove the cover material. If the top cover would be removed less high conductivity material could absorb the incoming heat.

**27. The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and increasing the ambient temperature with  $10\text{ }^{\circ}\text{C}$ .**

Analogue to the former combinations with increased ambient temperature this combination will not give surprising results.

**28. (11) The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and increasing the power consumption by  $10\%$ .**

This simulation is interesting to run if the aluminium block would be even more effective with increased power consumption for the components.

**29. (12) The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and increasing the conductivity on the aluminium to  $k = 200$ .**

The cover in the single simulation with the aluminium block and TIM showed a little higher temperature gradient. In this combination the increased conductivity could play a bigger role than the single simulation with the higher conductivity.

**30. (13) The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and replacing the aluminium cover with a plastic cover.**

The simulation with a plastic cover showed a temperature rise. The simulation with the aluminium block showed a decrease. This simulation will show the impact of the aluminium at a higher temperature.

**31. The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and using silver screws.**

Since the high conductive screws showed little result with the chips placed as original the difference will be small even in this simulation.

**32. The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and removing the cover.**

The meaning of placing the aluminium block on the heated chip was to take advantage of the high conductive cover. The removal of the top cover will decrease this and this simulation was not valid.

**33. (14) The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and placing the components on the PCB close together.**

The single simulations both gave a decreased temperature of the most heat generating chip. The result of these combined could show a higher decrease.

**34. (15) The combination between placing a TIM in combination with a piece of aluminium over the most heat generating chip and placing the components on the PCB wide apart.**

Both these simulations gave the highest increase in the single simulations. The combination of these two would logically give the highest decrease of the combined simulations. This should at this stage be the best solution.

**35. The combination between a thin cover of zinc and increasing the ambient temperature with 10 °C.**

The simulation with a zinc cover was not efficient in a heat decreasing view. Just like previous results with higher ambient temperature the combined simulation will not show surprises. The simulations will not be showing new results combined either.

**36. The combination between a thin cover of zinc and increasing the power consumption by 10 %.**

Since the thin zinc cover did not give a decrease of temperature the increased power consumption will only add more heat. The contributed heat from the separate cases will be hard to discover.

**37. The combination between a thin cover of zinc and increasing the conductivity on the aluminium to  $k = 200$ .**

A zinc cover has a higher conductivity already. No temperature gradients were shown on the results from the single zinc cover scenario.

**38. The combination between a thin cover and changing the cover material to plastic.**

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The results from the single scenario with a thin cover showed an increased temperature. To change the material to plastic would increase the temperature further and not give any particularly interesting results.

**39. The combination between a thin cover of zinc and using silver screws.**

From earlier results with silver screws and components placed as originally no gain was made of this.

**40. The combination between a thin cover of zinc and removing the cover.**

The simulation with no cover showed that convection does not have as much effect as wanted. This simulation is not worth to run to discover the same results over again.

**41. The combination between a thin cover of zinc and placing the components on the PCB close together.**

As shown from the simulation with the zinc cover the ability to absorb the heat decreased. To place the components close will not show a better result than the simulation with an aluminium cover.

**42. The combination between a thin cover of zinc and placing the components on the PCB wide apart.**

Analogue to the combined simulation with close components a less good result showed in the single simulations.

**43. The combination between deepen the bottom cover and increasing the ambient temperature**

The deepened cover showed little effect of the natural convection. Even if the convection current existed the ability to cool was inefficient. To increase the ambient temperature will not show any surprising results analogue to former single simulation.

**44. (16) The combination between deepen the bottom covers and increasing the power consumption by 10 %.**

Since the convection inside the cover was low the combination will give an interesting result. The increased power consumption will increase the temperature without the deepened cover will be able to match this increase.

**45. The combination between deepen the bottom covers and increasing the conductivity on the aluminium to  $k = 200$ .**

The temperature gradient was indefinitely in the single simulation with the deepened cover. The conductivity increase will not be showing in this combined simulation.

**46. The combination between deepen the bottom cover and replacing the aluminium cover with a plastic cover.**

The convection might increase a bit from the increased temperature with the replaced plastic cover. Still the increase will not match the increase of the temperature in the plastic cover.

**47. The combination between deepen the bottom cover and using silver screws.**

High conductivity screws will not show any improvements since negligible change occurred in the single simulation. As well as the single solution with deepened bottom cover.

**48. The combination between deepen the bottom covers and removing the cover.**

With small differences between the single simulation and the original the combination will not give an interesting result.

**49. The combination between deepen the bottom covers and placing the components on the PCB close together.**

The placement of the components may decrease the temperature slightly. Still the convection will not increase and the combination will not give much better result than the single solutions.

**50. The combination between deepen the bottom covers and placing the components on the PCB wide apart.**

Analogue to the combination 49 the simulation will not give the decrease in temperature that would make the difference. The convection current is too weak inside the cover and the temperature decrease of placing the components wide is too small.

**51. The combination between deepen the bottom covers and placing a TIM in combination with a piece of aluminium over the most heat generating chip**

The geometry to make an aluminium piece to touch both the TIM and the cover will be unreal in its appearance. Even if the result showed a great increase it would be impossible to make in reality.

**52. The combination between deepened cover and a thin cover of zinc.**

Since the deepened cover showed a slight decrease and the zinc cover scenario showed a slight increase. The combined result will be near the original and not give any new information.

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## 6.6 Verifying the Fictive Scenarios with Simplified Model

When simulating the combined scenarios listed above it was necessary to use the same model all the way through. As have been shown, some of the fictive scenarios were simulated with the reduced model and some were simulated with the simplified model. Combining scenarios with both of these would not be appropriate since they are not from the same reference point; their differences would follow as a big uncertainty. Therefore one of the two models had to be chosen for *all* the combination tests.

The model that was chosen was the simplified model. The reason for this was that the simplified model hypothetically could have been made in an early stage of a product development process. Doing the combinations with this model would therefore in a better way symbolize a real development process, which lies in AXIS's interest to investigate.

Thus the simulations that were included in the combination matrix and had *not* been done with the simplified model were now simulated before starting the combining. To verify that these simulations lied closely enough to the corresponding simulations with the reduced model, the results were listed in a chart. In this chart the deviation between the models were also listed. The chart is shown in appendix H.

As the chart shows, the results between the models never deviates more than 6 percent. This was considered to be close enough to use them for the combinations. Now the combinations were simulated. The results are analysed in the next section.

### **6.7 Analysing the Results of the Combined Scenarios**

Of the 52 combined scenarios in the combination matrix (figure 6.27), there are 16 scenarios considered motivated for simulation. Of these 16 scenarios there are 5 scenarios that were considered extra interesting according to previous results. (marked with green in figure 6.27)

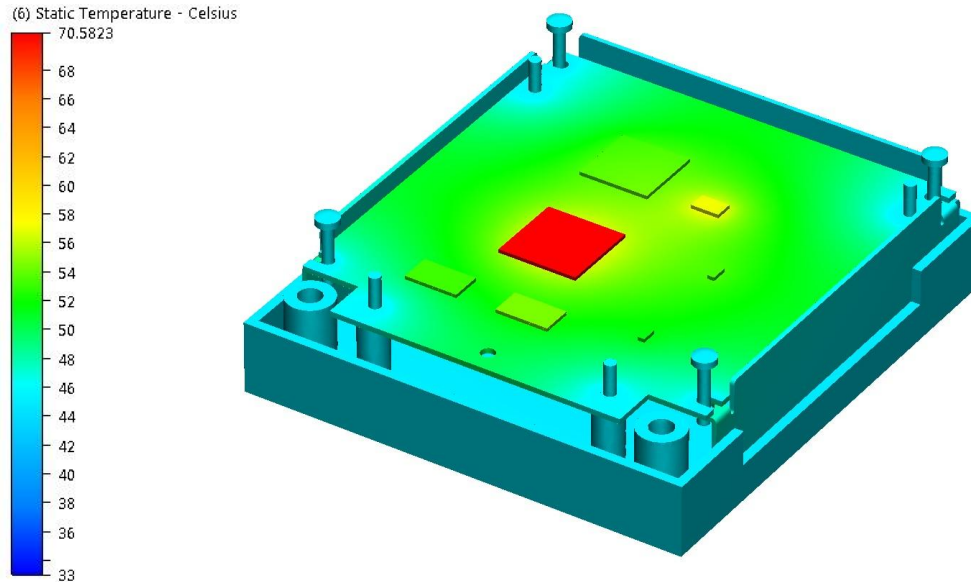
The 16 scenarios are listed below in a new list for a better overview:

1. Power consumption increased by 10 % and ambient temperature increased by 10 °C.
2. Cover  $k = 200 \text{ W/mK}$  and power consumption increased by 10 %
3. Silver screws and power consumption increased by 10 %
4. Silver screws and cover  $k = 200 \text{ W/mK}$
5. Top cover removed and power consumption increased by 10 %
6. Cover removed and plastic cover used
7. Components closely packed and power consumption increased by 10 %
8. Silver screws and components tightly packed
9. Components spread out and power consumption increased by 10 %
10. Silver screws and components spread out
11. Aluminium block and increasing the power consumption by 10 %
12. Aluminium block and cover  $k = 200 \text{ W/mK}$
13. Aluminium block and applying a plastic cover
14. Aluminium block and components tightly packed
15. Aluminium block and components spread out
16. Bottom cover deepened and power consumption increased by 10 %

The results of the scenarios are now presented one by one.



### 6.7.1 Power Consumption Increased by 10 %, Ambient Temp. by 10 °C.

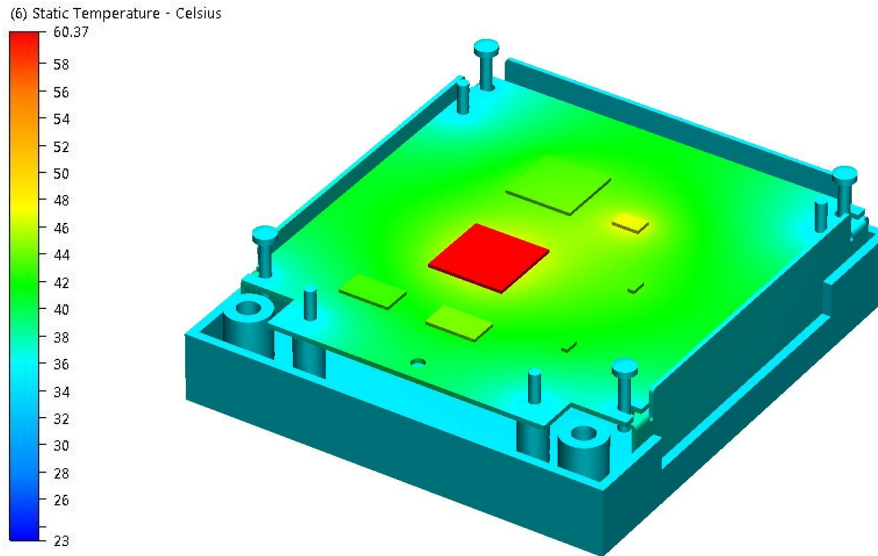


**Figure 6.28** Power consumption increased by 10 %, ambient temperature by 10 °C.

The CPU temperature has increased 14 degrees when both the power consumption is raised by 10 % and the ambient temperature is increased by 10 degrees. This increase is similar to the sum of the two single simulation temperature rises. This states that in the combined simulation, 10 degrees of the temperature rise is due to the increased ambient temperature. The other degrees are caused by the increased power consumption. Thus there is in this combination no unexpected combined effect when the two scenarios are combined.

**Table 6.18** Comparing values from increased power consumption and ambient temperature 33°C

COMBINED SCENARIOS					
Component	Original	W110%	10°C +	W110%/10°C +	
	temperatures[°C]	rise [°C(%)]	rise °C(%)	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	3.2 (5.6%)	9.5(16.6%)	<b>70.6</b>	13.5(23.6%)
<b>Memory</b>	42.5	1.9(4.5%)	9.6(22.6%)	<b>54.6</b>	12.1(28.5%)
<b>Video chip</b>	42.0	1.7(4.0%)	9.6(22.9%)	<b>53.9</b>	11.9(28.3%)
<b>Ethernet</b>	40.6	1.7 (4.2%)	9.6(23.6%)	<b>52.6</b>	12.0(29.6%)
<b>PCB/Others</b>	41.7	1.8(4.3%)	9.6(23.0%)	<b>53.7</b>	12.0(28.8%)
<b>Bottom cover</b>	34.3	1.0(2.9%)	9.7(28.3%)	<b>45.2</b>	10.9(31.8%)
<b>Average rise</b>	-	<b>1.9(4.3%)</b>	<b>9.6(22.8%)</b>	-	<b>12.1(28.4%)</b>

6.7.2 Cover  $k = 200 \text{ W/mK}$  and Power Consumption Increased by 10 %

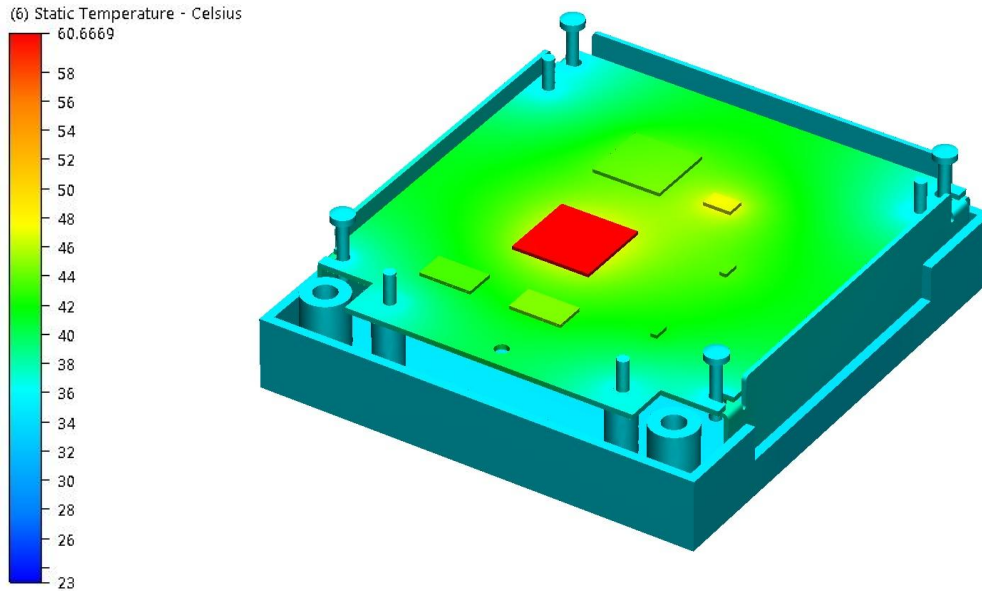
**Figure 6.29** Cover  $k = 200 \text{ W/mK}$  and power consumption increased by 10 %

As seen in the table below the conductivity increase resulted in a negligible increase in the single simulation. The power consumption increase resulted in an increase about 4 percent as average. The result from combination is very close to the increased power consumption simulation. This is logical since the power increase has the biggest influence and the conductivity increase has a very influence small in comparison. Even if the conductivity is increased in the cover, the high temperature gradient lies between the CPU and the PCB and between the cover and the air outside. That is why the heat dissipation will not become better in spite of the higher heat transfer ability in the cover.

