

End of Bachelor Degree Project

**Grau en Enginyeria en Tecnologies Industrials**

**E-Nanocluster: Thermal design for the heat extraction  
from a computer cluster based on Raspberry Pi 2's  
single board computers.**

**THESIS**

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## Summary

A computer cluster is a group of interconnected computers. They work as a single supercomputer that can run simulations and operations that require big computational calculations. A computer cluster has several applications from climatological predictions and astrological applications to molecular simulations. On the other hand, the Raspberry Pi 2 is a computer with the size of a credit card but with a high performance. At the *Escola Tècnica i Superior d'Enginyeria Industrial de Barcelona* (Spain) was born the idea of building a small computer cluster for small research centres and universities by using a hundred Raspberry Pi 2 boards: The E-Nanocluster.

The E-Nanocluster requires a series of projects that delve into different branches of the engineering science. This particular project is the first one and it focus on the heat extraction and the structure design of the cluster. The structure of this document follows all the steps that bring the cluster from a simple idea to a real solution.

First there is a presentation of the main characteristics of the computer clusters and the Raspberry Pi 2 boards and then is analysed the state of the art of the actual heat extraction systems in computers. Once the best system is chosen, it is provided a basic design for the cluster.

From that design is developed an adaptable thermal and fluidic model made with Microsoft Office Spreadsheet. This model calculates in just a few seconds which is the fan power required for the correct heat extraction. All the parameters such as the air temperature, heat sink characteristics or the power generated can be modified.

With this model it is done a sensibility analysis for optimizing the solution by minimizing the cost and the space of the machine. After that, it has been done a Computational Fluid Dynamic (CFD) simulation to verify the model. The CFD program used has been SolidWorks *Flow Simulation*.

Finally, there is an analysis of the environmental impact, the budget of the project and a plan for the next projects that should be done for bringing the E-Nanocluster to life.

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# 1. Prologue

## 1.1. Project Origin

A computer cluster is a set of connected computers that work together as a single and powerful supercomputer. The performance of a computer cluster is really high and very hard to achieve with a single computer.

These computer clusters are usually located in universities, research centers and R&D business departments. They have lots of applications such as:

- Climatological predictions
- Astrological simulations
- Simulate nuclear explosions
- Test aerodynamic properties
- Molecular dynamics
- Fluid dynamics
- Analyze the blood flow in the heart

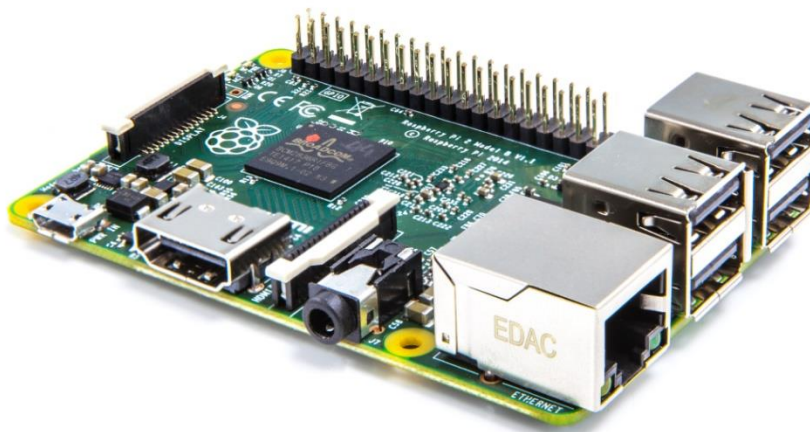
One example is the *MareNostrum* (see Figure 1.1) in Barcelona Supercomputing Center (Spain). It is the most powerful supercomputer in Spain and one of the most powerful of Europe [1].



*Figure 1.1 The MareNostrum computer cluster [2].*

It is located in a 9 x 18 x 5 meters cooling room. It has 6112 processors of 64 bits working at 2,03 GHz. In total it has 48896 cores, 280 TB of hard disk memory, 20 TB of RAM memory and it can make 110 billion of operations per second (1,1 PetaFLOPS). Its use is scheduled by an assignment committee that allocates the computing time depending on the value of the projects to be undertaken.

