Assignment 1

Thermal Study on Cooling of a Central Processing Unit

Heat and Mass Transfer – ME306

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1. Introduction

In almost every real life engineering problem, the question of cooling and heating remains one of the greatest challenges faced. Thanks to physical laws posed on heat transfer mechanism, we are able to find solutions to this issue and effectively cool or heat up certain objects by modifying surface area, convection or conduction heat transfer coefficients and similar parameters.

In this specific paper, we are observing heat dissipation rate of a central processing unit (CPU) by bringing together both conduction and convection heat transfer mechanisms in order to inspect the most affected areas of high temperature, as well as to compare the effects of number of fins on heat transfer rate. We will see how increasing the exposed surface area can significantly increase heat dissipation, hence lead to effective cooling of critical components such as CPUs.

Heat transfer rate for practical cases is almost always obtained by solving heat conduction equation numerically, as the conditions it is based on make it impossible for us to obtain an analytical solution. These conditions include multidimensionality and transient heat transfer conditions which in most cases do not even have a solution. That is why we use softwares such as Solidworks and Ansys that use numerical methods in order to simulate temperature, velocity and pressure fields. These softwares incorporate number of advanced mathematical models which solve governing equations such as Navier-Stokes equations, and after a number of steps such as generating mesh and providing initial and boundary conditions, can deliver a very respectable approximation of solution used for a real life model.

The main software used for this thermal analysis is Solidworks, as it has a user friendly interface and provides fast and clear study of results. The complete steps to this thermal study will provide the reader with good understanding of heat transfer mechanism present in CPU analysis, and more specifically of importance of increasing the exposed surface area for achieving effective cooling of CPUs.

2. Heat Transfer Mechanisms

Heat transfer rate ($\dot{Q}$) tells us about amount of heat that is either lost or gained in time and its unit is $\left[\frac{J}{s}\right]$. Having said that, we can assume that the direction in which the heat travels matters and therefore it has not only magnitude but also direction which makes it a vector quantity. There are three main types of heat transfer rate:

- Conduction
- Convection
- Radiation

Heat transfer in most practical cases is multidimensional, as heat is lost or gained in more than one direction. What also adds to this complexity is time dependance of transient heat transfer problems. Even though there are number of cases when we conduct steady heat transfer analysis due to reaching constant temperatures in both mediums involved, greater portion of heat transfer problems involve time dependancy which increases the number of independant variables in the governing equations and makes it more perplexing to find their solution.

Two main heat transfer mechanisms we are dealing with in this thermal study are conduction and convection.

2.1. Conduction

Heat conduction is a heat transfer through solids or non-moving fluids and it is described mathematically by Fourier's law of heat conduction where:

$$\dot{Q} = -k\frac{dT(x)}{dx}A = -k\frac{\Delta T}{\Delta x}A$$

- k – heat conduction coefficient
- $\frac{dT(x)}{dx}$ - temperature gradient
- $\frac{\Delta T}{\Delta x}$ - temperature difference over the width
- A – area exposed to heat transfer

Based on the type of geometry we are dealing with, we can use either rectangular, cylindrical or spherical coordinate system to describe the conditions of our problem.

Since we know that temperature is a function of both space and time coordinates ($T(x, y, z, t)$), then heat conduction can be expressed in form of its three main components:

$$\dot{Q} = \dot{Q}_x \vec{\imath} + \dot{Q}_y \vec{\jmath} + \dot{Q}_z \vec{k}$$

where $\vec{\imath}$, $\vec{\jmath}$ and $\vec{k}$ are unit vectors and $\dot{Q}_x$, $\dot{Q}_y$ and $\dot{Q}_z$ are the magnitudes of heat transfer rates in x-, y- and z- directions.

Heat conduction depends on the type of material used, its geometry and most importantly on the temperature difference present. In this study, we will primarily see how increasing surface area has impact on reducing the overall temperature and increasing the heat loss over the CPU.

2.2. Convection

Heat convection is heat transfer mechanism that occurs when a moving fluid transfers heat from a solid object. There are two main types of convection; natural and forced convection. In natural convection, the movement of the fluid is caused by the bouyancy forces naturally present in the fluid due to temperature differences which affect the density of the fluid in different regions. However in forced convection, the fluid is blown over a solid object by a fan, pump or any similar mechanism. Convection is mathematically described by Newton's law of cooling which states:

$$\dot{Q}_{conv} = hA(T_S - T_\infty)$$

where:

- h - heat transfer coefficient
- A – exposed surface area of the object
- T_S – temperature at the surface of the object
- T_∞ - temperature of the fluid far from the object

In our specific case, convection plays crucial role in cooling the CPU and we are going to play with the area of the object in order to increase the cooling rate.

3. Thermal Study - Preprocessing

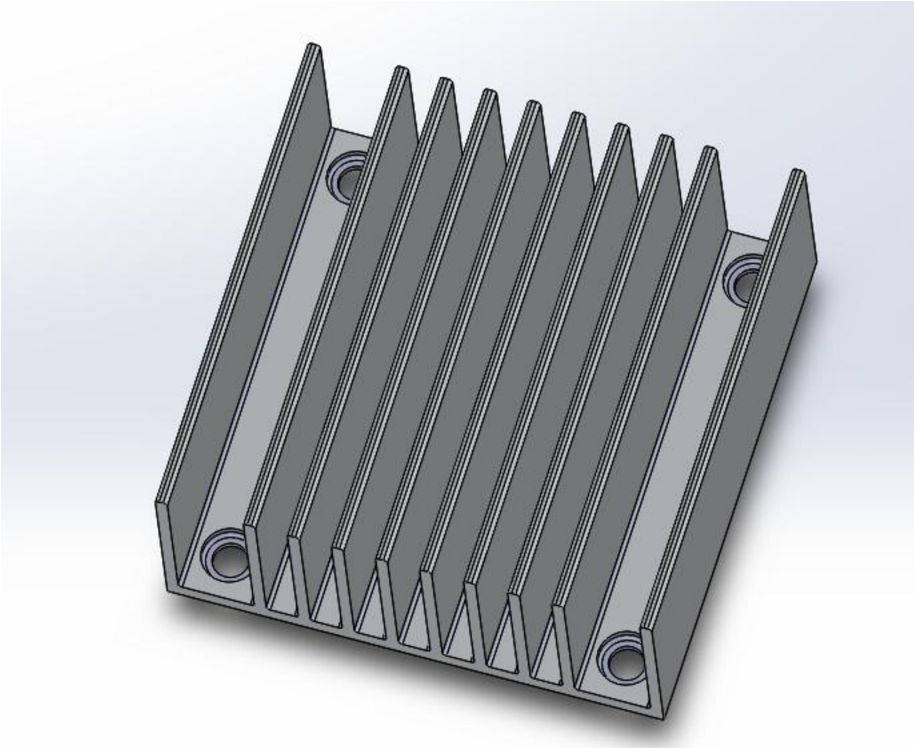
In order to conduct the thermal study on a CPU, we will need to go through a few steps that are part of preprocessing. These include:

- Creating 3D models in Solidworks
- Creating an assembly
- Applying materials
- Applying thermal loads
- Generating mesh

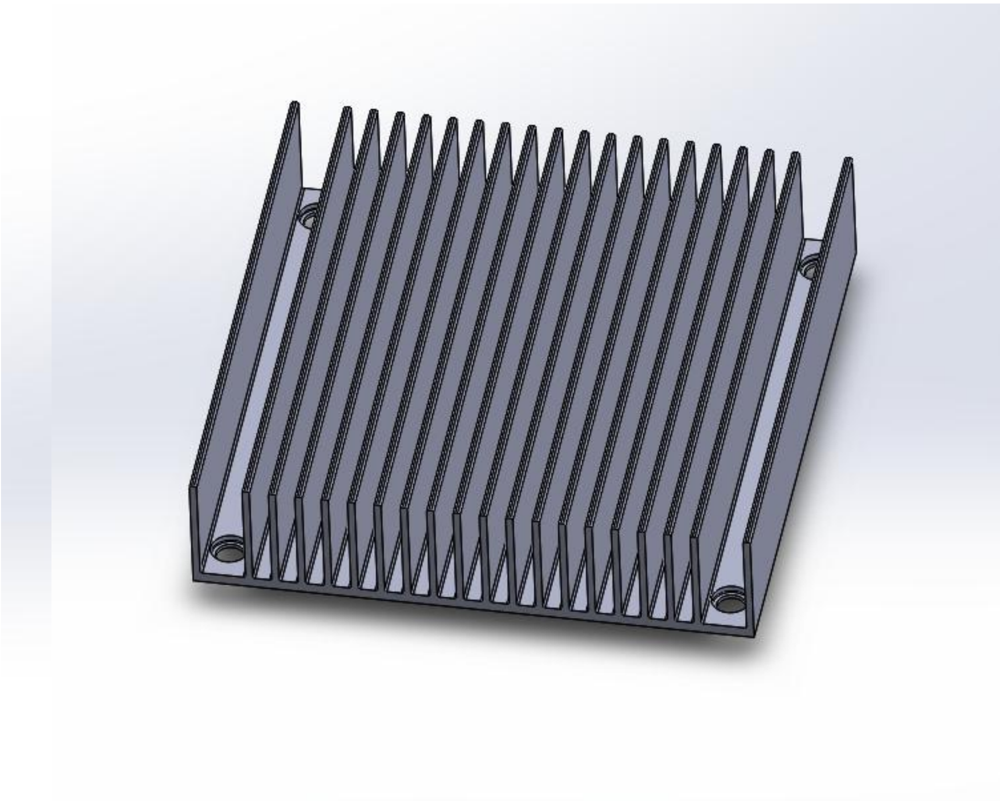
In the first step, we design a chip of a simple rectangular shape and also two different heat sinks. The generic case is that of 12 fins (10 after skipping two instances, but we will refer to it as a 12-fin heat sink), and the other is 22-fin heat sink.

By conducting thermal analysis with both these models, we will see how heat dissipation rate is affected by increasing the surface area.

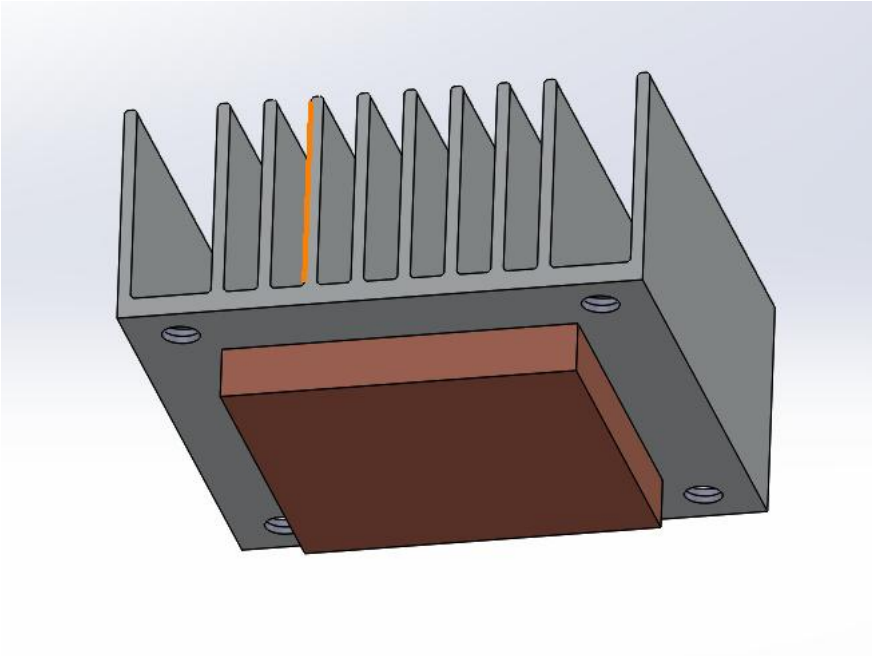
Below are the the required part for the study:



Picture 1 – CPU 42x42 Model

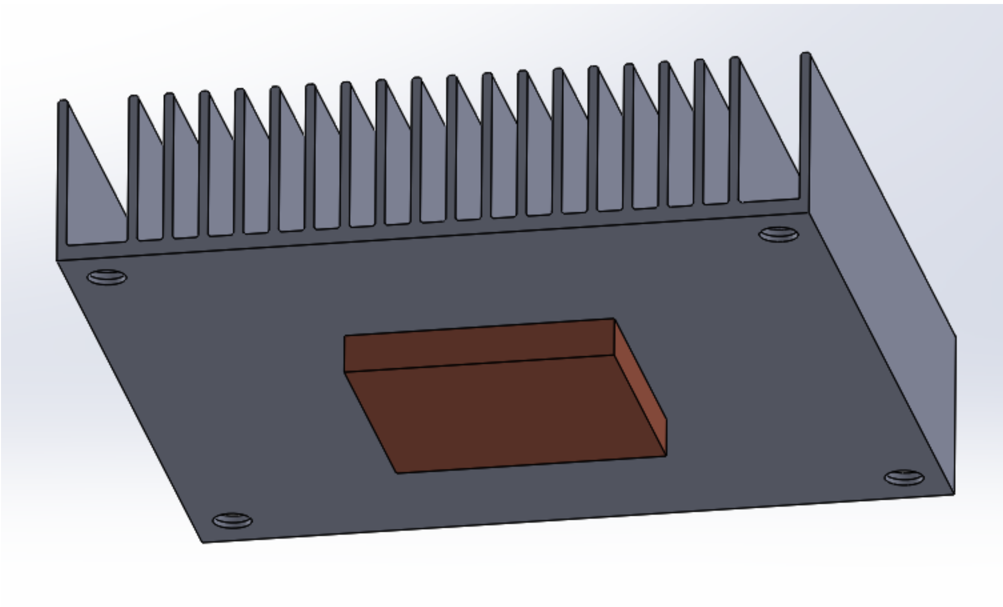


Picture 2 – 12-fin heat sink



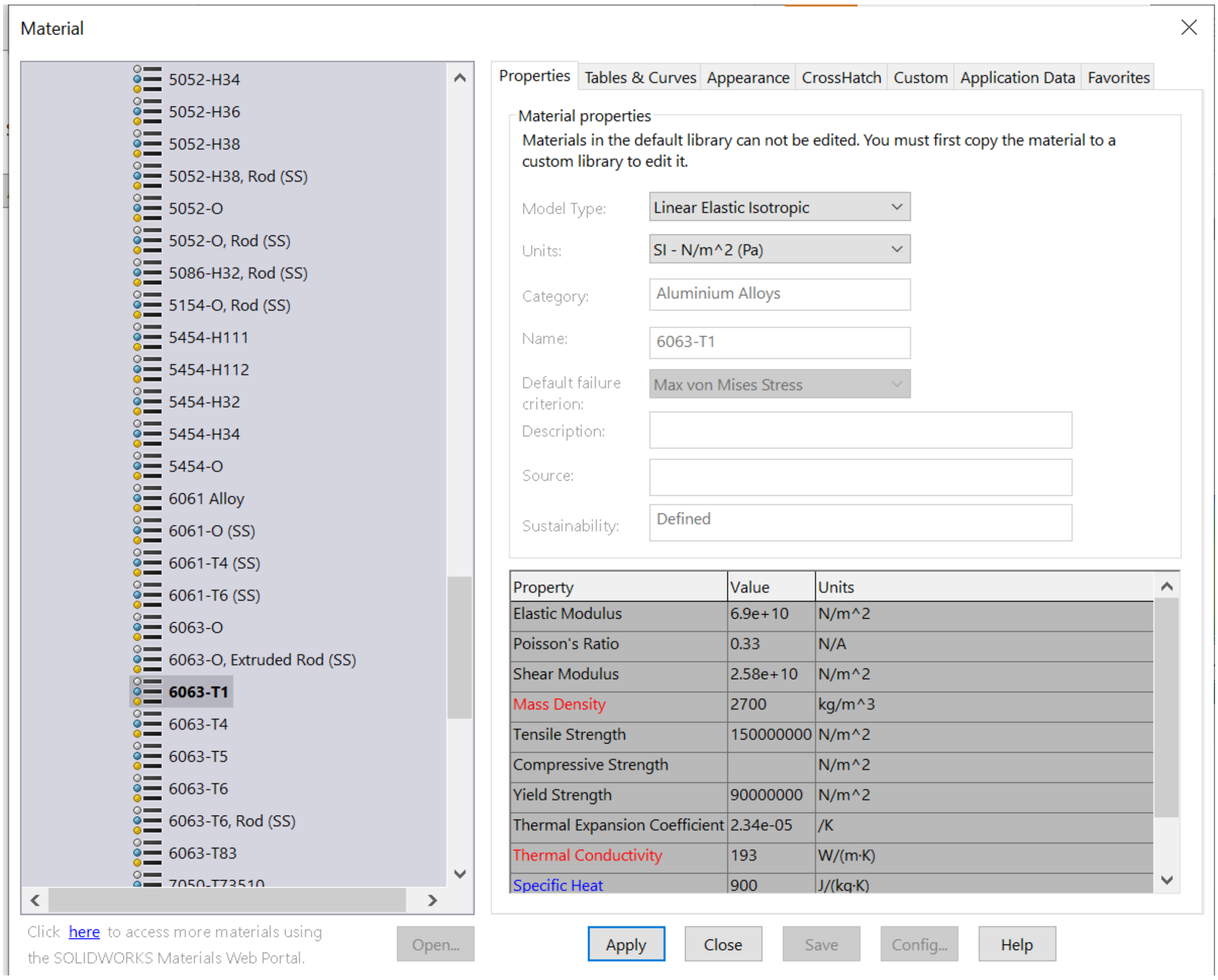
Picture 3 – 12-fin heat sink and CPU assembly

After creating the basic parts, we continue with making an assembly and then conducting a thermal study.



Picture 4 – 22-fin heat sink and CPU assembly

Next step includes setting the materials for both CPU and heat sink. For CPU the material is copper and for heat sink we choose aluminium alloy type 6063-T.



Picture 5 – Aluminium alloy 6063-T properties.

The choice of material for heat sink especially matters because it transfers heat directly from the CPU, and the higher its thermal conductivity, the higher will be the heat conduction between CPU and heat sink, which will result in a more effective cooling.

We can see that this particular aluminium alloy has a very high thermal conductivity which suits this case quite well.

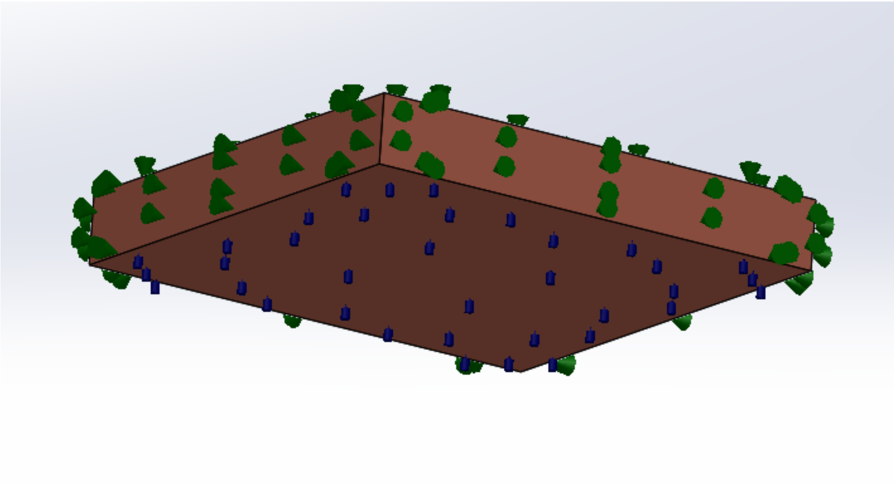
Next thing is applying thermal loads to the assembly. We observe two different cases for each type of heat sink:

- bottom of CPU is dissipating power of 40 W, and other remaining assembly surfaces are subjected to convection
- both bottom of CPU and the bottom of heat sink are excluded from convection