**Table 6.19** Comparing values from  $k=200 \text{ W/mK}$  and increased power consumption

Component	COMBINED SCENARIOS				
	Original	k=200	W110%	k=200/W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.5(-0.9%)	3.2 (5.6%)	<b>60.4</b>	3.3(5.8%)
<b>Memory</b>	42.5	-0.5(-1.2%)	1.9(4.5%)	<b>44.4</b>	1.9(4.5%)
<b>Video chip</b>	42.0	-0.5(-1.2%)	1.7(4.0%)	<b>43.7</b>	1.7(4.0%)
<b>Ethernet</b>	40.6	-0.4(-1.0%)	1.7 (4.2%)	<b>42.3</b>	1.7(4.2%)
<b>PCB/Others</b>	41.7	-0.4(1.0%)	1.8(4.3%)	<b>43.4</b>	1.7(4.1%)
<b>Bottom cover</b>	34.3	-0.2(-0.6%)	1.0(2.9%)	<b>35.3</b>	1.0(2.9%)
<b>Average rise</b>	-	<b>-0.4(-1.0%)</b>	<b>1.9(4.3%)</b>	-	<b>1.9(4.2%)</b>

### 6.7.3 Silver Screws and Power Consumption Increased by 10 %

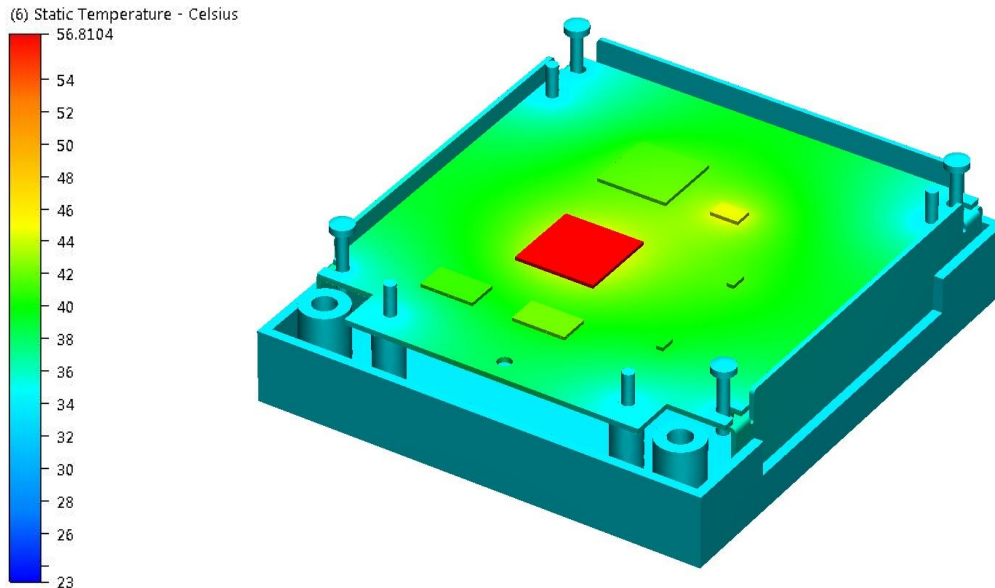


**Figure 6.30** Silver screws and power consumption increased by 10 %

The material change in the screws from steel to the high conductive silver did not make any difference in the single scenario. The same weak influence occurred in this combination, and the total temperature change comes only from the power consumption change. The screws are too small to be able to transfer the heat and it is still the heat to travel from the heated chip to the PCB that is the major difficulty, not from the PCB to the cover.

**Table 6.20** Comparing values from silver screws and increased power consumption

COMBINED SCENARIOS					
Component	Original	Silver screw	W110%	Silverscrew/W110%	
	temperature [°C]	rise [°C(%)]	rise [°C(%)]	temperature [°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.3(-0.5%)	3.2 (5.6%)	<b>60.7</b>	3.6(6.3%)
<b>Memory</b>	42.5	-0.3(-0.7%)	1.9(4.5%)	<b>44.6</b>	2.1(4.9%)
<b>Video chip</b>	42.0	-0.3(-0.7%)	1.7(4.0%)	<b>44.0</b>	2.0(4.8%)
<b>Ethernet</b>	40.6	-0.3(-0.7%)	1.7 (4.2%)	<b>42.6</b>	2.0(4.9%)
<b>PCB/Others</b>	41.7	-0.3(-0.7%)	1.8(4.3%)	<b>43.7</b>	2.0(4.8%)
<b>Bottom cover</b>	34.3	0.0(0.0%)	1.0(2.9%)	<b>35.6</b>	1.3(3.8%)
<b>Average rise</b>	-	<b>-0.3(-0.6%)</b>	<b>1.9(4.3%)</b>	-	<b>2.2(4.9%)</b>

6.7.4 Silver Screws and Cover  $k = 200 \text{ W/mK}$ 

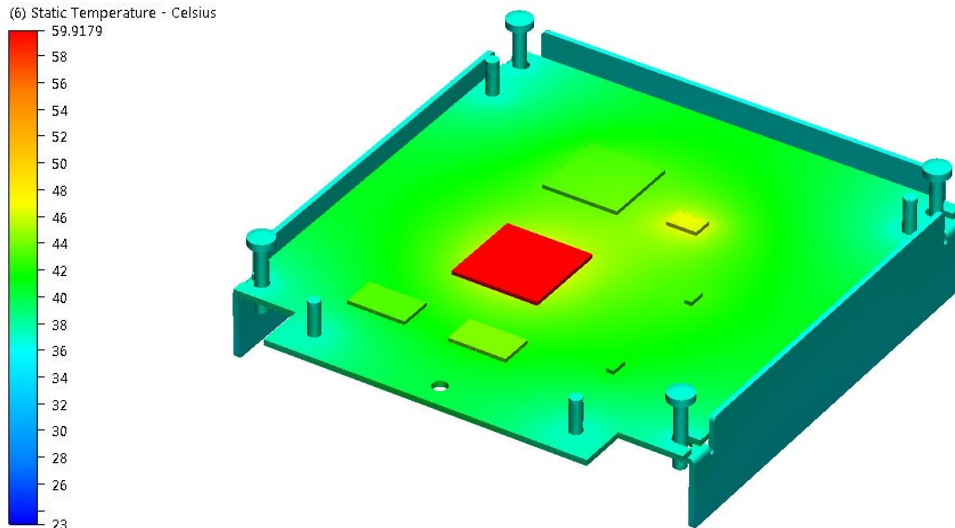
**Figure 6.31** Silver screws and cover  $k = 200 \text{ W/mK}$

To increase the conductivity on the sites where the gradient is already negligible will not result in any significant decrease in temperature. Thus, as seen in the single simulations, neither of these two modifications gave any significant temperature even if the conductivity is much higher in the screws and the cover. Consequently the temperature decrease is slight even if the two scenarios are combined.

**Table 6.21** Comparing values from silver screws and  $k = 200 \text{ W/mK}$

COMBINED SCENARIOS					
Component	Original	Silver screws	k=200	Silverscrews/k=200	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.3(-0.5%)	-0.5(-0.9%)	<b>56.8</b>	-0.3(-0.5%)
<b>Memory</b>	42.5	-0.3(-0.7%)	-0.5(-1.2%)	<b>42.2</b>	-0.3(-0.7%)
<b>Video chip</b>	42.0	-0.3(-0.7%)	-0.5(-1.2%)	<b>41.7</b>	-0.3(-0.7%)
<b>Ethernet</b>	40.6	-0.3(-0.7%)	-0.4(-1.0%)	<b>40.4</b>	-0.2(-0.5%)
<b>PCB/Others</b>	41.7	-0.3(-0.7%)	-0.4(-1.0%)	<b>41.4</b>	-0.3(-0.7%)
<b>Bottom cover</b>	34.3	0.0(0.0%)	-0.2(-0.6%)	<b>34.2</b>	-0.1(-0.3%)
<b>Average rise</b>	-	<b>-0.3(-0.6%)</b>	<b>-0.4(-1.0%)</b>	-	<b>-0.3(-0.6%)</b>

### 6.7.5 Top Cover Removed and Power Consumption Increased by 10 %



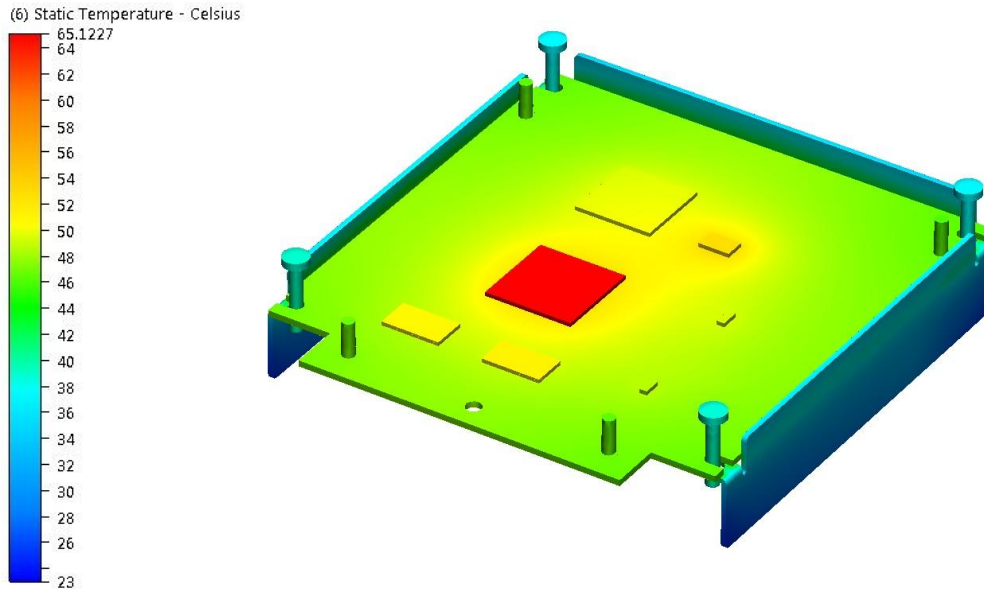
**Figure 6.32** Top cover removed and power consumption increased by 10 %

The removal of the cover increased the convection influence and thus gave a small temperature decrease. Unfortunately the increased convection does not compensate for the temperature increase due to the increased power consumption; it is simply not strong enough. As seen in the table the combination result in an increase in temperature but less than in the single solution with only the power consumption increased.

**Table 6.22** Comparing values from removed top and increased power consumption

Component	COMBINED SCENARIOS				
	Original	No cover	W110%	No cover/W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.9(-1.6%)	3.2 (5.6%)	<b>59.9</b>	2.8(4.9%)
<b>Memory</b>	42.5	-1.3(-3.1%)	1.9(4.5%)	<b>44.2</b>	1.7(4.0%)
<b>Video chip</b>	42.0	-0.2(-0.5%)	1.7(4.0%)	<b>43.4</b>	1.4(3.3%)
<b>Ethernet</b>	40.6	0.8(-2.0%)	1.7 (4.2%)	<b>41.9</b>	1.3(3.2%)
<b>PCB/Others</b>	41.7	-0.4(-1.0%)	1.8(4.3%)	<b>42.6</b>	0.9(2.2%)
<b>Bottom cover</b>	34.3	-0.2(-0.6%)	1.0(2.9%)	<b>36.5</b>	2.2(6.4%)
<b>Average rise</b>	-	<b>-0.6(-1.4%)</b>	<b>1.9(4.3%)</b>	-	<b>1.7(4.0%)</b>

## 6.7.6 Cover Removed and Plastic Cover



**Figure 6.33** Cover removed and plastic cover

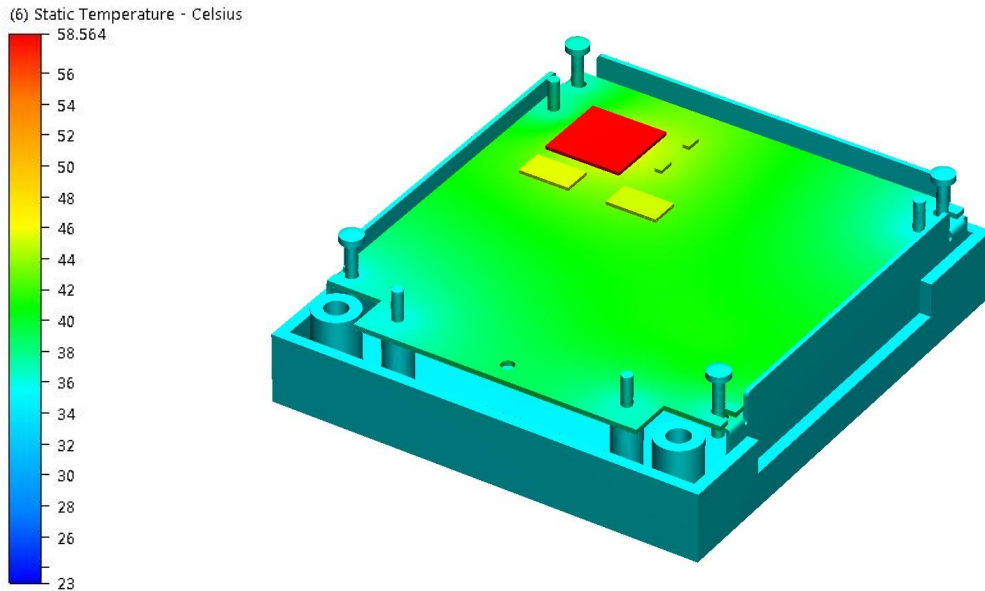
The increased natural convection due to the removed cover is not able to match the temperature rise from the cover material change. Since the plastic material has isolating properties the components will have difficulties to transfer the heat away. However, compared to the results from the scenario with only plastic cover, the combined result are significantly better; instead of a CPU temperature increase of 24 degrees it is now only an increase of 8 degrees.