The origin of this project is not the origin of the computer clusters, is at December 2015: The Raspberry Pi 2 (see Figure 1.2) hit the market [3]. Raspberry Pi is a series of single-board computers developed at the United Kingdom by the Raspberry Pi Foundation. It was made to promote the teaching of computers basics and developing countries. The processor has 4 cores working at 900 MHz (by default), 1GB of RAM and a MicroSDHC slot for inserting an external memory up to 32 GB [4].



*Figure 1.2 The Raspberry Pi 2. The microprocessor is on the top of the board and the RAM*

*at the bottom [5][4].*

At the *Escola Tècnica i Superior d'Enginyeria Industrial de Barcelona* (ETSEIB) was born the idea of taking the advantage of the low cost and the higher performance of the Raspberry Pi 2 for building a cheap but powerful computer cluster made with a hundred of these little computer boards. It was called the E-NanoCluster.

The biggest advantage of the E-NanoCluster is the low price and size, so the medium sized companies and small research departments can afford it without having to pay for using the big ones such as the *MareNostrum*.

## 1.2. Knowledge areas

The total design of the E-NanoCluster involves different areas from the engineering science and it is too big for a unique final degree project. But with this project, the idea of the E-NanoCluster will take off and it will be predicted the path until it will become a reality.

This paper will study one of the most important and critical parts of the E-NanoCluster, the heat extraction. Without the correct thermal design, the cluster can be overheated and become unusable. The analysis will focus on the branches of heat transfer and fluid dynamics.



## **2. Introduction**

### **2.1. Goals**

The first goal is making an alternatives analysis of the actual solutions on the market. Based on this analysis it will be provided a preliminary design for the cluster. Secondly, the main goal is to make a thermal and fluidic model for the proposed solution and improve the first design. This model will be adaptable for future modifications. Thirdly, it will be used CFD software (Computational Fluid Dynamics) in order to validate the calculations and see the most critical points of the cluster.

By then, the objective is to plan the next steps for the E-NanoCluster until it become a reality. This planning will provide also a budget and an environmental analysis.

### **2.2. Viability**

The higher challenge to overcome is the economic and thermal viability. One of the clue points of the cluster as a product is that small research departments and personal costumers can afford the prize. This viability relies on the technology used on the heat extraction system. The biggest cost of the cluster will come from the prize of the hundred Raspberry Pi boards.

On the other hand, the E-NanoCluster will have another clue point: the thermal viability. It consists on implementing the most efficient cooling systems for getting the best performance and the highest reliability. In order to assure this viability, it will be made an intensive analysis considering the Raspberries Pi 2 working at the maximum power and at the worst environmental conditions.

### **2.3. Scope**

This paper aims to give a first design of the E-NanoCluster, providing real components, planes and general characteristics. This design will be a real solution, but after this project it will be required a series of another projects for developing another branches such as the manufacturing process, the network... However, this project will provide the next steps for the following projects to undertake.

### 3. Heat extraction systems in computers

In the world of computer cooling there are some different ways to refrigerate the main heat generators (such as processors, RAM...). This chapter pretends analyze each one of the main cooling systems and choose the best option for the E-NanoCluster.

#### 3.1. Forced convection with air

Nowadays, forced convection with air is the most common way to refrigerate conventional computers. A metallic heat sink is adhered to the main heat generators (see Figure 3.1). In order to get the best performance and a better heat transfer, heat sinks are made with copper or aluminium [6].

A fan is located on the cover of the workstation or just above the heat sink. This fan moves the air inside the workstation. Fans are used for giving motion to the fluid (air).

The heat generated by the processors is transferred through a thermal paste (by conduction), through the metallic heat sink (by conduction) and finally to the cool air (by forced convection).