Convection conditions are:

$$T_{BULK} = 294\ K$$

$$h = 200\ \frac{W}{m^2 K}$$



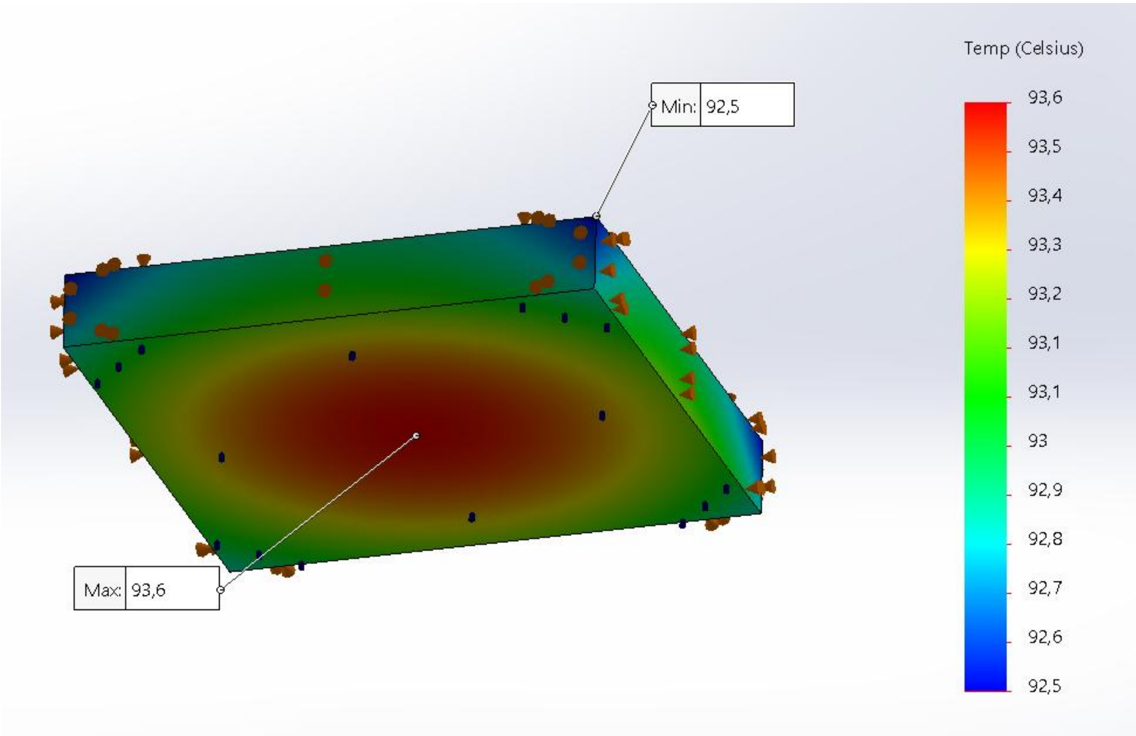
Picture 6 – CPU chip subjected to power dissipation at the bottom and heat convection on other exposed surfaces.

Next, we generate the mesh which was medium coarse and then run the thermal study.

4. Results and Data Comparison

Below we show the temperature distribution over the CPU before any cooling and then the effects of adding both types of heat sink on the amount of heat dissipation.

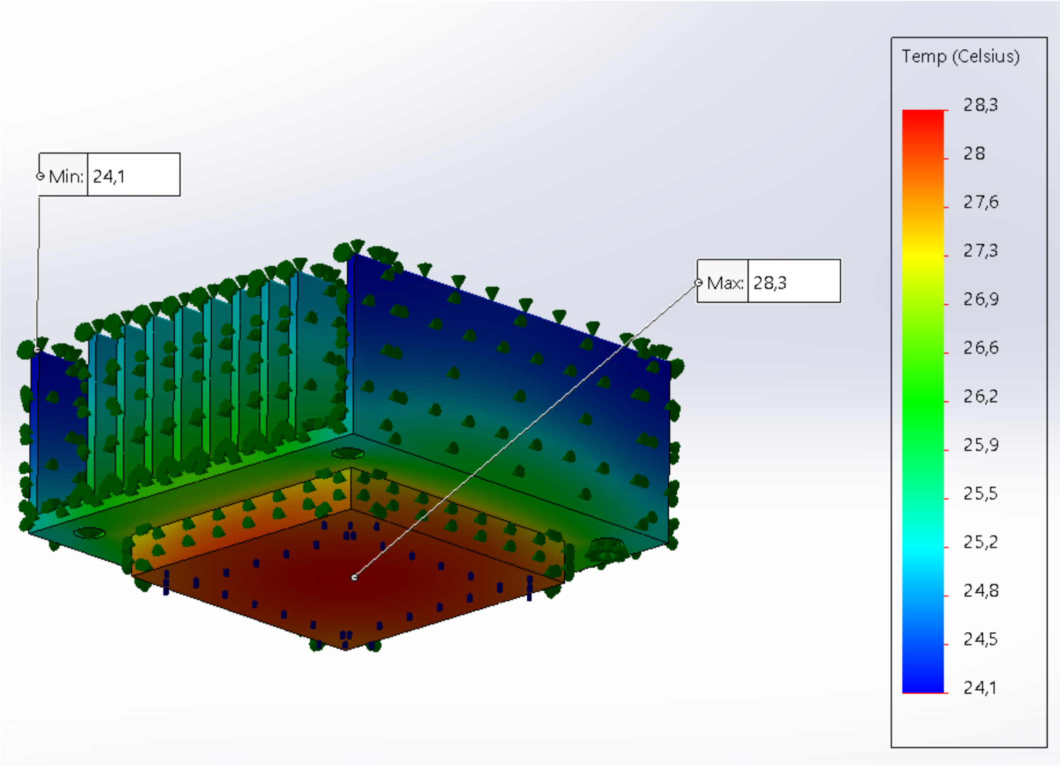
We can see that currently CPU temperature range is quite high and without any cooling mechanism, this amount of heat would spread throughout all other critical components inside a computer which would result in its failure due to overheating.



Picture 7 – Temperature distribution over CPU before cooling.

The maximum temperature is at the center of the CPU where there is greates concentration of heat due to the power being dissipated uniformly throughout the chip.

Next, we show the effect of adding a 12-fin heat sink to the CPU.