**Table 6.23** Comparing values from removed top and cover out of plastic

COMBINED SCENARIOS					
Component	Original	No cover	Plastic cover	No cover/Plastic cover	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.9(-1.6%)	24.4(42.7%)	<b>65.1</b>	8.0(14.0%)
<b>Memory</b>	42.5	-1.3(-3.1%)	25.3(59.5%)	<b>51.2</b>	8.7(20.5%)
<b>Video chip</b>	42.0	-0.2(-0.5%)	24.3(57.9%)	<b>49.9</b>	7.9(18.8%)
<b>Ethernet</b>	40.6	0.8(-2.0%)	24.9(61.3%)	<b>48.7</b>	8.1(20.0%)
<b>PCB/Others</b>	41.7	-0.4(-1.0%)	24.2(58.0%)	<b>49.1</b>	7.4(17.7%)
<b>Bottom cover</b>	34.3	-0.2(-0.6%)	21.6(63.0%)	<b>43.6</b>	9.3(27.1%)
<b>Average rise</b>	-	<b>-0.6(-1.4%)</b>	<b>24.1(57.1%)</b>	-	<b>8.2(19.7%)</b>



### 6.7.7 Components Closely Packed, Power Consumption Increased by 10 %



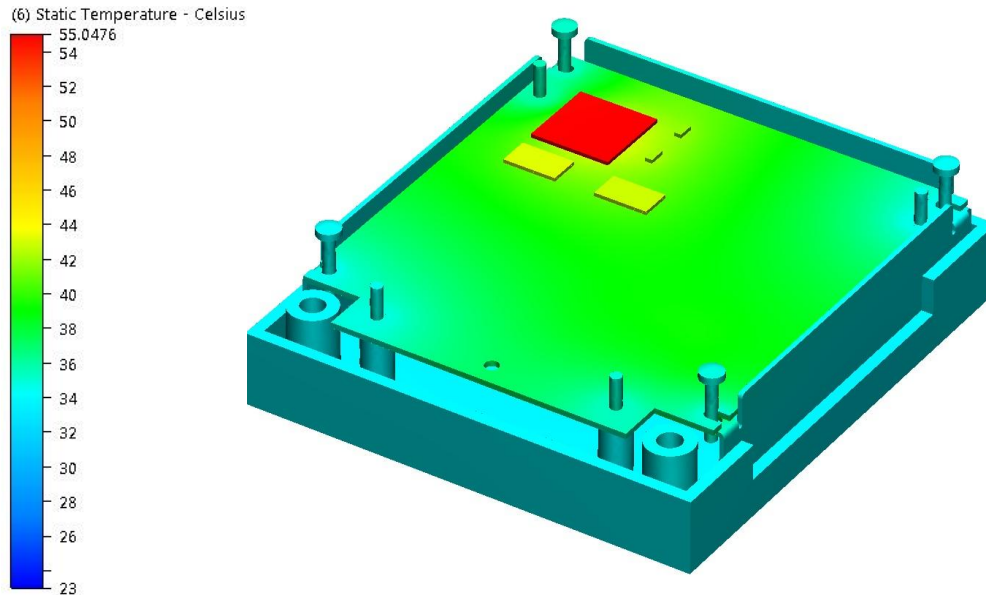
**Figure 6.34** Components closely packed, power consumption increased by 10 %

The tight placement of the components caused an increased heat transfer from the most heat generating chip down through the closest screw boss, resulting in a colder CPU and a hotter Memory chip since this received heat from the CPU. The combination results show that these phenomena occur in the same way when the power consumption is raised. The influence from the raised power consumption seems to be the same as before.

**Table 6.24** Comparing values from close components and increased power consumption

COMBINED SCENARIOS					
Component	Original	Comp close	W110%	Comp close/W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-1.9(-3.3%)	3.2 (5.6%)	<b>58.5</b>	1.4(2.5%)
<b>Memory</b>	42.5	1.0(2.4%)	1.9(4.5%)	<b>45.1</b>	2.6(6.1%)
<b>Video chip</b>	42.0	-1.9(-4.5%)	1.7(4.0%)	<b>41.8</b>	-0.2(-0.5%)
<b>Ethernet</b>	40.6	0.6(1.5%)	1.7 (4.2%)	<b>43.1</b>	2.5(6.2%)
<b>PCB/Others</b>	41.7	-2.2(-5.3%)	1.8(4.3%)	<b>41.2</b>	-0.5(-1.2%)
<b>Bottom cover</b>	34.3	0.1(0.3%)	1.0(2.9%)	<b>35.6</b>	1.3(3.8%)
<b>Average rise</b>	-	<b>-0.7(-1.5)</b>	<b>1.9(4.3%)</b>	-	<b>1.2(2.8%)</b>

### 6.7.8 Silver Screws and Components Tightly Packed



**Figure 6.35** Silver screws and components tightly packed

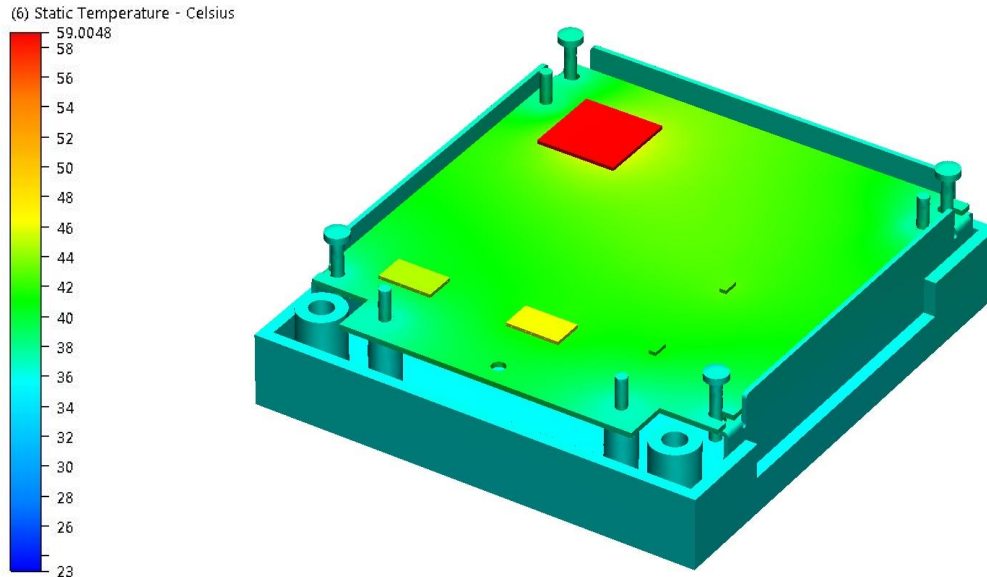
The previous result with silver screws made no significant temperature difference. Placing the components close together resulted in that the CPU temperature decreased since the heat easier than before could escape through the closest screw towel. Combining these scenarios could therefore be assumed to give a combined positive effect since it would let the heat escape even easier down through the screw boss. However no such combined effect can be seen, which is surprising. The reason is believed to be that the heat is transferred directly from the PCB to the screw boss, rather than going via the screws. Another reason can be that the single simulations and the combined simulation were not done with the exact same amount of elements, which could result in some inaccuracy.

**Table 6.25** Comparing values from high conductive screws and components close

COMBINED SCENARIOS					
Component	Original	Silver screws	Comp close	Silver screws/Comp_close	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.3(-0.5%)	-1.9(-3.3%)	<b>55.0</b>	-2.1(-3.7%)
<b>Memory</b>	42.5	-0.3(-0.7%)	1.0(2.4%)	<b>42.9</b>	0.4(0.9%)
<b>Video chip</b>	42.0	-0.3(-0.7%)	-1.9(-4.5%)	<b>39.8</b>	-2.2(-5.2%)
<b>Ethernet</b>	40.6	-0.3(-0.7%)	0.6(1.5%)	<b>40.9</b>	0.3(0.7%)
<b>PCB/Others</b>	41.7	-0.3(-0.7%)	-2.2(-5.3%)	<b>39.3</b>	-2.4(-5.8%)
<b>Bottom cover</b>	34.3	0.0(0.0%)	0.1(0.3%)	<b>34.5</b>	0.2(0.6%)
<b>Average rise</b>	-	<b>-0.3(-0.6%)</b>	<b>-0.7(-1.5)</b>	-	<b>-1.0(-2.1%)</b>



### 6.7.9 Components Spread Out and Power Consumption Increased by 10 %



**Figure 6.36** Components spread out and power consumption increased by 10 %

To place the components spread on the PCB resulted in a smaller decrease in temperature for the single simulation, increasing the power consumption resulted in smaller increase. The temperatures when combining the two scenarios should end up somewhere in between the two, although it does not. Thus the results in this simulation are clearly doubtful. The reason for the miscalculations are considered to be that the combined scenario and the two single scenarios consisted of different amounts of elements, as this sometimes leads to deviations in the results. The lesson taught from this is that the element count has to match when comparing two simulations.

**Table 6.26** Comparing values from spread components and increased power consumption

COMBINED SCENARIOS					
Component	Original	Spread comp	W110%	Spread comp/W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-2.4(-4.2%)	3.2 (5.6%)	<b>59.0</b>	1.9(3.3%)
<b>Memory</b>	42.5	-2.4(-5.6%)	1.9(4.5%)	<b>46.3</b>	3.8(8.9%)
<b>Video chip</b>	42.0	-1.4(-3.3%)	1.7(4.0%)	<b>43.6</b>	1.6(3.8%)
<b>Ethernet</b>	40.6	-1.3(-3.2%)	1.7 (4.2%)	<b>42.2</b>	1.6(3.9%)
<b>PCB/Others</b>	41.7	-1.4(-3.4%)	1.8(4.3%)	<b>43.6</b>	1.6(3.8%)
<b>Bottom cover</b>	34.3	0.1(0.3%)	1.0(2.9%)	<b>36.4</b>	2.1(6.1%)
<b>Average rise</b>	-	<b>-1.5(-3.2%)</b>	<b>1.9(4.3%)</b>	-	<b>2.1(5.0%)</b>

6.7.10 Silver Screws and Components Spread out

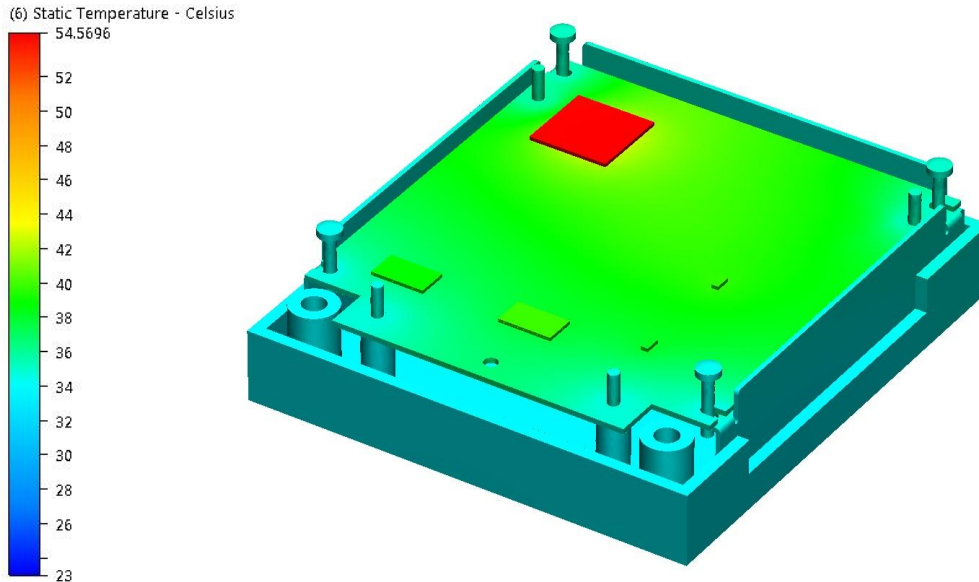


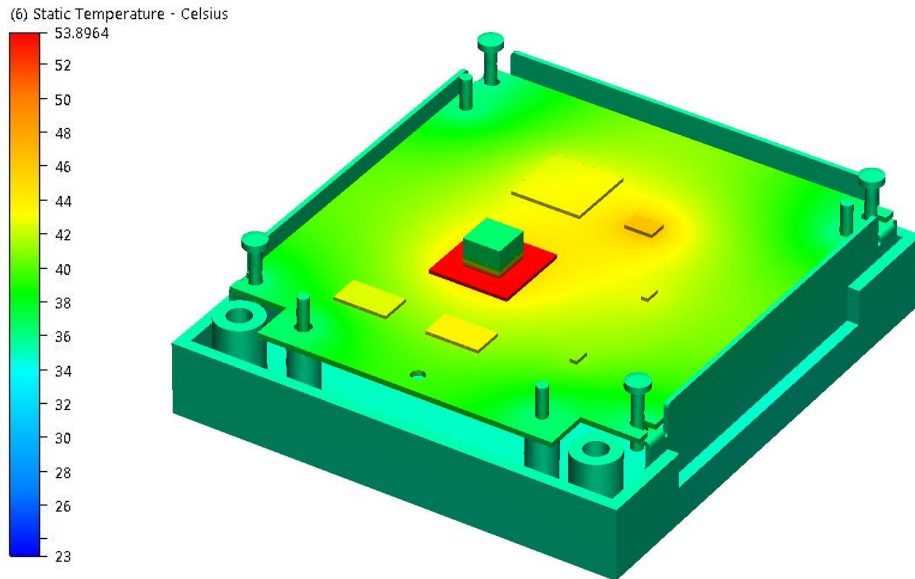
Figure 6.37 Silver screws and components spread out

To combine the spread components and in this case place the most heat generating chip near a silver screw was favourable. The combined simulation show a stronger decrease than the two single simulations summed up since the new screws are able to take use of the fact that the components now are placed close to them. However the extra decrease is still too small to be able to recommend higher conductivity on the screws that holds the cover together.