The amount of power extracted depends on many factors such as:

- Thermal paste conductivity
- Fixation between the heat sink and the heat generator (adhesive, screws...)
- Heat sink material
- Design and number of fins
- Air flow
- Air temperature



*Figure 3.1 Heat sink for convection with air [7].*

This system is used in most of the nowadays commercial computers. Some programs require great use of computational calculation and the heat generators must be cooled with an external system. Just with the natural convection with the air without any type of heat sink is not enough. The main benefits of this system is the low costs and easy implementation. In spite of that, there are two disadvantages:

- This system is closely related to the ambient temperature from the room where the computer is working.
- To extract a big amount of thermal power, the amount of fan power is big too. With the use, the support bushings from the fans get wasted. This phenomenon is related with the noise that makes the fan while it is working. If we use too much fans, the noise from the cluster could be excessive.

### **3.2. Forced convection with liquid**

This system is used in computers that require a quieter operation or improved processor speeds (overclocking) [8]. The operating principle of this system is the same as the forced convection with air. A metallic heat sink is adhered to the heat generator. However, the heat sink has a water or oil closed circuit integrated. At the Figure 3.2 is shown a heat sink for liquid cooling.



*Figure 3.2 Heat sink for liquid cooling [9].*

The water or oil closed circuit is constituted by the heat sink, a pump and a liquid-to-air heat extractor.

The main benefit of this system is that the heat capacity from the water or the oil is much higher than the air heat capacity. This allows the system to extract more thermal power than the forced convection with air.

The main disadvantages of this system are the following:

- The individual cost of a heat sink is higher
- The implementation of this system is more complex
- The cluster is more vulnerable in front of hits
- The risk of a possible leakage is high and it could mean the disablement of the cluster

### **3.3. Immersion in a dielectric liquid**

It is the alternative that extracts more thermal power from any of the other ones. It consists in bringing all the electronic components into a workstation filled with a dielectric liquid [10]. Every surface from the computer is in contact with a liquid and transfers its heat by convection. It is like natural convection but using a dielectric liquid instead of air.



The workstation has a recirculation system in order to filter and refrigerate the dielectric liquid.

The main disadvantages of this systems are the following:

- The weight of the workstation is higher
- The cluster is more vulnerable in front of hits
- The cover must be watertight

### **3.4. Alternatives resolution**

It is decided to use heat sinks for forced convection with air. This system has the less heat extraction power, but has some clue advantages in front of the others:

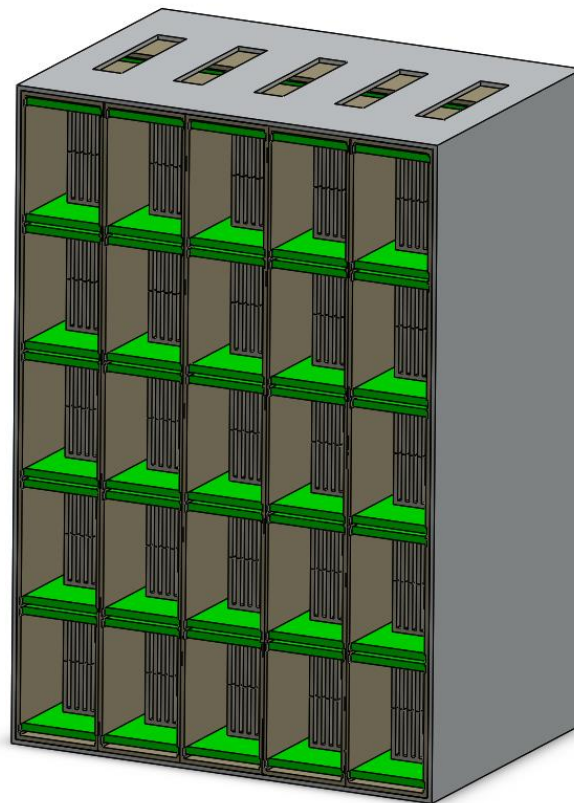
- Is the cheapest system
- The thermal model is simple and predictable
- Easy implementation
- It is easy to remove and change one single board

It is decided firstly to use 100 Raspberry Pi 2 boards and 100 metallic heat sinks. Each board have a heat sink on the microprocessor. The following chapters will show the first designs and the thermal model for the heat extraction.