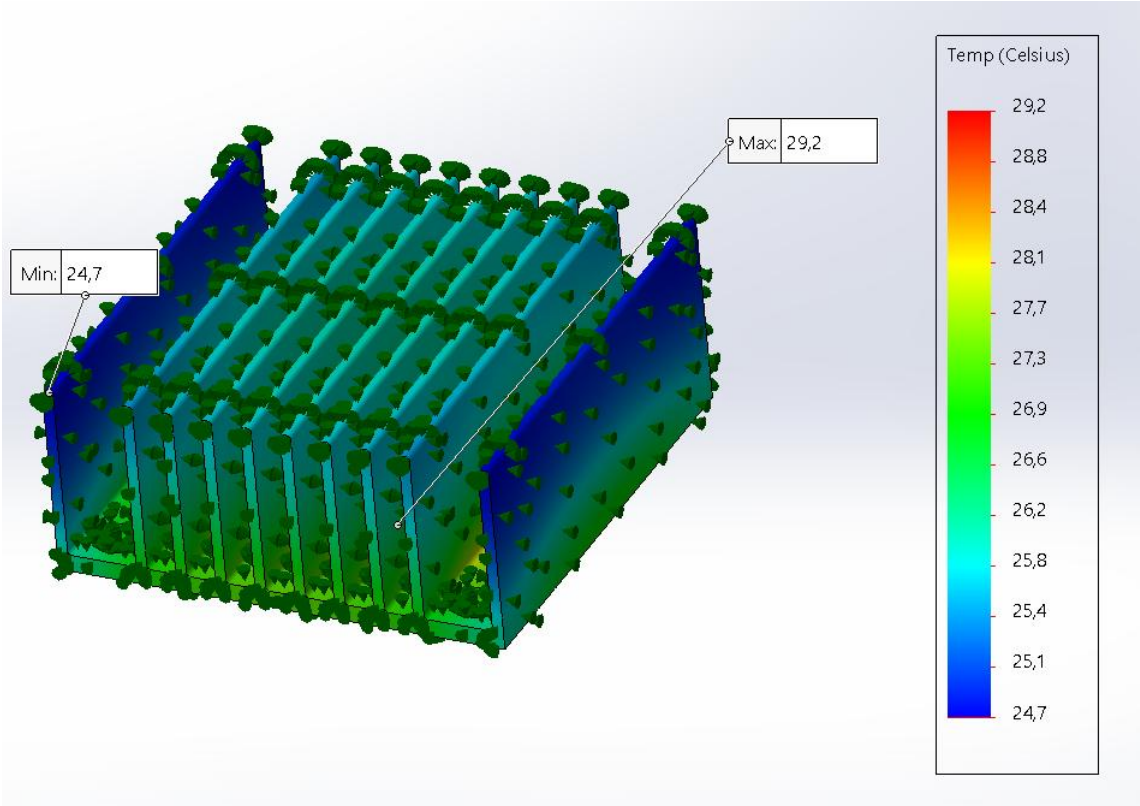


Picture 8 – Cooling of a CPU with a 12-fin heat sink.

It is obvious that adding a heat sink reduces the temperature range dramatically. The main reason for this is increasing the surface area of the entire assembly which by Newton's law of cooling means that there will be a higher heat transfer rate by convection.

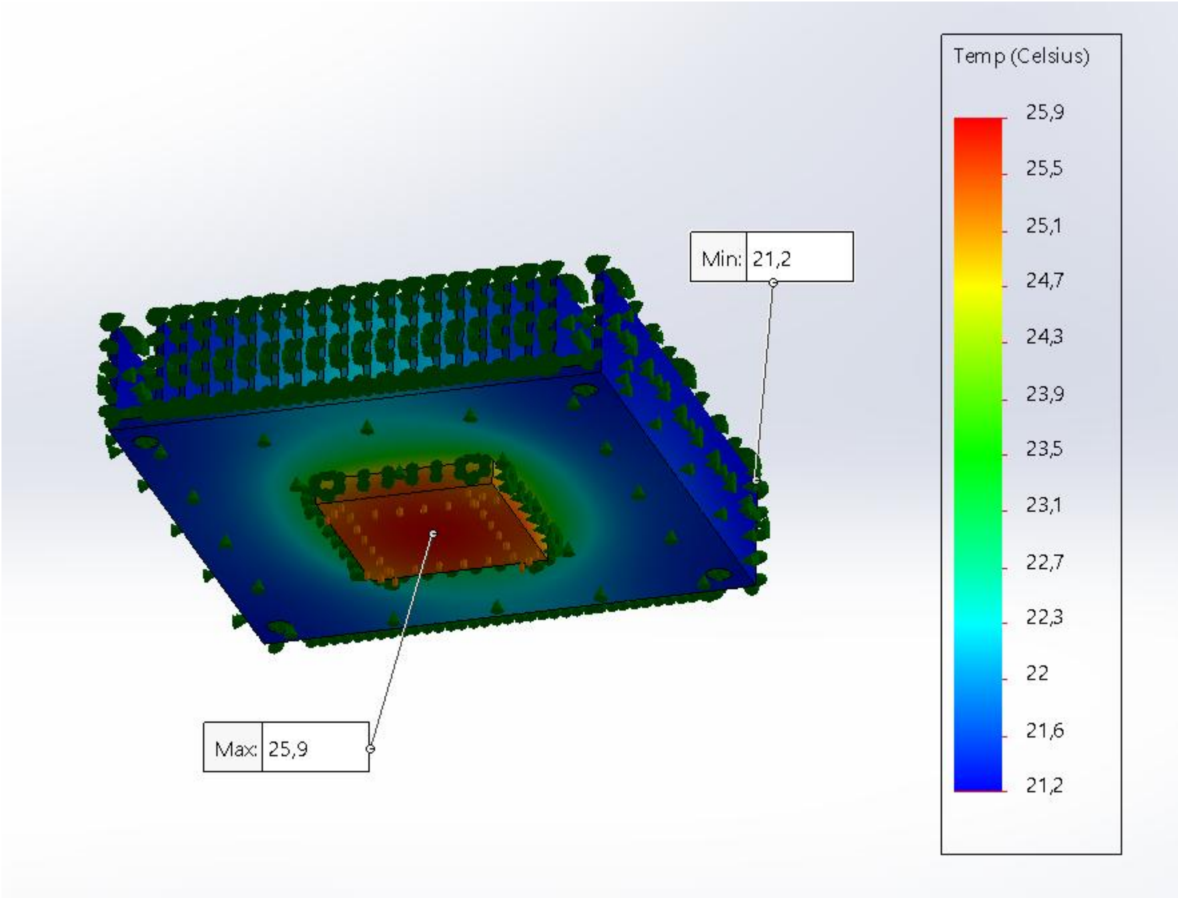
Also, it is also important to note that the material from which the heat sink is made must also be of very high conductivity for effective cooling since the heat from the chip must first be transfered by conduction to the heat sink.

For demonstrating the importance of having a large area for better cooling, we also conducted a thermal analysis by excluding the bottom surface of the heat sink from convection. This leads to slightly higher temperature range which is noticable by the maximum and minimum temperatures and in this case the overal heat transfer will be reduced by that amount of area.



Picture 9 – The effect of reducing exposed area at the bottom of the heat sink on temperature range.