Table 6.27 Comparing values from using silver screws and spread components

COMBINED SCENARIOS					
Component	Original	Silver screws	Spread comp	Silverscrews/Spread_comp	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-0.3(-0.5%)	-2(-4%)	<b>54.5</b>	-2.6(-4.6%)
<b>Memory</b>	42.5	-0.3(-0.7%)	-2(-6%)	<b>39.9</b>	-2.6(-6.1%)
<b>Video chip</b>	42.0	-0.3(-0.7%)	-1(-3%)	<b>40.4</b>	-1.6(-3.8%)
<b>Ethernet</b>	40.6	-0.3(-0.7%)	-1(-3%)	<b>39.1</b>	-1.5(-3.7%)
<b>PCB/Others</b>	41.7	-0.3(-0.7%)	-1(-3%)	<b>40.1</b>	-1.6(-3.8%)
<b>Bottom cover</b>	34.3	0.0(0.0%)	0(0%)	<b>34.4</b>	0.1(0.3%)
<b>Average rise</b>	-	<b>-0.3(-0.6%)</b>	<b>-1(-3%)</b>	-	<b>-1.6(-3.6%)</b>

### 6.7.11 Aluminium Block and Increasing the Power Consumption by 10 %



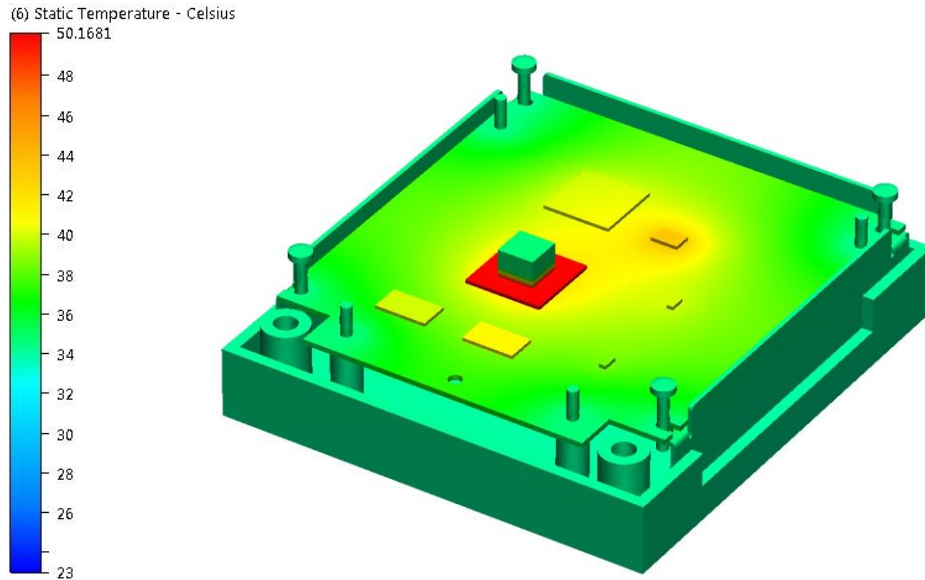
**Figure 6.38** Aluminium block and increasing the power consumption by 10%

Even if the overall temperature is low inside the aluminium block it was proven very effective for decreasing the CPU temperature in the single scenario. It now shows that the impact of the increased power consumption is also decreased when combined with the aluminium block. Even if the power consumption is increased, the aluminium block is able to decrease the CPU temperature with almost 4 degrees. This is quite a lot considering that it is only 1 degree temperature decrease less than without the power increase.

Thus it seems that when the temperature gets higher the aluminium block solution become even more effective in transferring the heat away from the CPU.

**Table 6.28** Comparing values from aluminium block and increased power consumption

Component	COMBINED SCENARIOS				
	Original	Al-block	W110%	Al-block/W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-5.3(-9.3%)	3.2 (5.6%)	<b>53.5</b>	-3.6(-6.3%)
<b>Memory</b>	42.5	0.2(0.5%)	1.9(4.5%)	<b>43.6</b>	1.1(2.6%)
<b>Video chip</b>	42.0	0.2(0.5%)	1.7(4.0%)	<b>43.1</b>	1.1(2.6%)
<b>Ethernet</b>	40.6	0.5(1.2%)	1.7 (4.2%)	<b>41.8</b>	1.2(3.0%)
<b>PCB/Others</b>	41.7	0.1(0.2%)	1.8(4.3%)	<b>42.6</b>	0.9(2.2%)
<b>Bottom cover</b>	34.3	1.7(5.0%)	1.0(2.9%)	<b>36.0</b>	1.7(5.0%)
<b>Average rise</b>	-	<b>-0.4(-0.3%)</b>	<b>1.9(4.3%)</b>	-	<b>0.4(1.5%)</b>

6.7.12 Aluminium Block and Cover  $k = 200 \text{ W/mK}$ 

**Figure 6.39** Aluminium block and cover  $k = 200 \text{ W/mK}$

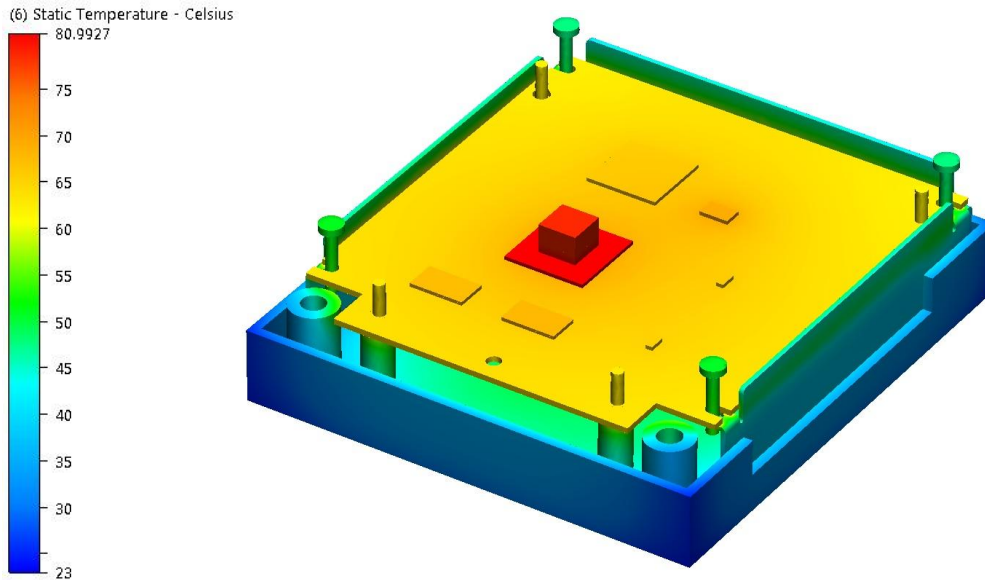
When combining the aluminium block with a high conductivity cover a strong positive combined effect occurred. In the single scenario for the aluminium block a heat gradient occurred on the top cover where the heat box came into contact with the cover. When the cover conductivity was increased this heat gradient almost disappeared. This states that the new conductivity was needed to transport the heat away from the place where the aluminium block hits the cover.

The conclusion of this is that it is only in situations like with the aluminium block that the increased cover conductivity on the cover will be effective.

**Table 6.29** Comparing values from placing spread components and  $k = 200 \text{ W/mK}$

Component	COMBINED SCENARIOS				
	Original temperatures[°C]	Al-block rise [°C(%)]	k=200 rise [°C(%)]	Al-block/k=200 temperatures[°C] rise [°C(%)]	
<b>CPU</b>	57.1	-5.3(-9.3%)	-0.5(-0.9%)	<b>49.9</b>	-7.2(-12.6%)
<b>Memory</b>	42.5	0.2(0.5%)	-0.5(-1.2%)	<b>40.8</b>	-1.7(-4.0%)
<b>Video chip</b>	42.0	0.2(0.5%)	-0.5(-1.2%)	<b>40.3</b>	-1.7(-4.0%)
<b>Ethernet</b>	40.6	0.5(1.2%)	-0.4(-1.0%)	<b>39.3</b>	-1.3(-3.2%)
<b>PCB/Others</b>	41.7	0.1(0.2%)	-0.4(1.0%)	<b>39.9</b>	-1.8(-4.3%)
<b>Bottom cover</b>	34.3	1.7(5.0%)	-0.2(-0.6%)	<b>34.5</b>	0.2(0.6%)
<b>Average rise</b>	-	<b>-0.4(-0.3%)</b>	<b>-0.4(-1.0%)</b>	-	<b>-2.3(-4.6%)</b>

### 6.7.13 Aluminium Block and Applying a Plastic Cover



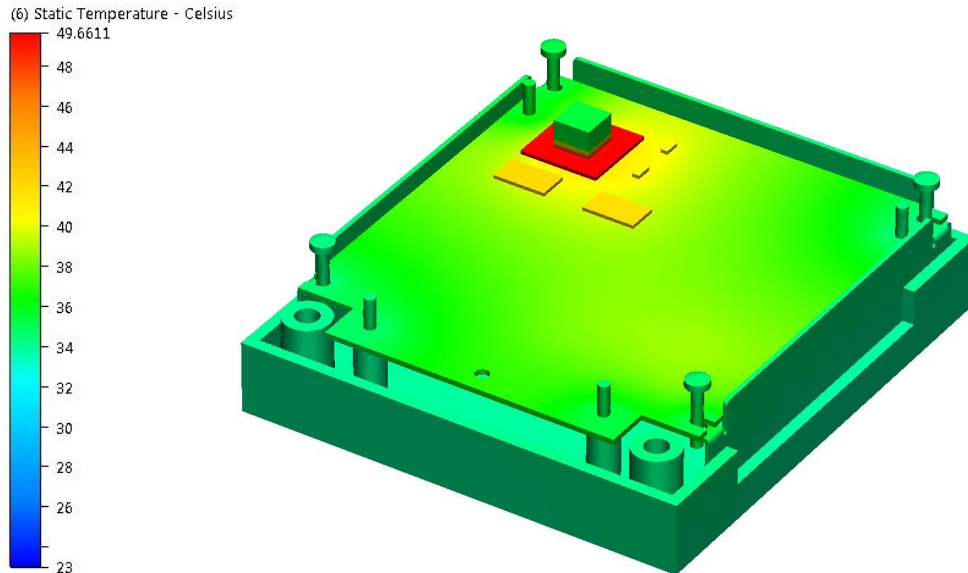
**Figure 6.40** Aluminium block and applying a plastic cover

Since the cover is made of plastic, with much lower conductivity than the aluminium block, the aluminium block will no longer serve as a heat transporter. The aluminium block gets heated but will not be able to dissipate the heat anywhere. The temperature difference is thus very similar to the single simulation with the plastic cover.

**Table 6.30** Comparing values from placing a plastic box and a plastic cover

COMBINED SCENARIOS					
Component	Original	Al-block	Plastic cover	Al-block/Plastic cover	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-5.3(-9.3%)	24.4(42.7%)	<b>81.0</b>	23.9(41.9%)
<b>Memory</b>	42.5	0.2(0.5%)	25.3(59.5%)	<b>67.7</b>	25.2(59.3%)
<b>Video chip</b>	42.0	0.2(0.5%)	24.3(57.9%)	<b>66.2</b>	24.2(57.6%)
<b>Ethernet</b>	40.6	0.5(1.2%)	24.9(61.3%)	<b>65.4</b>	24.8(61.1%)
<b>PCB/Others</b>	41.7	0.1(0.2%)	24.2(58.0%)	<b>65.8</b>	24.1(57.8%)
<b>Bottom cover</b>	34.3	1.7(5.0%)	21.6(63.0%)	<b>57.1</b>	22.8(66.5%)
<b>Average rise</b>	-	<b>-0.4(-0.3%)</b>	<b>24.1(57.1%)</b>	-	<b>24.2(57.4%)</b>

## 6.7.14 Aluminium Block and Components Tightly Packed



**Figure 6.41** Aluminium block and components tightly packed

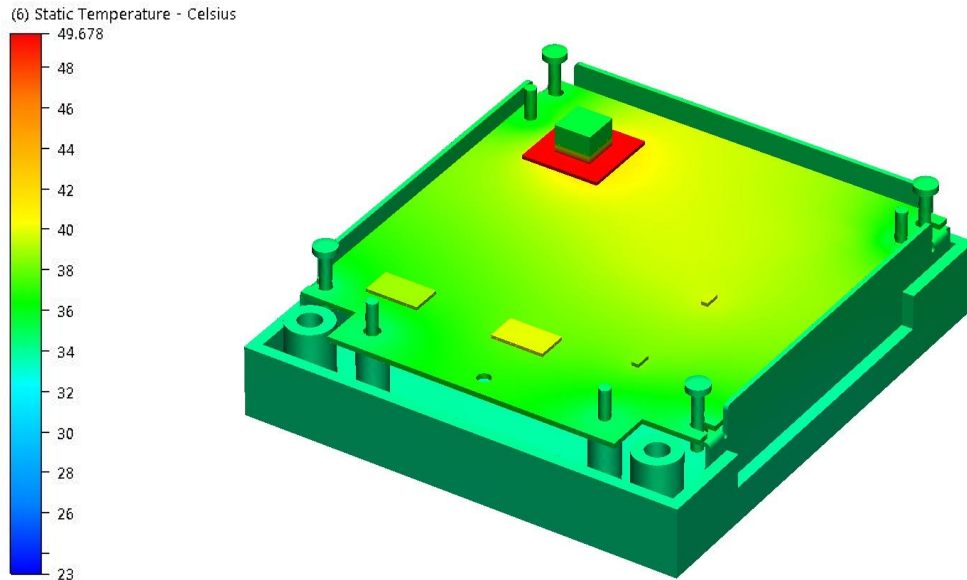
Since the components in this scenario are concentrated around the aluminium block heat from all components is transferred through the aluminium block. As a result a combined effect occurs where the two modifications are helping each other out. This can be seen by looking at the average temperature rise at the bottom of the result legend. In the combined scenario the temperatures has decreased by 5.2 %. This is clearly more than the decreased from the single scenarios added together. (0.3 % and 0.7 %) The simulation shows that the aluminium block helps to cool down not only the components that it is directly attached to but also nearby placed components.