## 4. Preliminary designs

### 4.1. First design

At the beginning of the project it was decided to use heat sinks only on the microprocessor. At the Figure 4.1 is shown the first design of the E-Nanocluster.



*Figure 4.1 First design of the E-Nanocluster*

The first design has 10 modules with 10 Raspberry Pi 2 boards and one heat sink on each microprocessor. The idea of this design was to insert each board in couples, one up and one down. This would allow an optimized distribution of the space and an easy way to remove and change one board.

In this design the air has two paths, the one between microprocessors and sinks, and the one between the bottom of the boards (where it is located the RAM).

With the first calculations this model became unusable. The heat power generated at the RAM's path was too high for not using any kind of heat sink.

## 4.2. Second design

This problem with the RAM's path became an important change in the heat extraction model. It was decided to flip the boards and insert all them up.



*Figure 4.2 The second design of the E-Nanocluster with the boards flipped.*

This design has 10 modules with 10 Raspberry Pi 2 boards (see Figure 4.2). Each board has 2 heat sinks, one on the microprocessor and one on the RAM. This design makes the structure more symmetric because the air has only one type of path to pass through. This fact simplifies the thermal model.

From now on the following chapters will explain the thermal and fluidic model based on this second design.

## 5. Thermal model

In order to assure the thermal viability of the E-Nanocluster, this model will detail the thermal conditions of each Raspberry Pi 2 board, from the heat generation to the required air speed at the heat transfer zone.

### 5.1. Heat generation

A Raspberry Pi 2 has a maximum consumption of 10W [4]. It will be considered the worst case where the Raspberry is extracting the 10W by heat transfer in order to assure the thermal viability.

It is supposed that the microprocessor will consume 70% of the total power and the RAM the 30%.

### 5.2. Heat Transfer conditions

In order to simplify the model, it will be considered conductive only the bakelite in contact with the heat generators. The rest of the Raspberry will be considered adiabatic, so the heat transfer in each generator will be considered in two paths, the path through the heat sink and the path through the bakelite (see Figure 5.1).

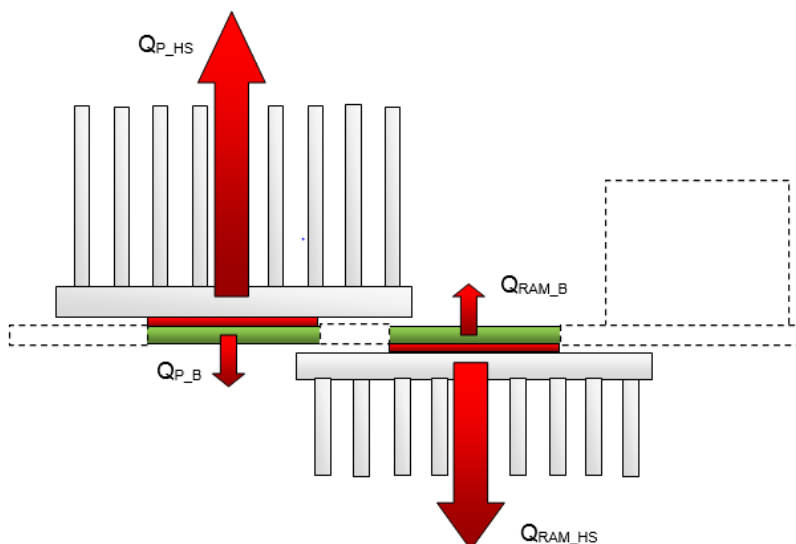


Figure 5.1 Representation of the heat transfer hypothesis at the Raspberry Pi 2 board.