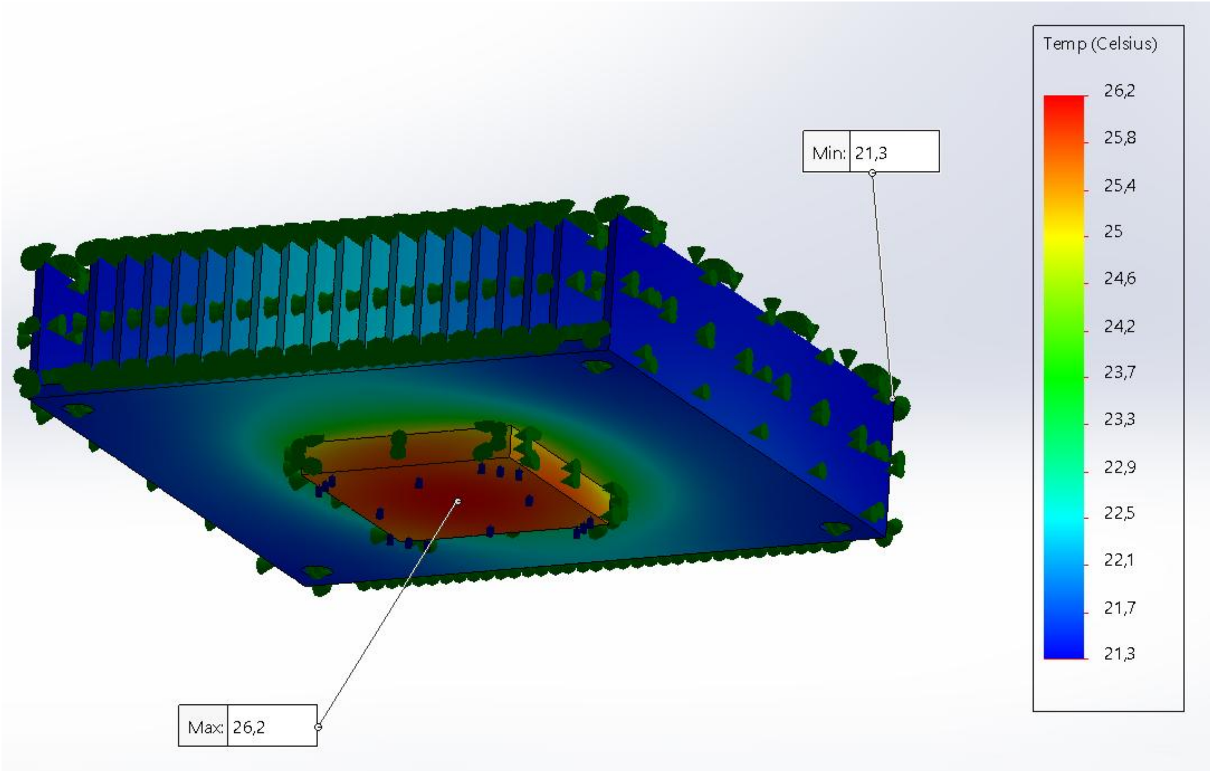
Next we will observe the thermal study with a 22-fin heat sink and see that now the increase in number of fins will additionaly reduce the temeprature of the CPU.



Picture 10 - Cooling of a chip with a 22-fin heat sink.

Now the tempretaure is in the range of 25.9 – 21.2 °C which means significant increase of heat loss. Now we have confirmed that increasing the area also increases the heat transfer rate. This amount may seem insignificant but can mean much better lifetime and overall performance of the central processing unit. Of course, there are often limitations in space within this unit which puts the limit on the maximum number of fins possible to place, and so in that case other parameters such as type of material must be considered for adjustment.

Just as in the previous case we will provide an example of a 22-fin heat sink where its bottom is excluded from convection and see that in this case the cooling will be slightly drawn back.



Picture 11 – Reducing the surface area resulting in a higher temperature range in case of a 22-fin heat sink.

As in the previous case, after reducing the exposed area, the study results in a slightly higher temperature range due to a decrease in heat dissipation rate and less effective cooling.

Temperature Plots

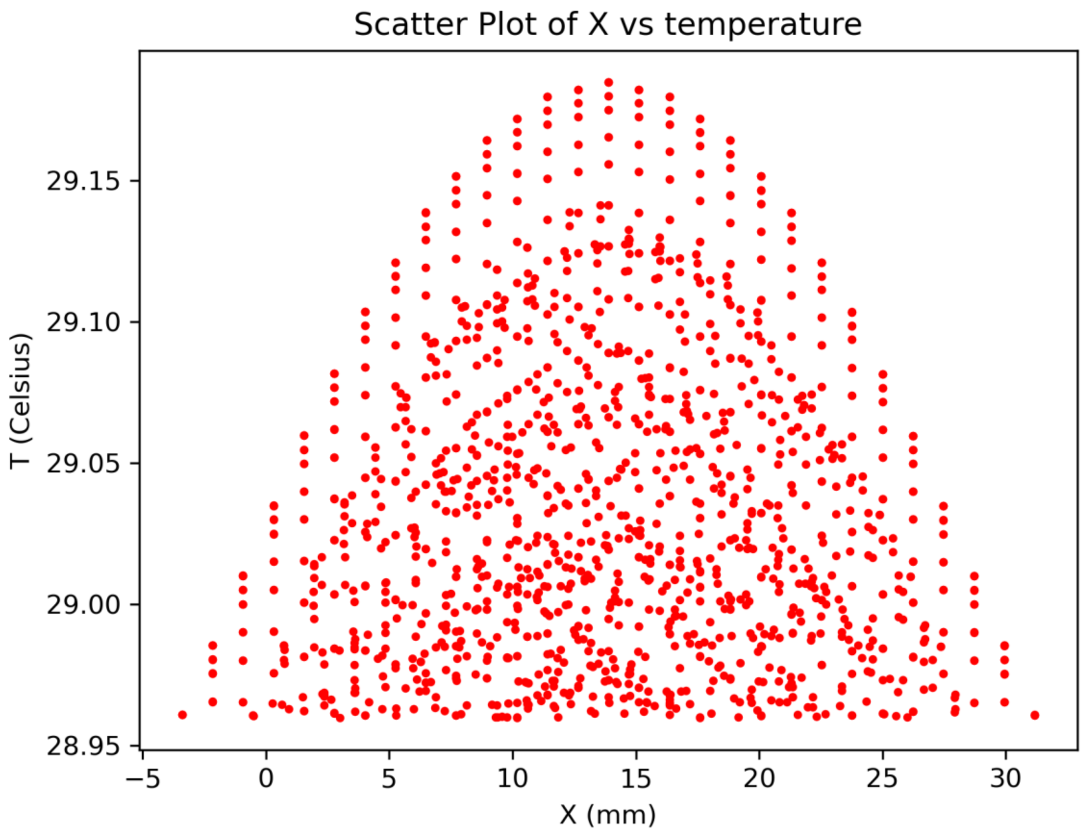


Figure 1 – Temperature distribution across x-axis for the 12-fin heat sink showing thermal symmetry.

As expected, the temperature distribution scatter plot shows the maximum temperature at the center of the entire assembly. This is due to the thermal symmetry as the heat flows equally in all directions. The same can not be said for y axis.

To understand the high temperature values at the beginning of y-axis we need to consider a physical visualisation of CPU and a fan blowing air over it. Picturing a fan rigth behind the model in picture 11, we then take a closer look to the heat transfer due to moving fluid over the CPU approximated as a flat plate.

The incoming fluid has the most potential to remove heat due to thin thermal boundary layer in the areas attacked by the flow. As the air moves further across the same y direction, the boundary layer increases and the efficiency of heat removal becomes smaller and smaller. This results in higher temperatures at the outermost areas of y-axis, as seen from the back of the model.