**Table 6.31** Comparing values from an aluminium block and components close

COMBINED SCENARIOS					
Component	Original	Al-block	Comp close	Al-block/Comp close	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	56.3	-5.3(-9.3%)	-1.9(-3.3%)	<b>49.3</b>	-7.8(-13.7%)
<b>Memory</b>	42.5	0.2(0.5%)	1.0(2.4%)	<b>41.7</b>	-0.8(-1.9%)
<b>Video chip</b>	42.0	0.2(0.5%)	-1.9(-4.5%)	<b>39.5</b>	-2.5(-6.0%)
<b>Ethernet</b>	40.6	0.5(1.2%)	0.6(1.5%)	<b>39.4</b>	-1.2(-3.0%)
<b>PCB/Others</b>	41.8	0.1(0.2%)	-2.2(-5.3%)	<b>38.6</b>	-3.1(-7.4%)
<b>Bottom cover</b>	34.3	1.7(5.0%)	0.1(0.3%)	<b>34.5</b>	0.2(0.6%)
<b>Average rise</b>	-	<b>-0.4(-0.3%)</b>	<b>-0.7(-1.5)</b>	-	<b>-2.5(-5.2%)</b>



### 6.7.15 Aluminium Block and Components Spread out



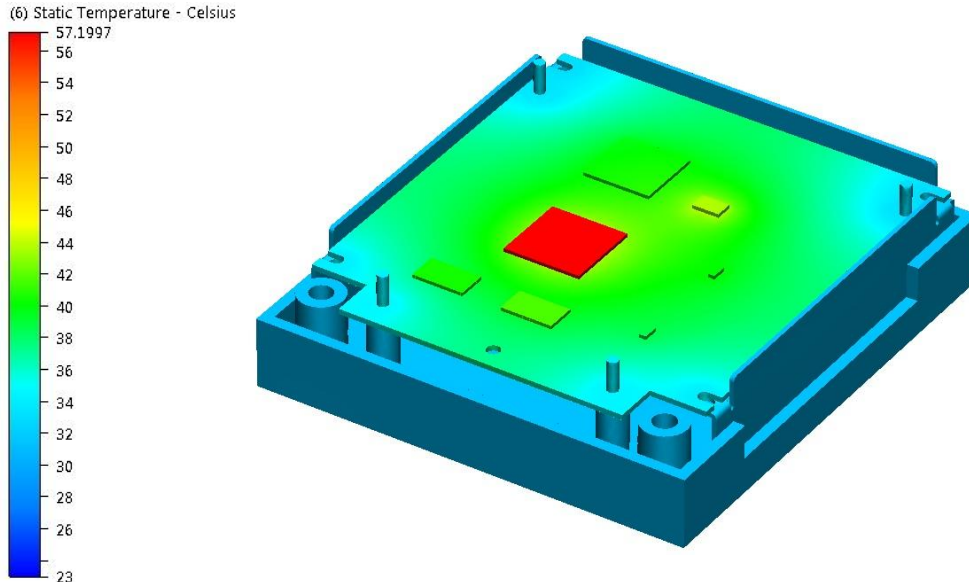
**Figure 6.42** Aluminium block and components spread out

No significant combined effect occurred here since the aluminium block was placed far from the other components. An interesting point is however that when it comes to the CPU, the influences from the aluminium block and from the fact that the CPU is close to the PCB edge adds up. It would rather be assumed that since so much heat is escaping through the aluminium block it would not help to place the CPU close to a screw boss. Obviously that is not the case.

**Table 6.32** Comparing values from an aluminium block and components spread

COMBINED SCENARIOS					
Component	Original	Al-block	Spread comp	Al-block/Spread comp	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-5.3(-9.3%)	-2.4(-4.2%)	<b>49.4</b>	-7.7(-13.5%)
<b>Memory</b>	42.5	0.2(0.5%)	-2.4(-5.6%)	<b>39.9</b>	-2.6(-6.1%)
<b>Video chip</b>	42.0	0.2(0.5%)	-1.4(-3.3%)	<b>40.2</b>	-1.8(-4.3%)
<b>Ethernet</b>	40.6	0.5(1.2%)	-1.3(-3.2%)	<b>39.2</b>	-1.4(-3.4%)
<b>PCB/Others</b>	41.7	0.1(0.2%)	-1.4(-3.4%)	<b>40.0</b>	-1.7(-4.1%)
<b>Bottom cover</b>	34.3	1.7(5.0%)	0.1(0.3%)	<b>34.7</b>	0.4(1.2%)
<b>Average rise</b>	-	<b>-0.4(-0.3%)</b>	<b>-1.5(-3.2%)</b>	-	<b>-2.5(-5.0%)</b>

## 6.7.16 Bottom Cover Deepened and Power Consumption Increased by 10 %



**Figure 6.43** Bottom cover deepened and power consumption increased by 10 %

The extra space inside the encoder allows the air to flow in a circular motion. The difference in temperature was however proven to be small. Combining this deepened bottom cover with the increased power consumption revealed no surprises. The two modifications do not seem to affect each other.

**Table 6.33** Comparing values from deepened cover and increased power consumption

COMBINED SCENARIOS					
Component	Original	Deepened	W110%	Deepened /W110%	
	temperatures[°C]	rise [°C(%)]	rise [°C(%)]	temperatures[°C]	rise [°C(%)]
<b>CPU</b>	57.1	-2.7(-4.7)	3.2 (5.6%)	<b>57.2</b>	0.1(0.2%)
<b>Memory</b>	42.5	-2.2(-5.2%)	1.9(4.5%)	<b>41.6</b>	-0.9(-2.1%)
<b>Video chip</b>	42.0	-2.7(-6.4%)	1.7(4.0%)	<b>40.4</b>	-1.6(-3.8%)
<b>Ethernet</b>	40.6	-2.3(-5.7%)	1.7 (4.2%)	<b>39.3</b>	-1.3(-3.2%)
<b>PCB/Others</b>	41.7	-2.6(-6.2%)	1.8(4.3%)	<b>40.1</b>	-1.6(-3.8%)
<b>Bottom cover</b>	34.3	-3.6(-10.5%)	1.0(2.9%)	<b>31.6</b>	-2.7(-7.9%)
<b>Average rise</b>	-	<b>-2.7(-6.5%)</b>	<b>1.9(4.3%)</b>	-	<b>-1.3(-3.4%)</b>



## 7 Conclusions and Discussion

*In this section the final conclusions of the project will be stated. The sources of error throughout the whole project will be pointed out as well and ranked after their potential magnitude. Then follows a discussion section where other problems during the way are brought up. Also the presumptions for using the simulation application on a company like AXIS are discussed, in terms of the communication and information channels that are necessary for using such an application effectively. Finally there will be a number of suggestions and recommendations for future simulations to be done if AXIS chooses to use the software. These recommended simulations will provide the company with further understanding about the thermal situation in their products plus prepare them somewhat for future simulation projects.*

### 7.1 Sources of Error

When doing the type of computer-based simulations that were used in this project a number of sources of error always occur. The sources that were considered to have most influence on the result have been listed below.

#### 7.1.1 Accuracy During the Heat Tests

The temperature probes used during the heat tests are attached with isolating tape and thermal conductive paste. The process can be a little difficult and there is always a chance that the probe slides a little in some direction. Since the microchips in general are hotter in the middle and colder along the edges, this can result in an error in the temperature results from the probes. The chip temperature is not however considered to vary that much, and furthermore the conductive paste will help making up for the errors by trying to keep the temperature constant over the whole chip top surface.

#### 7.1.2 Simplifications in Pro/Engineer

A large number of simplifications were made on the model in Pro/Engineer before launching it in CFXDesign. This will of course result in some inaccuracy in the results since the model is no longer the same as in reality. These simplifications are well thought thru though and will not contribute to any critical errors.

#### 7.1.3 The “Other Components” were Approximately Spread Out

All the components that were not considered to generate any critical level of heat on their own were placed under the category “other components”. The heat generation from all of these were then spread out equally over the whole PCB. These components represent 8 % of the total heat generation in the product, which could not be

seen as negligible. However, according to the thermal image pictures of the PCB, the heat dissipation for the other components seemed to be quite equally spread out over the board. This fact ensures that the approximation is not that far from reality.

### *7.1.4 Component Power Consumption Came from Theoretical Values*

The values for the components' power consumption were taken from AXIS' database. However, as these were merely theoretical values they are valid only when the microchips are working at maximal operation. Since the microchips did not reach this level during the heat tests the theoretical values were cut down, based on the *total* power consumption during the tests. This relatively strong approximation ratio of 0.54 makes this the one of the most critical source of error in the whole project. Although 0.54 seems very dramatic it should however be noticed that the total power consumption in the simulation still are exactly in line with the heat tests. Furthermore the power *relations* between the components should also be close to correct since they are based on the relations from the theoretical values.

### *7.1.5 Thermal Resistances Under and Over the Microchips*

The thermal resistances between the microchips and their surroundings, also referred to as  $R_{\theta \text{ junction to case}}$  and  $R_{\theta \text{ junction to board}}$ , could not be found for more than one of the components. The other components were defined as a solid silicon object in CFDesign, meaning that the thermal resistances between the PCB and its surrounding air were left for solving themselves according to the thermal equilibrium. Because of this, some of the heat from the active components was "sent" in the wrong direction in the simulation. This is considered to be the biggest source of error; it remains a major problem. If AXIS decides to use simulation in the future it is strongly recommended that they locate this information for their most heat generating components.

### *7.1.6 General Contact Resistances in the Product During Simulation*

Between two solid objects there will always arise some contact resistance, depending on the pressure between them and on the surface finish of the connecting surfaces. As default, CFDesign will not take these resistances into account. The magnitude of this source of error depends in other words on how tightly together the different parts in the product are put together. Since AXIS products always are screwed or glued together and thus has very good contact between the surfaces, this error should be almost negligible. It should however be kept in mind for future products and simulations that it in some cases is recommended to manually place thermal resistances between parts that are considered to exchange less heat than if they had full contact.

### *7.1.7 The Simulation Accuracy in CFDesign*

No matter how fine the mesh is in the simulation application it will always be an approximation of the reality which could be seen as a scenario with an infinite amount of elements. If the mesh is made properly, with enough elements in the more critical areas however, these errors should be as good as negligible as well.

### *7.1.8 Ranking of the Errors*

Below the sources of error have been ranked after what is considered to be their potential error magnitude:

1. Thermal resistances under the microchips
2. Component power consumption came from theoretical values
3. Accuracy during the heat tests
4. General contact resistances in the product during simulation
5. The “other components” were approximately spread out
6. Simplifications in Pro Engineer
7. The simulation accuracy in CFDesign

The two at the top of the list are considered to be the only critical ones. These are however a question of gathering the right information, and can thus be dealt with in the future if this information can be gained.

### *7.1.9 Further Inaccuracy Without an Existing Reference Product*

It should finally be pointed out that the simulations made in this project were validated on an existing product. If these types of applications are to be used at AXIS, this will not be the case. Instead the simulation will be based on a product concept during development where the geometries are far from decided. This will of course result in an even bigger inaccuracy. It depends on how far into the development process the development team has come when the simulation is made.

## **7.2 Problems During the Project**

During the project several problems occurred as a result of lack of experience and human errors. Even if the authors had experience in both CFDesign and Pro/Engineer several difficulties were encountered.

### *7.2.1 Pro/Engineer*

The original encoder CAD-model was made by professional CAD engineers and due to its complexity hard to edit. This was a problem when the simplifications were to be made. Despite from deleting features the model was considered too complex to modify. The issue was solved by building a new, simplified model from scratch for those simulations where bigger geometrical changes were required.

### *7.2.2 CFDesign*

The general problem field in CFDesign was how to define the boundary conditions in a proper way. This would have been an even harder task without support from Validus. Another issue was to find out how much simplifying that could be done on the CAD-model without losing too much accuracy in the simulation results.

### 7.2.3 Other Problems

Many problems around the necessary input data arose, mainly since the thermal resistances within the chips could not be found. Approximated solutions were necessary to do here. Backdoors were also used when merely the theoretical values for the component's power consumption could be found.

## 7.3 General Discussion

In this section the advantages and disadvantages with the simulation approach will be discussed. Various problems that have occurred throughout the project will be brought to light, together with other aspects around the necessary presumptions for start using CFDesign at AXIS. The conclusions and suggestions drawn in this chapter are subjective; they are the opinions of the authors of this study if nothing else is declared.

### 7.3.1 Areas of Use for Simulation

The main use of simulations is to save time and money by simulating ideas instead of making prototypes. There are mainly two ways of using the results. The first is that the product temperatures can be estimated. The second, and maybe even more important, is that you can *compare* different solutions to evaluate which is better. The advantage of only comparing and not paying too much attention to the actual temperatures is that the accuracy demands are much lower; the relative difference is quite accurate. Since it in many situations is enough to find out which of two solutions is better rather than exactly how good they are a comparison is often sufficient enough. Furthermore, some of the sources of error can be eliminated when doing only a comparison.

Still, if it for some reason is important to receive temperature results with very high accuracy, let us say that a non-existent product is to be simulated with ten different surface finishes, it is possible to make one prototype, validate one simulation after this prototype and then simulate the nine scenarios that are left.

### 7.3.2 Accuracy Demands

Initially it could be stated that the accuracy of the simulations in this project was as good as could be expected from an application of this type. This statement is based on the fact that the deviation from results in the heat tests does never exceed 10% at any location in the designed scenarios. These deviations are acceptable [4]. In other words; CFDesign as an application has been proven suitable for the type of products that is being developed at AXIS.