The hypothesis of heat transfer will be the following:

- Steady state
- Microprocessor and RAM are plane generators, conductive and very thin, so it will be considered a uniform temperature in all of their volume.
- The bakelite conductivity will be considered of 0,23 W/(m·K) [11] with a thickness of 1 mm. The heat transfer through the bakelite will be considered unidimensional.
- There will be a thermal paste between the generators and the heat sinks. The thermal resistance will be considered of  $9 \cdot 10^{-6}$  (m<sup>2</sup> ·K)/W [12].
- It will be assumed a uniform convection coefficient in each heat sink. For its calculation will be used the Gnielinski correlation (see Equation 5.15).
- The microprocessor will generate 7 W, with a temperature of 50 °C (maximum admissible temperature) in a surface of 198,81 μm<sup>2</sup> (real surface of the microprocessor).
- The RAM will generate 3 W, with a temperature of 50 °C (maximum admissible temperature) in a surface of 144 μm<sup>2</sup> (real surface of the RAM).
- The air temperature at the heat transfer zone will be considered of 40 °C in order to simulate the worst room conditions.
- The distance between 2 Raspberries will be considered of 10 cm.
- Radiation won't be considered. The main reasons are because the temperature difference between all the components will be low and because the vision factors will be too complex to calculate. The radiation effects will be considered in following projects.

### 5.3. Heat sinks characteristics

There will be considered 2 heat sinks with the same characteristics but the fin length. The fin length for the microprocessor heat sink will be of 30,4 mm, and for the RAM heat sink of 12,4 mm (see Figure 5.2) [13].

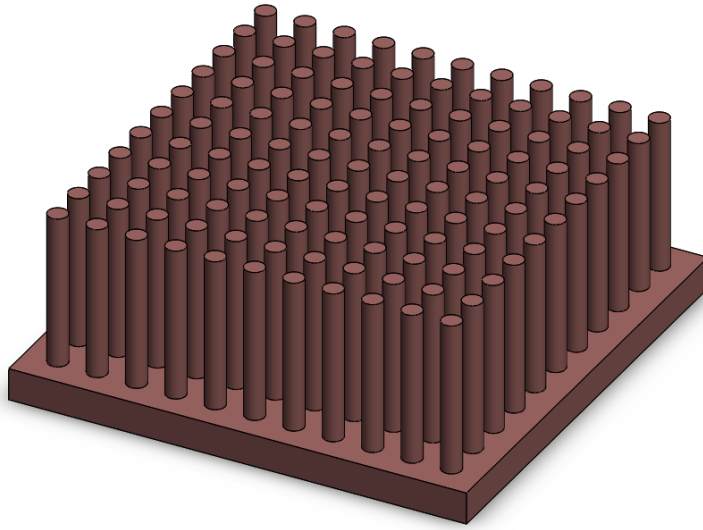


Figure 5.2 RAM heat sink representation.

Both heat sinks are made of copper. Its conductivity will be considered of 385 W/(m·K) [11]. The fins are cylindrical with a diameter of 1,6 mm. Each heat sink has 121 fins.

It will be evaluated the Biot number, which determines whether or not the temperatures inside the fins will vary significantly in space. This number must be less than 0,625 and is determined with the air convection coefficient  $h$  [W/(m<sup>2</sup>·K)], the characteristic fin length  $2d$  [m] (in this case the diameter of the fin) and the fin conductivity  $\lambda$  [W/(m·K)] (see Equation 5.1) (Bonals, 2011) [14].

$$Biot = \frac{h \cdot 2d}{\lambda} \quad (\text{Equation 5.1})$$

For the convection will be considered two surfaces: the primary  $A_p$  and the fin  $A_f$  surfaces. The primary surface will be considered as the surface of the heat sink base, and the fin surface the one composed by the sum of all the fins surfaces. At the convection calculation will be required a value for the fin efficiency (see Equation 5.3). This efficiency will be determined by the fin area  $A$  [m<sup>2</sup>], the fin perimeter  $P$  [m], the fin length  $L_{fin}$  [m], the air convection coefficient  $h$  [W/(m<sup>2</sup>·K)] and the fin conductivity  $\lambda$  [W/(m·K)] (see Equation 5.2). It is introduced a parameter called  $m$  (Bonals, 2011) [14].