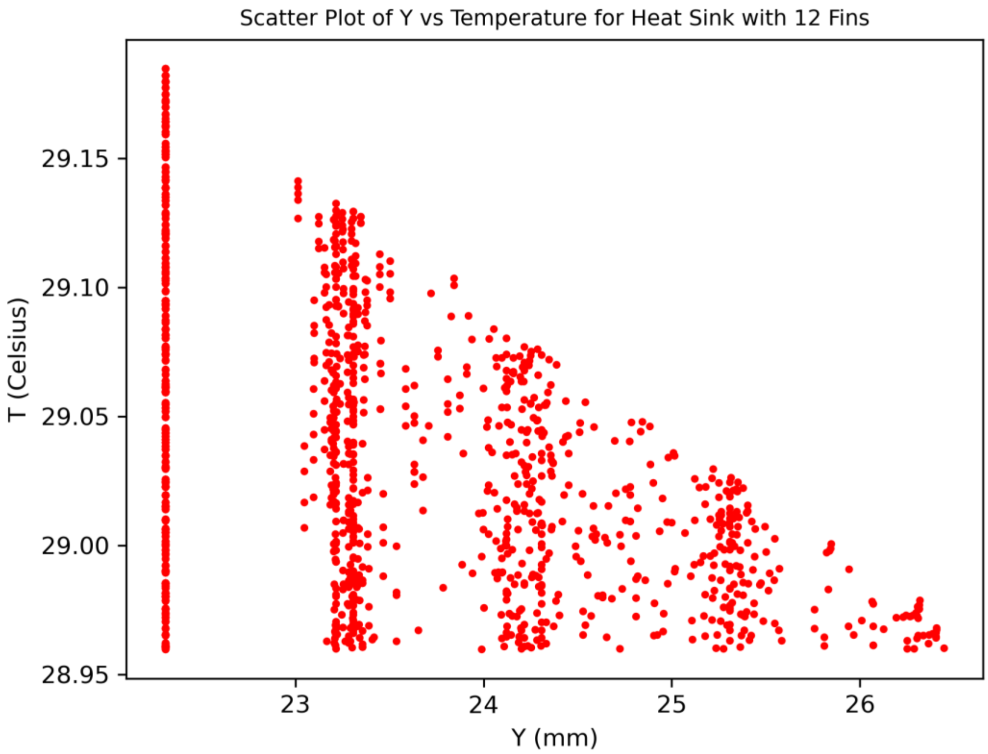


Figure 2 – Temperature distribution across y-axis for the 12-fin heat sink due to thermal boundary layer.

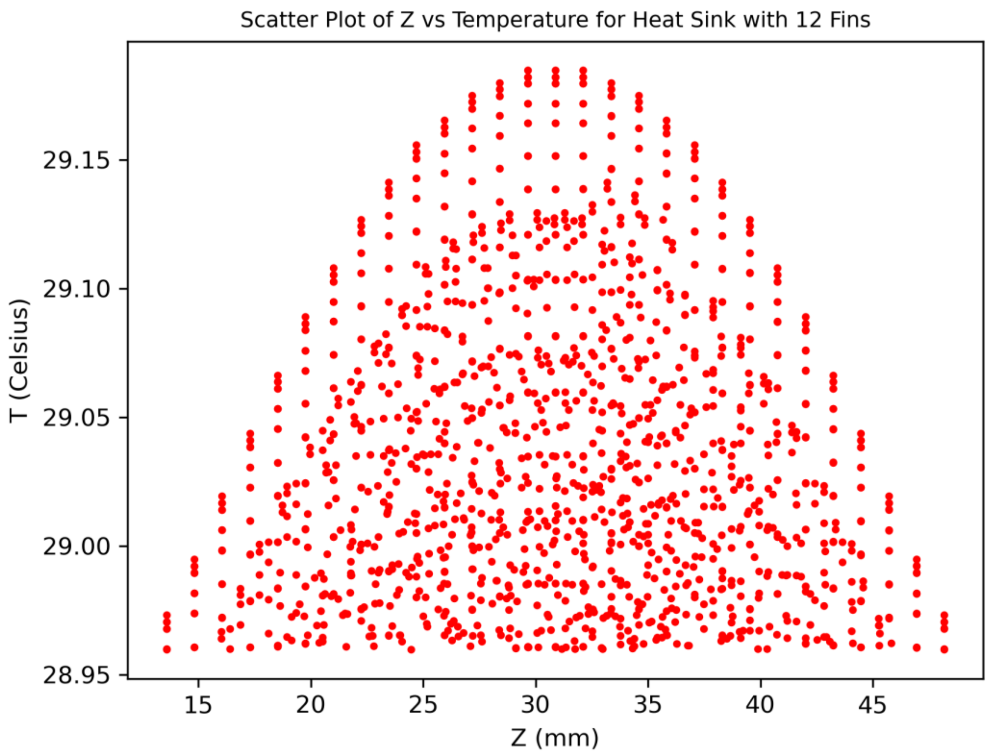


Figure 3 – Temperature distribution across z-axis for the 12-fin heat sink due to uniform heat generation.

As for the temperature distribution in z-direction, the outcome scatter plot shows that the maximum temperature is rigth at the center of the CPU due to uniform heat generation. As we move out of the center of heat generation across the z-axis in both directions, we notice that the temperature on both sides drops symmetrically.

The same analysis is conducted for the heat sink with 22 fins as well.

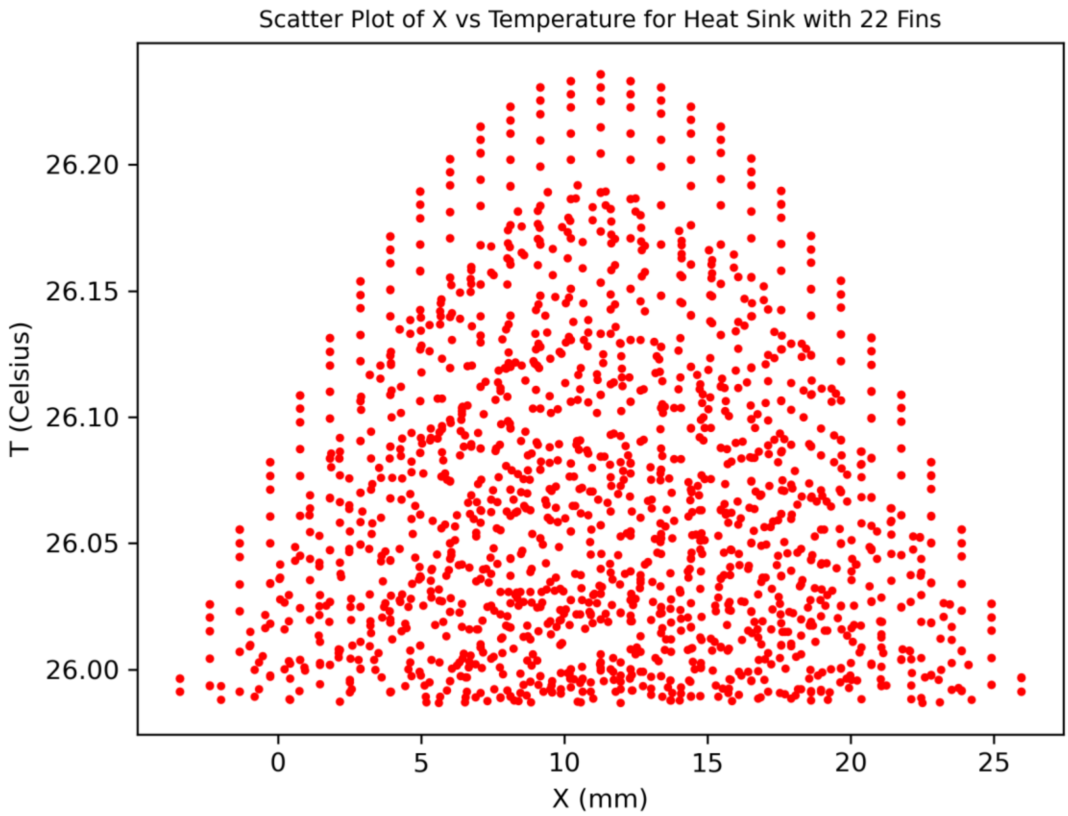


Figure 4 – Temperature distribution across x-axis for the 22-fin heat sink.