When it comes to the accuracy that is desired from AXIS's point of view, it has here as well been considered to be a sufficient accuracy for simulating AXIS's future products. In most cases the deviation was not bigger than 5 %. Although the existence of this deviation means that the application never can answer exactly what temperature a product is going to get, it will be close enough to decide whether further thermal optimization is necessary on the product or not. Furthermore, even if the deviation sometimes is bigger, the software will still be useful for *comparing* different

hypothetical scenarios. This would probably be the main purpose for the application for AXIS. By comparing different solutions throughout the whole thermal optimization process the project team could easily deselect less effective options and focus on the more effective options.

### 7.3.3 Access to Input Data

Implementing the use of simulations at AXIS would include people from both mechanics department and electronics department. Electronics department need to contribute regarding component input data, for example  $R_{\theta \text{ junction to board}}$ , PCB copper content and component composition.

### 7.3.4 Future Aspects

Using CFDDesign at AXIS will become more effective after a period of time. Initially there will probably be uncertainties about the reliability of the results. The developing team will be questioning whether they really should discard a potentially good solution just because a simulation shows that it is inefficient. Thus the prototyping used for heat testing today continue until the simulators learn in what scenarios the simulation results can be trusted. Over time the simulators will also gain more experience and become more skilled in using the mesh settings in the application, which will result in more accurate results.

As a validation an example could be to build additional adjusted products. These products could be adjusted in thickness or material. Lab test should then verify the performed simulations and the values from the both could be compared.

### 7.3.5 Result Highlights

A number of conclusions were drawn during the analysing of the simulation results. For a better overview the most important of these conclusions are listed in this section.

- The relation between the ambient temperature and the temperatures inside the product is linear. (Only verified in the temperature range 13 to 33 degrees Celsius.)
- Increasing/decreasing the total power consumption by 10 % results in an average temperature increase/decrease of 3 %. (Only verified for the encoder)
- Increasing the conductivity for the cover to more than 100 W/mK in these types of products is only favourable if there is a *direct solid high conductivity material* between the chip and the cover. (For instance an aluminium rod)

- If using a plastic cover, a direct solid high conductivity material between the chip and the cover is close to useless, since the cover will not be able to get rid of the heat that is transported through the high conductivity material.
- Using a plastic cover for a product like the encoder results in a major CPU temperature increase. Major temperature gradients will occur all across the cover.
- When predicting the radiation influence it does not matter what *colour* that is chosen for the cover; merely the *surface finish* is of importance. However if the product will be exposed to sunlight the choice of colour once again becomes important.
- Doing the simulation without taking the radiation into account results in a CPU temperature increase of 15 %. (For the encoder this is 7 degrees Celsius). Thus the radiation represents a relatively small part of the cooling.
- The radiation influence is negligible at low temperatures.
- If the convection and conduction should decrease from point A to B, the importance of radiation increases from point A to B.
- Increasing the cover volume on a product like the encoder results in an average temperature increase of 7 %. (3 degrees Celsius for the encoder)
- When the heat is transferred from a chip directly to the cover via a high conductive solid, almost *all* the thermal resistance occur in the TIM material between the chip and the solid, not in the very solid.
- In order for a screw boss to transfer any significant heat from nearby components, these components must be placed really closed to the screw boss. (In this case less than a centimetre)

### 7.4 Final Conclusions

The main purpose for this project was to investigate whether using thermal simulations is a current possibility for AXIS or not. Our answer is yes. Considering the results together with the advantages and disadvantages in the discussion section above, it would be, from a technical as well as from a practical point of view, an alternative for the company to start using thermal simulation software.

The main reasons that led to this conclusion are:

- The simulation accuracy is sufficient for comparing different thermal solutions in the type of products that is being developing at AXIS.
- The time for doing one simulation ranges from 3 hours to 10 hours. This is a very short time compared to how long it takes to order and receive a prototype, plus running a heat test on this prototype.

The main technical requirements for start using simulation software at AXIS are:

- Access to input data about the components thermal resistances must be gained.
- A ratio between the theoretical power consumption values in the component descriptions and the real power consumption must be gained.

## **7.5 Interesting Simulation Scenarios**

Throughout the project a number of ideas of future simulation alternatives occurred. These suggestions do not fit within the frames of this study but were still considered to be important enough to be mentioned in this section. If AXIS decides to start using CFDesign, these simulations could be helpful.

Some of them will contribute with even further understanding of the thermal relations that exist within the encoder and similar products. Some of them investigate how more complex materials and devices could be simulated in CFDesign. Finally some of them give an example on further thermal optimization.

### *7.5.1 Relation-plots*

Increasing a products power generation will undoubtedly result in an overall temperature increase inside the product. But what is the ratio between the power increase and the temperature increase? Is this ratio the same in different temperature regions?

By doing simulations on a chosen product where the power consumption is gradually increased (+10 %, +20 %, +30 % ...), the relations could be plotted out and studied. These relations would probably be the same for similar geometries which is why it could come in handy when developing new products. Observe that this only would serve as guidelines when developing new products. To have a well-supported picture of these relations may be helpful during the thermal optimization. These types of simulations could of course even be made with other parameters such as ambient temp/inside temp, or volume increase/inside temp.

### *7.5.2 Contact Resistance*

The heat conduction between two solids depends on how tightly pressed together they are and what surface finish they have. CFDesign does not take this into account automatically but will assume no contact resistance between solids. Although it is possible to manually apply contact resistances it is hard to know how big these should be. To get an understanding for this a number of heat tests can be done on two solids where one solid is heated. By varying the surface finish and the pressure between the solids, and then trying to simulate the same scenarios in CFDesign it could be decided what contact resistances that are appropriate for a specific scenario.

### *7.5.3 Simulating Graphite*

The use of graphite as a cooling material is, due to its rare heat conduction properties, constantly developing. Since graphite could be an appropriate choice in various AXIS products, being able to do simulations with this anisotropic material could be of use. Due to these properties some validations are recommended to be done before trusting these simulations.

### *7.5.4 Simulation Heat Pipes*

In the same way as graphite, simulating heat pipes can always be a favourably possibility. Since heat pipes are somewhat more complex than a common solid this would

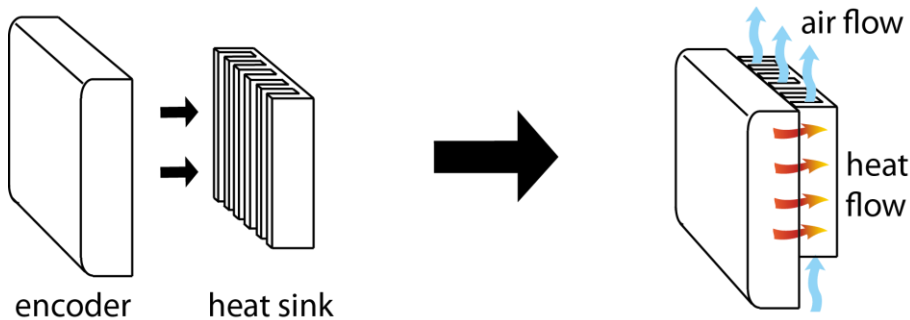


take some effort, but once a heat pipe prototype was done inside CFDesign this could be placed in any CAD-model.

**7.5.5 Possible Thermal Solutions**

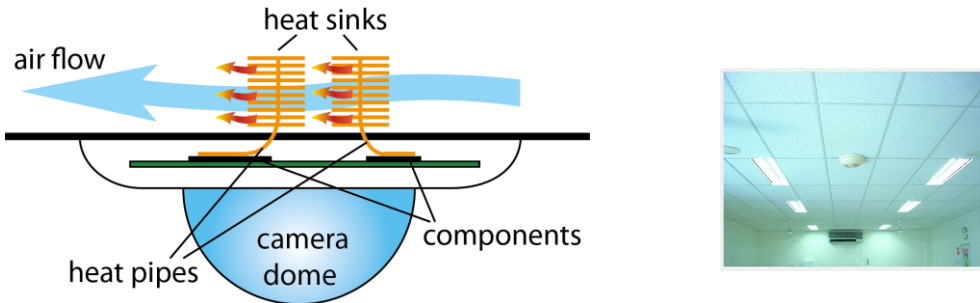
Two spontaneous cooling conceptions are here presented, one for the encoder and one for AXIS indoor cameras in general.

To be able to transfer the heat away from the CPU even more effectively a heat sink should be placed on the cover. However since all the heat generating components are placed on the bottom, the heat sink should be placed beneath the product. Since there will be no effective airflow here the idea is to place the whole encoder vertically, attached to a stand or even a wall, with the vertical heat sink placed between the wall and the product. The aluminium block from previous simulations is also to be used in this solution for transporting the heat from the CPU directly to the heat sink.



**Figure 7.1** The encoder placed vertically and with a heat sink

The other concept works for cameras that are mounted in office environment. The ceiling in these types of rooms consists in many cases of gypsum panels. In the open space between the panels and the concrete, ventilation systems are usually installed, cooling and rotating the air. This cooled, moving air could be used for cooling the camera if the geometrical design is made correctly. By placing some kind of heat conductors, for instance graphite or aluminium or even heat pipes, the heat could be transferred up to the moving air above the panels. Here a heat sink could be used for spreading the heat to the surrounding air, a potentially effective process since the air is in fact cooled and moving.



**Figure 7.2** Heat sinks above the ceiling cooling the camera



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## Appendix A: FEM - The Weak Formulation

In the finite element method it is essential to transform the strong form to the weak form, for the retrieval of the final finite element method expression.

To establish the weak formulation an arbitrary function is multiplied with the strong formulation. The arbitrary function is called the weight function and is named  $v(x)$ .

$$v \left[ \frac{d}{dx} \left( Ak \frac{dT}{dx} \right) + Q \right] = 0$$

The equation is integrated over the region, from 0 to L.

$$\int_0^L v \left[ \frac{d}{dx} \left( Ak \frac{dT}{dx} \right) + Q \right] dx = 0$$

Integration by parts is used to evaluate the expression further.

$$\int_a^b \frac{dy}{dx} dx = \int_a^b dy = [y(x)]_a^b$$

Use the expression and derive

$$y(x) = \phi(x)\psi(x)$$

$$\frac{dy}{dx} = \frac{d\phi}{dx} \psi + \frac{d\psi}{dx} \phi$$

From these expressions we get:

$$\int_a^b \left( \frac{d\phi}{dx} \psi + \phi \frac{d\psi}{dx} \right) dx = [\phi(x)\psi(x)]_a^b$$

And from some rearranging from the former equation we finally get:

$$\int_a^b \phi \frac{d\psi}{dx} dx = [\phi\psi]_a^b - \int_a^b \frac{d\phi}{dx} \psi dx$$

This result concludes:

$$\int_a^b v \frac{d}{dx} \left( Ak \frac{dT}{dx} \right) dx = \left[ vAk \frac{dT}{dx} \right]_0^L - \int_0^L \frac{dv}{dx} Ak \frac{dT}{dx} dx$$

## Appendix A: FEM - The Weak Formulation

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This expression will form by using the strong form multiplied with the weight function with this latest expression:

$$\int_0^L \frac{dv}{dx} Ak \frac{dT}{dx} dx = \left[ vAk \frac{dT}{dx} \right]_0^L + \int_0^L vQ dx$$

Using the expression  $q = -k \frac{dT}{dx}$  and the boundary conditions we get:

$$\left[ vAk \frac{dT}{dx} \right]_0^L = \left( vAk \frac{dT}{dx} \right)_{x=L} - \left( vAk \frac{dT}{dx} \right)_{x=0} = -(vAq)_{x=L} + (vA)_{x=0}h$$

where the flux  $q = (x = L)$  is unknown and the flux  $q = (x = 0)$  is known.

Using the two former equations we finally will get the weak formulation of one-dimensional heat flow.

$$\int_0^L \frac{dv}{dx} Ak \frac{dT}{dx} dx = -(vAq)_{x=L} - (vA)_{x=0}h + \int_0^L vQ dx$$

$$T(x = L) = g$$

The weak formulation can now be seen in two dimensions.

$$\int_A (\nabla v)^T t \bar{D} \nabla T dA = - \int_{\mathcal{L}_h} vht d\mathcal{L} - \int_{\mathcal{L}_g} vq_n t d\mathcal{L} + \int_A vQt dA$$

The approximation of the temperature over the region is generally written as

$$T = \bar{N} \bar{a}$$

$\bar{N}$  is the global shape function matrix (description of nodes and element and placing) and  $\bar{a}$  contains the temperature at the nodal points of the entire body.

$$\bar{N} = [N_1 \quad N_2 \quad \dots \quad N_n]; \quad \bar{a} = \begin{bmatrix} T_1 \\ T_2 \\ \vdots \\ T_n \end{bmatrix}$$

Further  $n$  denotes the number of nodal points for the entire body and  $N_i = N_i(x)$ . Since  $\bar{a}$  doesn't depend in  $x$ ,  $T = \bar{N} \bar{a}$  implies that

$$\frac{dT}{dx} = \bar{B} \bar{a} \quad \text{where} \quad \bar{B} = \frac{d\bar{N}}{dx}$$

$$\bar{B} = \begin{bmatrix} \frac{dN_1}{dx} & \frac{dN_2}{dx} & \dots & \frac{dN_n}{dx} \end{bmatrix}$$

The temperature is given by

$$T = \bar{B} \bar{a}$$

For one dimensional elements the expression follows

$$\bar{\Delta}T = \frac{dT}{dx}; \quad \bar{B} = \left[ \frac{dN_1}{dx} \quad \frac{dN_2}{dx} \quad \dots \quad \frac{dN_n}{dx} \right]$$

The schematic formulation of the weak formulation

$$\int_a^b \frac{dv}{dx} Ak \frac{dT}{dx} dx = -[vAq]_a^b + \int_a^b vQ dx$$

The weak formulation is then retrieved and finally expressed

$$\left( \int_a^b \frac{dv}{dx} Ak \bar{B} dx \right) \bar{a} = -[vAq]_a^b + \int_a^b vQ dx \quad \textit{The weak formulation}$$

From the weak formulation further steps will eventually lead to the finite element method expression (see section 2.2)[2].