$$A = \left( \frac{\pi \cdot (2d)^2}{4} \right) \quad P = \pi \cdot 2d \quad m = \sqrt{\frac{h \cdot P}{\lambda \cdot A}} \quad (\text{Equation 5.2})$$

$$ef = \frac{\tanh\left(m \cdot \left(L_{fin} + \frac{A}{P}\right)\right)}{m \cdot \left(L_{fin} + \frac{A}{P}\right)} \quad (\text{Equation 5.3})$$

The values of the characteristics of each heat sink are represented on the Table 5.1 (using the final air convection coefficient  $h$ , which will be calculated in the next chapter).

*Table 5.1 Heat sinks characteristics.*

<i>Concept</i>	<i>Microprocessor Heat Sink</i>	<i>RAM Heat Sink</i>
$L_{fin}$	30,4 mm	12,4 mm
$2d$	1,6 mm	1,6 mm
$A$	$2,011 \cdot 10^{-6} \text{ m}^2$	$2,011 \cdot 10^{-6} \text{ m}^2$
$P$	0,005 m	0,005 m
$m$	15,705	14,585
$ef$	0,929	0,988
$Biot$	$7,893 \cdot 10^{-5}$	$6,808 \cdot 10^{-5}$
$Af$	$18,733 \cdot 10^{-3} \text{ m}^2$	$7,785 \cdot 10^{-3} \text{ m}^2$
$Ap$	$1,519 \cdot 10^{-3} \text{ m}^2$	$1,519 \cdot 10^{-3} \text{ m}^2$

## 5.4. Thermal model resolution

This chapter will be a step by step resolution of the thermal model calculations. The main goal is to obtain the air speed at the heat transfer zone. All the model was built using Microsoft Office Excel, including tools such as Solver and Macros. All the equations from this chapter have the same source, the book *Transferència de calor* (Bonals, 2011) [14].

### 5.4.1. Air convection coefficient

The first step is to make a heat transfer balance for each heat generator (see Equation 5.4). The thermal power of each generator will be distributed to its heat sink and to the bakelite and finally to the air. The percentage of power that will go for each path will depend on the thermal resistances of each path.

$$Q_{generator} = \frac{T_{generator} - T_{air}}{R_{contact} + R_{hs\_base} + R_{hs\_fins}} + \frac{T_{generator} - T_{air}}{R_{bakelite} + R_{convection}} \quad (Equation 5.4)$$

Where:

- $Q_{generator}$  [W] is the power generated by the heat generator.
- $T_{generator}$  [K] is the temperature of the heat generator.
- $T_{air}$  [K] is the temperature of the air.
- $R_{contact}$  [K/W] is the thermal resistance of the thermal paste. It is calculated by dividing the thermal resistance of the thermal paste  $R_{tc}$  [m<sup>2</sup>·K/W] by the heat generator surface  $A_{generator}$  [m<sup>2</sup>] (see Equation 5.5).

$$R_{contact} = \frac{R_{tc}}{A_{generator}} \quad (Equation 5.5)$$

- $R_{hs\_base}$  [K/W] is the thermal resistance of the base from the heat sink. It relates the height of the heat sink base  $L_{height\_hs\_base}$  [m] with the heat sink conductivity  $\lambda_{hs}$  [W/(m·K)] and the heat sink base surface  $A_{hs\_base}$  [m<sup>2</sup>] (see Equation 5.6).

$$R_{hs\_base} = \frac{L_{height\_hs\_base}}{\lambda_{hs} \cdot A_{hs\_base}} \quad (Equation 5.6)$$

- $R_{hs\_fins}$  [K/W] are the thermal resistances of the group of the heat sink fins and the convection with the air at the heat sink side. It relates the air convection coefficient  $h$  [W/(m<sup>2</sup>·K)] with the primary  $A_p$  and fins  $A_f$  surface [m<sup>2</sup>] and the fins efficiency (see Equation 5.7).