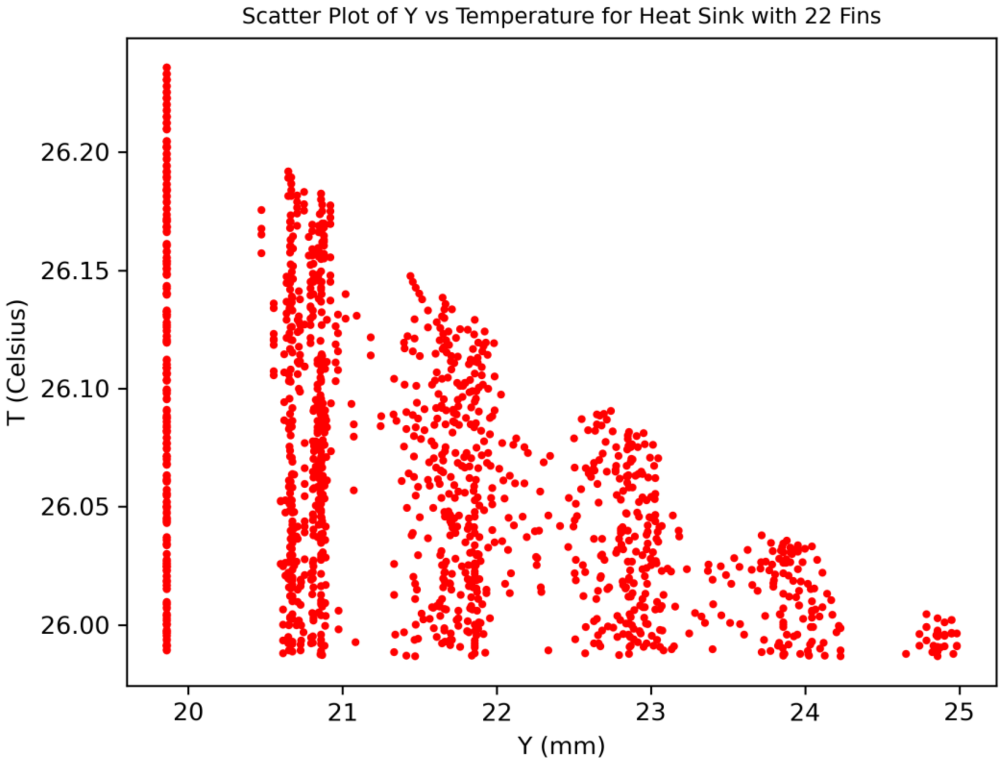


Figure 5 – Temperature distribution across y-axis for the 22-fin heat sink.

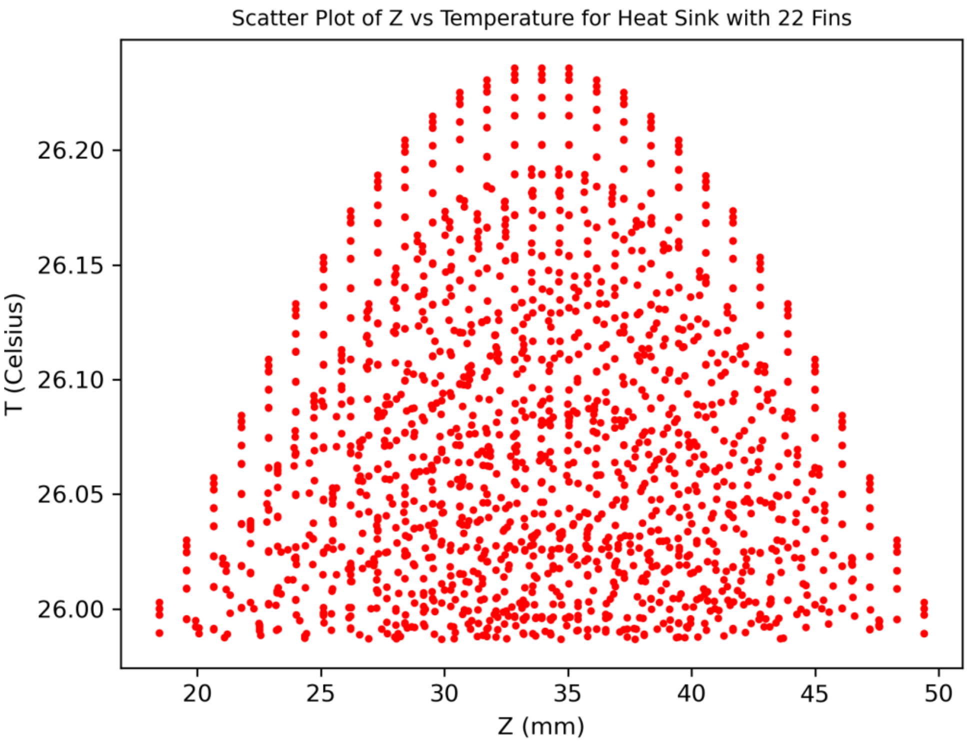


Figure 6 – Temperature distribution across z-axis for the 22-fin heat sink.

5. Conclusion

Heat transfer rate can generally occur in three main forms: conduction, convection and radiation. Cooling of a central processing unit is a heat transfer process where conduction and convection mainly take place and therefore, we must take special measures to ensure that this process will be as effective and as successful as possible.

That is why we must ensure that the heat sink is of proper material which enables maximum possible conduction of heat between the chip and the heat sink.

We saw that heat transfer depends greatly on the flow regime and its thermal boundary layer which dictates the behavior of the temperature distribution across the model.

These effects must not be overseen and explain how the velocity of the incoming flow affects the efficiency of the fluid to remove heat.

Another extremely important parameter which increases the heat dissipation rate is the number of fins on a heat sink which by Newton's law of cooling means an increase in exposed surface area. Also, we saw how slight reductions in the area create a higher temperature range in the assemblies which can mean significant effects on the CPU.

Adjusting critical parameters such as heat sink geometry and type of material accordingly within the available space in the central processing unit, can garantuee an effective cooling process of the CPU which prolongs the overall lifetime and performance of the entire machine.

6. Table of Pictures and References

Heat and Mass Transfer by Yunus A.Cengel and Afshin J.Ghajar, fourth edition.