## Appendix B: Current Thermal Design Solutions

*There are currently a great number of ways to deal with heat problems in electrical devices. To be able to follow the arguments and conclusions from the simulation results the reader should be acquainted with some of the most common methods in thermal design. Thus a short walkthrough about available solutions is given in this chapter.*

### B.1 Passive Solutions

Passive solutions are solutions that do not require any type of power supply to operate. These are of course always if possible preferable over active solutions, that is, those that *require* power to operate.

#### B.1.1 High Conductivity Materials

The basic goal in most cases is to transfer heat energy from point A to point B in an efficient way. By efficient it means: Transferring the heat while keeping the temperature gradient low over the distance A to B. The first really intuitive approach will consequently be to use *high conductivity materials*. This is a broad term used for all materials considered to be good heat conductors. As an example there are aluminium, copper, gold and graphite.

*Aluminium* has the main advantage of being relatively cheap. It is used in heat sinks and all kinds of cover where high heat dissipation is desirable. The conductivity of aluminium also depends strongly on how it is processed and what materials that is included in the aluminium alloy. (As good as all aluminium on the market today exists as part of an alloy).

*Copper* has twice the thermal conductivity that aluminium has, although it is about three times as expensive. It is also used in heat sinks when aluminium cannot meet the heat requirements. Copper is typically the industrial standard when it comes to electrical conductivity, and is widely used as the electrical conductors in all kinds of printed circuit boards. The heat spread across the PCB is of course of great interest in thermal designing. This is why it is important to understand the relations between the amount of copper in the PCB:s and the general heat conductivity of the PCB:s. This will be discussed further in next chapter.

*Gold* possesses excellent conduction properties, both thermal and electrical. This together with its ability to resist oxidation makes it a good choice for electronic integrated circuitry, like for example in motherboards. However as a pure heat conductor, copper is both cheaper and more conductive than gold.

## Appendix B: Current Thermal Design Solutions

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*Graphite* is relatively new on the market as a high conductivity material. The material comes naturally in thin sheets, and it differs from the metals mentioned above in that it is an anisotropic material. This means that one or more properties, in this case heat conductivity, vary depending on direction. When it comes to graphite, the heat conductivity tends to be much higher in the planar direction of the sheets than in the normal direction of the sheet, about 100 times higher. Thus the big challenge is to get the heat energy into and out from the sheet, for once it is in there it will travel extremely well in the planar directions. Graphite sheets are often placed tightly against PCB:s, letting some of the heat from the PCB slip down in the high conductive sheets[5]. Below is a picture of how these sheets could look like.



**Figure B.1** Graphite sheets are used for transporting the heat away from PCB:s [5]

To get a feeling for how the high conductivity materials perform between themselves, their thermal conductivity is represented in the table below. Steel and air has also been included as references.

**Table B.1** Different high conductivity material compared from pros and cons [6].

Material	K [W/mK]	Pros	Cons
Aluminium	200	Rel. cheap and strong	Lower cond. then the others
Copper	380	Good electrical conductor	Too weak for many designs
Gold	318	Oxidation resistant	Expensive
Graphite	500	Very cheap	Very low cond. in normal dir.
Steel	17	-	-
Air	0.025	-	-

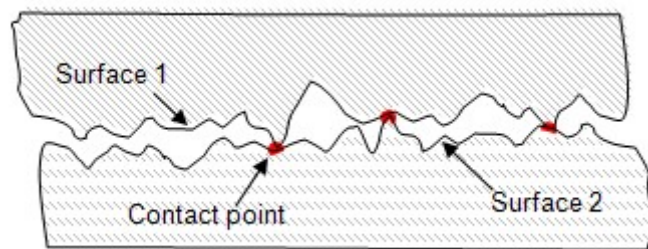
As the table implies, the conductivity for steel and air are very low compared to the others. Substances with conductivity less than 0.1, like air, are referred to as isolators.

With this in mind, thermal designs could often be thermally improved by transferring the heat over unwanted air gaps by placing heat bridges out of some high conductivity material.

**B.1.2 Thermal Interface Material**

A thermal interface material, referred to as TIM:s, is a high conductivity material used to fill the gaps between thermal transfer surfaces, that is surfaces between which a high heat transfer rate is desired. This could for instance be between microprocessors and heat sinks, between integrated circuits and heat pipes or between a PCB and a cover.

Two solid materials that are considered to be firmly pressed against each other have in fact in most cases a very low area where they actually touch each other. Usually no more than four percent of the total cross section is in full contact, see the illustration below.



**Figure B.2** The actual touching area is only four percentage of the total area

Since the heat transfer through a solid depends on the cross sectional area, see eq. 2.4, the heat transfer between materials is often very low. This results of course in an undesired temperature gradient across the material border, which is why thermal designers often choose to place a TIM in between.

TIM:s comes in many different shapes for practical reasons. The figure below gives a picture of how they could look like.

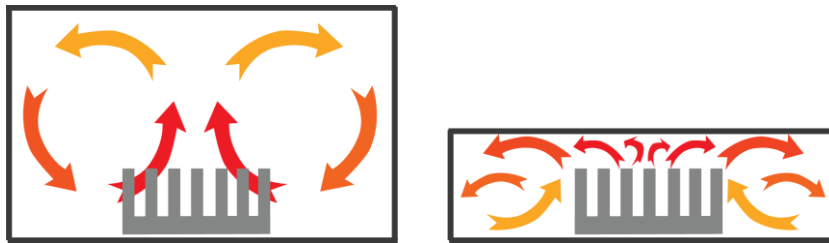


**Figure B.3** TIM:s meant for being attached between integrated circuits and heat sinks[7].

### B.1.3 Heat Sinks

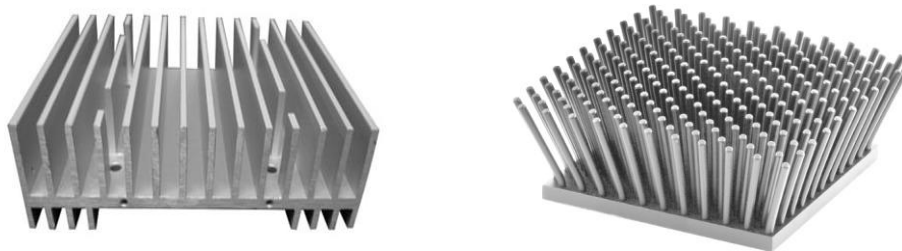
A heat sink is used for moving heat from a solid and into a fluid medium. The most common material in heat sinks is aluminium because of its high thermal conductivity and low price. Common fluid materials are air, water and refrigerants. The heat sink consists of a metal base with a number of metal fins or pins attached to it. The purpose of this is to maximize the contact surface between the heat sink and the fluid medium; the convective effect is directly proportional to this area. (See the theory chapter, section 2.1.2) Often the heat sink is placed in combination with a fan to increase the velocity of the air and in this way increase the amount of heat that are transported away from the fins. [8]

To be able to use heat sinks effectively it is important to have enough space for the surrounding air. If not, the typical circular convection currents will not arise.



**Figure B.4** Circular convection currents around a heat sink. To the left enough space is given, to the right the ceiling will prevent the typical circular motions to arise.

Below is an illustration of the most common types of heat sinks. The one with fins (to the left) are more efficient. However the air needs to enter in line with the fins, otherwise the efficiency will decrease drastically. The heat sink with pins (to the right) however, is not dependent on air flow direction. This makes it a somewhat more forgiving solution, used for instance if the designer is not certain of the air flow directions in the device.

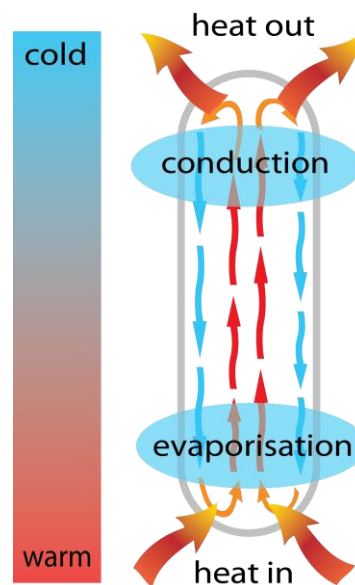


**Figure B.5** Two types of heat sinks; with fins (to the left) and with pins (to the right) [9], [10].

### B.1.4 Heat Pipes

This device consists of a hollow metal cylinder, partly filled with a fluid. The container isolates the working fluid from the outside environment. The idea is to place the heat pipe with one end in a cold medium and the other in a hot medium. Heat will then be transported from the hot medium, through the pipe, to the cold medium, just like it would if the heat pipe was an ordinary aluminium stick. However the transport process in a heat pipe differs from a solid heat conductor, where only convection takes place.

The heat transfer through a heat pipe starts with that the hot medium around the pipe causes the fluid inside this part of the pipe to evaporate. Since this end is set to be the lower end of the pipe, gravity will force the evaporated fluid to travel upwards. Thus the heat will also travel upwards, through convection. Once the evaporated fluid reaches the top end of the pipe it will condensate against the pipe walls due to the colder surroundings at this side. Because of this phase shift the heat will leave the pipe. The condensed fluid will now fall down along the pipe walls, letting evaporated fluid pass through the middle of the pipe. The picture below illustrates the complete process.



**Figure B.6** Heat pipe – the concept

It should be mentioned that the current heat pipes are provided with a wick from end to end. Through the wick the fluid travels due to *capillary forces*, with or without help from gravity. As a result, most heat pipes today works in every direction, although they often work better in vertical position.

The heat pipe is a simple device since it has no moving parts, making it tougher than for example fans. When it comes to efficiency it is hard to compare directly to pure materials as copper and aluminium since heat pipes does not have a set value for conductivity like materials do. The reason is this: The only thermal resistance in a heat

pipe is during the phase shifts in the pipe ends. Thus the number of joules per second going through the pipe does not depend on the length of the pipe. It is therefore not possible to provide the device with a property that *depends* on the length (like the conductivity  $k$  [W/mK]). However it could as a rule of thumb is said that the heat pipe has an efficiency of 10 to 1000 times higher than pure silver, depending on the geometry situation. [11]

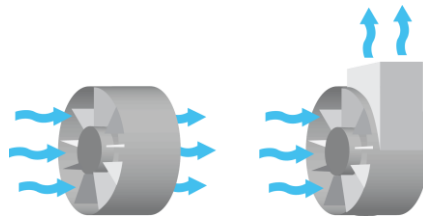
## B.2 Active Solutions

The active components are in general used when the passive components are not sufficient to transport the heat away from a specific spot. Since they often consist out of more parts and even movable parts, they are more sensitive to impacts and do often have shorter life cycles than the rest of the product.

### B.2.1 Fans

Fans are effective cooling devices since the high velocity air streams they create are able to rapidly remove the heat streaming out from the heat source. When a fan is added to the system, the natural convection that would arise around a heat source turns into forced convection, see natural vs. forced convection in chapter 2.

There are basically two types of fans; axial fans and radial fans. The axial fan sends the air forward, in an axial direction. (The rotation axis of the fan) In a radial fan, the air leaves the fan having a radial direction, see the figures below.



**Figure B.7** Axial fan (to the left), radial fan (to the right)

The two types will have different influence on the air stream. The axial fan creates high air velocities and a big air flow compared to the radial type. The radial fan on the other hand creates a higher air pressure than the axial fan. The fan operates with a higher sound level than other cooling devices. They can be very effective in combination with a heat sink, but they need a lot of space and are therefore sometimes not appropriate in smaller products. Below are two photos shown of an axial and a radial fan. [12]



**Figure B.8** Axial fan (to the left), radial fan (to the right) [11].

### B.2.2 Water Cooling

Water cooling offers very effective cooling plus low sound levels. The principle is that water is led through a number of coils close to the heat sources. The water heated water is transported away from the hotspots and cooled by ambient air.

When using water cooling for cooling *microchips* devices like the ones in the figure below are often used. They consist of a metal block through which a metal coil goes back and forth. The block is attached directly to the microchip. The water will then flow through the coil and will circulate between the block and a pump. In this way heat is transported from the metal block to the surroundings.



**Figure B.9** Cooling block to a CPU in a computer (left), Cooling block and water pump to a CPU in a computer (right) [13].

The system is often used in stationary computers; the system is not appropriate in cell phones or smaller devices since the tubes need a certain diameter to work effectively.

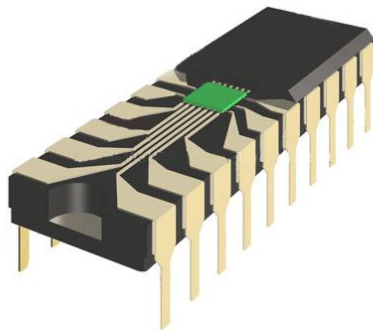
The risk of short circuit due to leakage should be taken into account before deciding to use water cooling, as well as its complexity and high prices.





## Appendix C: Microchip Interiors

An integrated circuit consists in most cases of a thin substrate of semiconductor material placed on a silicon plate. The semiconductor material consists as thin threads, out of which millions of electrical components are created. From the silicon plate electrical conductors are sending information between the silicon plate and the PCB. The integrated circuit is then packaged with some kind of coating, usually black plastic. The picture below shows how a typical microchip is designed; from the silicon chip in the middle the information is being sent via the electrical conductors which are then connected to the PCB.



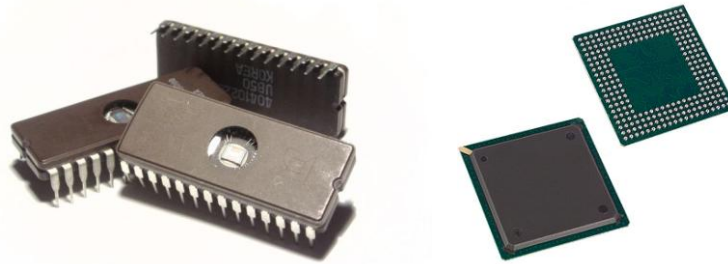
**Figure C.1** The interiors of an integrated circuit

How the information is being sent down to the PCB differs between different types of microchip, and depending on type even the heat transfer between the plate and the PCB differs. Two of the most common types of integrated circuits are shown in the illustration at next page. The packaging type to the right is called DIP (for Dual In-line Package). This has a rectangular housing and two parallel rows of electrical connecting pins. The pins point downwards, and extend past the bottom plane of the package. They are then through-hole-mounted to the PCB, that is, they are passed through a hole in the PCB and then moulded on the other side. The packaging type to the left is called a BGA (for Ball Grid Array). Here the electrical conductors exist as balls of solder stuck to the bottom of the package. The package is placed on a PCB that has copper pads that match the ball grid. By heating the assembly the balls will melt and connect to the PCB.