$$R_{aletas} = \frac{1}{h \cdot (A_p + ef \cdot A_f)} \quad (Equation 5.7)$$



- $R_{bakelite}$  [K/W] is the thermal resistance of the bakelite. It relates the bakelite thickness  $L_{bak\_thickness}$  [m] with the bakelite conductivity  $\lambda_{bak}$  [W/(m·K)] and the heat generator surface  $A_{generator}$  [m<sup>2</sup>] (see Equation 5.8).

$$R_{bakelite} = \frac{L_{bak\_thickness}}{\lambda_{bak} \cdot A_{generator}} \quad (Equation 5.8)$$

- $R_{convection}$  [K/W] is the thermal resistance of the convection at the bakelite side. It relates the air convection coefficient  $h$  [W/(m<sup>2</sup>·K)] and the heat generator surface  $A_{generator}$  [m<sup>2</sup>] (see Equation 5.9).

$$R_{convection} = \frac{1}{h \cdot A_{generator}} \quad (Equation 5.9)$$

The unique unknown variable is the air convection coefficient and each balance is solved by iterations. There are two balances, one for the microprocessor and one for the RAM. The heat sinks were chosen for getting the same required convection coefficient at the both heat generators. All the results for the thermal resistances, heat flows and the convection coefficients are on the Table 5.2.

Table 5.2 Thermal resistances of the thermal model.

Concept	Microprocessor	RAM
$R_{contact}$	0,045 K/W	0,063 K/W
$R_{hs\_base}$	0,005 K/W	0,005 K/W
$R_{hs\_fins}$	1,392 K/W	3,312 K/W
$R_{bakelite}$	21,869 K/W	30,193 K/W
$R_{convection}$	132,417 K/W	211,971 K/W
$Q_{X\_HS}$	6,935 W	2,959 W
$Q_{X\_B}$	0,065 W	0,041 W
$h$	37,985 W/(m <sup>2</sup> ·K)	32,761 W/(m <sup>2</sup> ·K)

The obtained coefficient for the microprocessor is of 37,985 W/(m<sup>2</sup>·K) and for the RAM of 32,761 W/(m<sup>2</sup>·K). The chosen coefficient for following the calculations is the one from the microprocessor in order to assure the thermal viability.

The total amount of power transferred through the bakelite side represents only the 1% of the total power generated. It could be considered adiabatic.

#### 5.4.2. Air flow characteristics

The next step is to obtain the air flow characteristics (speed, volume flow...) from the required convection coefficient.

The equations considered for obtaining the air characteristics will be the following (see Equation 5.10).

$$\left\{ \begin{array}{l} cp = 1004 \\ \lambda = \frac{3,807 + 0,074 \cdot T}{1000} \\ \mu = \left( 2,469 + 0,0536 \cdot T + \frac{P}{8,28 \cdot 10^6} \right) \cdot 10^{-6} \\ \nu = \frac{\mu}{\rho} \\ Pr = \frac{\mu \cdot cp}{\lambda} \\ \rho = 3,484 \cdot \frac{P}{1000 \cdot T} \end{array} \right. \quad (\text{Equation 5.10})$$

Where:

- $T$  [K] is the air temperature, considered of 40 °C (313,15 °K).
- $P$  [Pa] is the air pressure, considered of 101325 Pa (environmental).
- $cp$  [J/(Kg·K)] is the specific heat.
- $\lambda$  [W/(m·K)] is the thermal conductivity.
- $\mu$  [Pa·s] is the dynamic viscosity.

- $\nu$  [m<sup>2</sup>/s] is the kinematic viscosity.
- $Pr$  is the Prandtl number.
- $\rho$  [Kg/m<sup>3</sup>] is the density.

The heat transfer section is represented on the Figure 5.3.