## Appendix C: Microchip Interiors

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This method has descended from the DIP and has the main advantage that a bigger number of electrical conductors between the chip and the PCB are possible.



**Figure C.2** Different types of microchip packaging, DIP (dual in-line package) to the left and BGA (ball grid array) to the right

The silicon plate with the electrical components in the middle of the package has of course a maximum temperature that will if exceeded will cause damage to the device. This limit is usually relatively high but sometimes the temperature here, which is referred to as the *junction temperature*, could be of interest.

To find the junction temperature a number of parameters have to be known. The most common scenario is that the following parameters are known.

- The total heat flux out from the micro chip
- The temperature on the outside of the microchip package, or case
- The thermal resistance between the package surface and the silicon plate in the middle.

By knowing these three the junction temperature could be found from the following equation:

$$Q = \frac{\Delta T}{R_{\theta}} = \frac{T_{\text{junction}} - T_{\text{case}}}{R_{\theta \text{ junction to case}}} \quad (\text{C.1})$$

where

- $T_{\text{junction}}$  is the silicon plate temperature, the highest temperature in the microchip.
- $T_{\text{case}}$  is the package or case temperature.
- $R_{\theta \text{ junction to case}}$  is the thermal resistance between the junction and the case.

There is also a thermal resistance that is referred to as  $R_{\theta \text{ junction to board}}$ , where board refers to the PCB. This property is analogue to the  $R_{\theta \text{ junction to case}}$ , but in-

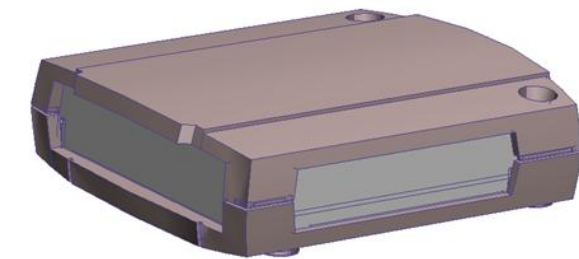
stead of representing the resistance between the junction and the top of the chip it represents the resistance between the junction and the PCB that the chip is attached to [1].



## Appendix D: The Test Product and Models



**Figure D.1** The Video Encoder



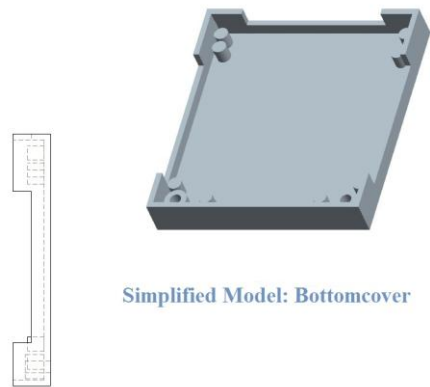
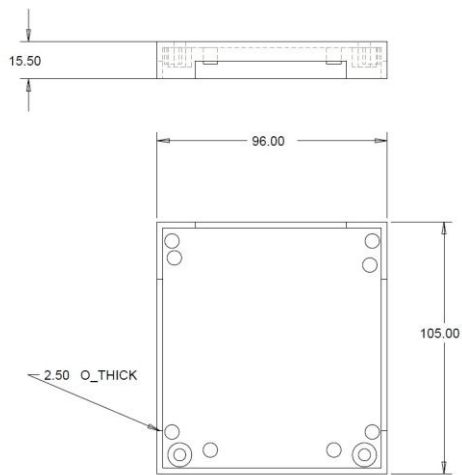
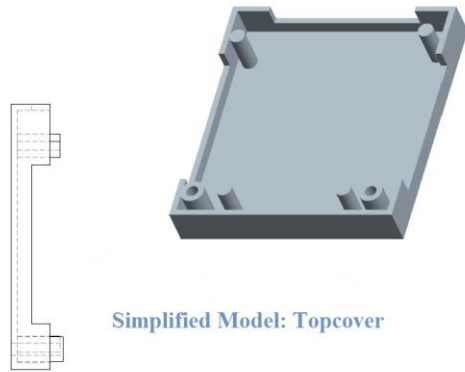
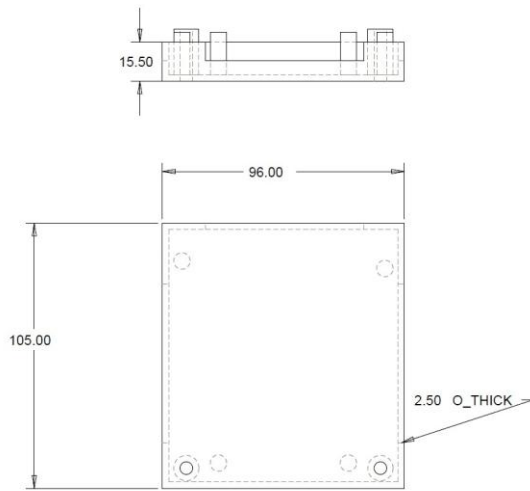
**Figure D.2** The reduced model



**Figure D.3** The simplified model



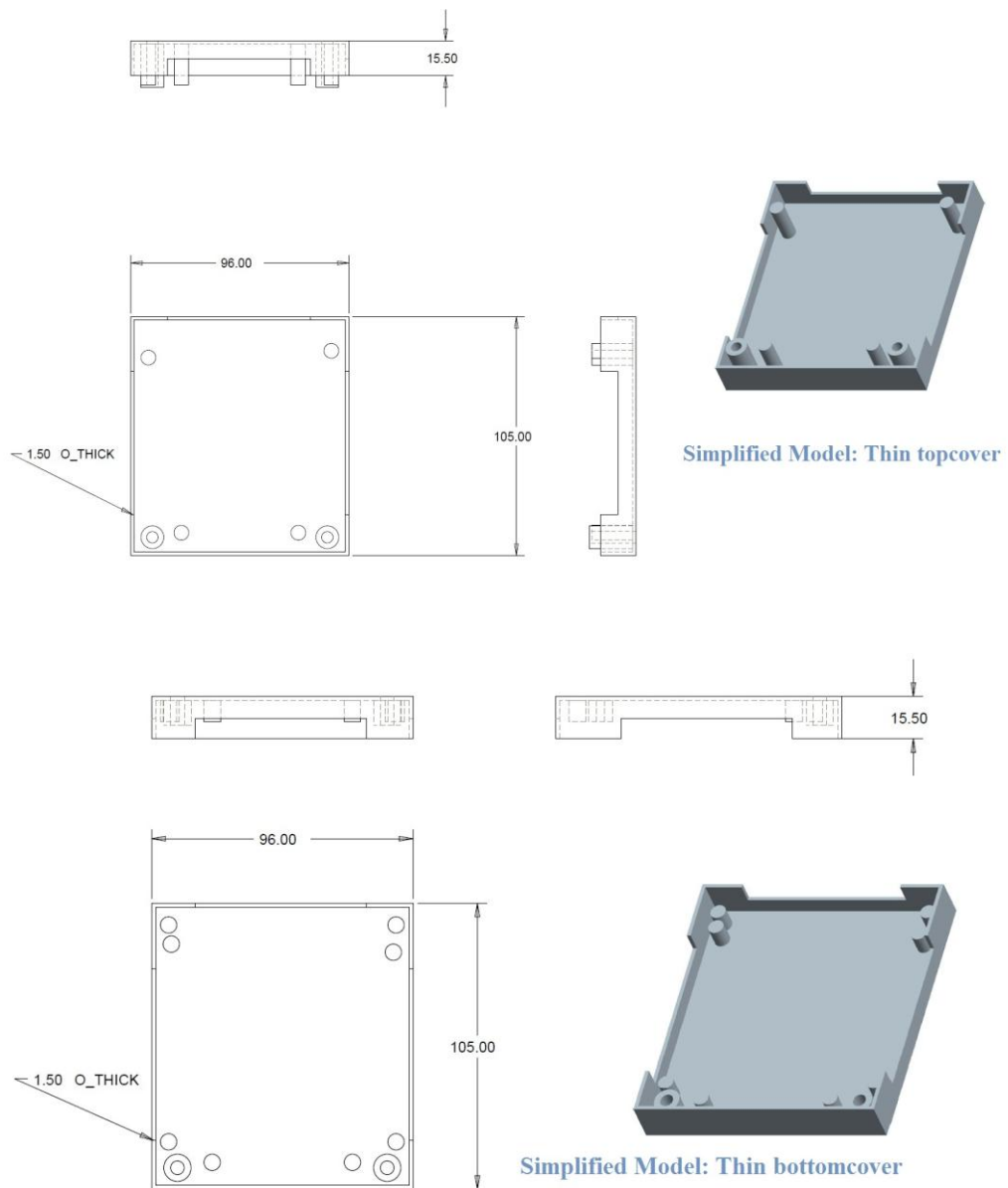
## Appendix E: Simplified Model





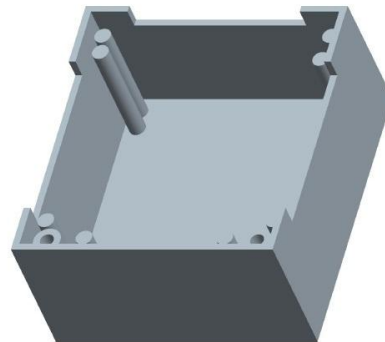
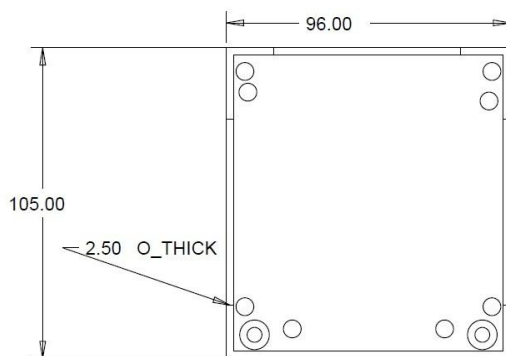


## Appendix F: Simplified Model with Zinc Cover

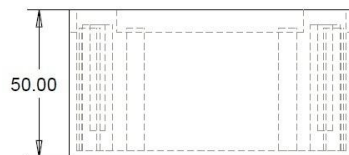




## Appendix G: Simplified Model Deepened Cover



Simplified Model:  
Deepened Bottomcover





## Appendix H: Reduced Model vs. Simplified Model

Below is the result presented with a short version to show the similarity between the reduced and the simplified model. See also appendix D for the image of the two models and sections 5.5 (reduced model) and 6.3 (simplified model) where the development of the models are presented. The table H1 presents the temperatures on the components from the simulation with the simplified model. The table H.2 shows the deviation between the same simulations with the reduced model and the simplified model. The similar temperature plots with the reduced model are found in section 6.2.

**Table H.1** The temperatures on the components from the simplified model

SIMPLE/REDUCED	Air temp. +10°C	Power gen. +10%	Cover cond. 200W/mK	Plastic cover	Silver screws
Component	simple (°C)	simple (°C)	simple (°C)	simple (°C)	simple (°C)
CPU	66.6	60.3	56.6	81.5	56.8
Video chip	51.6	43.7	41.5	66.3	41.7
Memory	52.1	44.4	42.0	67.8	42.2
Ethernet	50.2	42.3	40.2	65.5	40.3
PCB	51.3	43.5	41.3	65.9	41.4
Cover	44.0	35.3	34.1	55.9	34.3
Ambient air	33.0	23.0	23.0	23.0	23.0

**Table H.2** The temperature deviation between the simple and reduced model

SIMPLE/REDUCED	Air temp. +10°C	Power gen. +10%	Cover k = 200W/mK	Plastic cover	Silver screws
Component	deviation to reduced (%)	deviation to reduced(%)	deviation to reduced (%)	deviation to reduced (%)	deviation to reduced (%)
CPU	3	4	3	5	3
Video chip	4	3	6	4	3
Memory	4	3	3	4	3
Ethernet	4	4	3	4	3
PCB	3	5	4	5	4
Cover	4	4	3	6	3
Ambient air	0	0	0	0	0



## Appendix I: Division of Labour

*The different parts were divided between the authors:*

### **Majken Blixt**

1.5 Limitations and Delimitations  
2.2 Finite Element Analysis Fundamentals  
3.5 Monitor Points  
4.5 Critical Temperature Values  
5.2.2 Preparing the CAD Model for CFDDesign  
6.2 Analysing the Results of the First 9 Fictive Scenarios (Made by both authors)  
6.3 Simplifying the Model Further  
6.4 Analysing Results of the Remaining 6 Fictive Scenarios (Simulation material)  
6.5 Planning and Choosing the Combined Scenarios  
6.7 Analysing the Results of the Combined Scenarios  
7.2 Problems During the Project  
Appendix A FEM - The Weak Formulation  
Appendix B Current Thermal Design Solutions (except 4.1.1 High Conductivity materials)  
Appendix D-H (The Test Product and Models, Simplified Model, Reduced Model vs. Simplified Model)

### **Markus Giver**

1 Introduction (except 1.5 Limitations and Delimitations)  
2.1 Fundamental Thermodynamics and Heat Transfer  
3 CFDDesign – A Brief Introduction (Except 3.5 Monitor Points)  
4 The Test Product (Except 4.5 Critical Temperature Values)  
5.1 Heat Testing  
5.2 Simulation Preparations (Except 5.2.2 Preparing the CAD Model for CFDDesign)  
5.3 Validation of Simulation  
6.1 Planning and Choosing the Fictive Scenarios  
6.2 Analysing the Results of the first 9 Fictive Scenarios (Made by both authors)  
6.6 Verifying the Fictive Scenarios with Simplified Model

Appendix X: Heading

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7 Conclusions and Discussion (Except 7.2) (This part was discussed carefully between the authors before editing)

Appendix B (B.1.1 High Conductivity Materials)

Appendix C Microchip Interiors