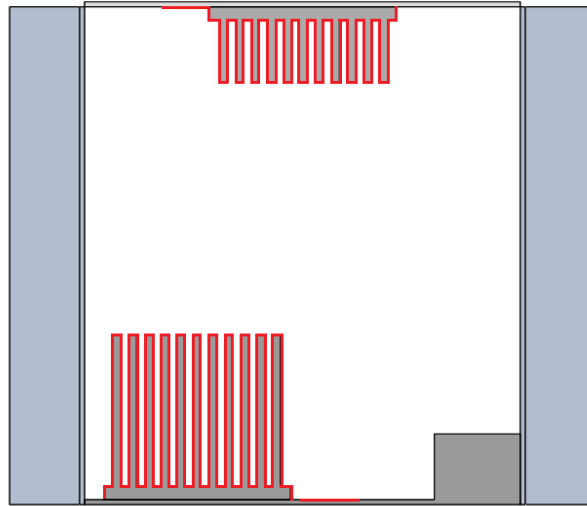


Figure 5.3 Hydraulic and Thermal perimeter at the heat transfer section.

All the lines that surround the section form the hydraulic perimeter  $Ph$ . In concrete, the red ones are the thermal perimeter  $Pt$ . As the thermal and hydraulic perimeters are significantly different, the air convection coefficient must be corrected. It is used the Hausen Duwell equation (see Equation 5.11).

$$h_{corrected} = \frac{h}{1 - \left[ \frac{0,75}{1 + Pr} \cdot \left( 1 - \frac{Pt}{Ph} \right) \right]} \quad (\text{Equation 5.11})$$

The new value for the air convection coefficient is of 41,75 W/(m<sup>2</sup>·K).

The hydraulic diameter  $Dh$  [m] for the section is calculated with the hydraulic perimeter  $Ph$  [m] and the section  $S$  [m<sup>2</sup>] (see Equation 5.12).

$$Dh = \frac{4 \cdot S}{Ph} \quad (\text{Equation 5.12})$$

The next step is to find the Nusselt number objective. It is calculated with the air convection coefficient  $[W/(m^2 \cdot K)]$ , the hydraulic diameter  $[m]$  and the air conductivity  $[W/(m \cdot K)]$  (see Equation 5.13).

$$Nu_{objective} = \frac{h_{corrected} \cdot Dh}{\lambda_{air}} \quad (Equation 5.13)$$

The next goal is to find which Reynolds number for the air provides this Nusselt number. This is step must be solved by iterating with the Reynolds number using the Filolenko and Gnielinski equations.

The Filolenko equation (see Equation 5.14) relates the Reynolds number  $Re$  with the friction coefficient  $Cf$ .

$$Cf = \frac{1}{(1,58 \cdot \ln(Re) - 3,28)^2} \quad (Equation 5.14)$$

The Gnielinski equation (see Equation 5.15) is used only for turbulent fluids ( $Re > 2300$ ) and it relates the Reynolds number  $Re$ , the friction coefficient  $Cf$ , the Prandtl number  $Pr$ , the hydraulic diameter  $Dh$   $[m]$  and the effective length  $L_{hs}$   $[m]$ . The value used for this length is the heat sinks length, which is the same at the microprocessor and at the RAM.

$$Nu = \frac{Cf \cdot (Re - 1000) \cdot Pr \cdot \left[ 1 + \left( \frac{Dh}{L_{hs}} \right)^{\frac{2}{3}} \right]}{2 + 17,96 \cdot Cf^{0,5} \cdot (Pr^{\frac{2}{3}} - 1)} \quad (Equation 5.15)$$

The last step is to find the air speed  $u_{air}$   $[m/s]$  by using the Reynolds number, the air kinematic viscosity  $[m^2/s]$  and the hydraulic diameter  $[m]$  (see Equation 5.16).

$$u_{air} = \frac{Re \cdot \nu_{air}}{Dh} \quad (Equation 5.16)$$

The obtained values for the air characteristics are on the Table 5.3.

Table 5.3 Air characteristics.

Concept	Value
$cp$	1004 J/(Kg·K)
$Pr$	0,717
$\lambda$	0,027 W/(m·K)
$\mu$	$1,927 \cdot 10^{-5}$ Pa·s
$\nu$	$1,709 \cdot 10^{-5}$ m <sup>2</sup> /s
$\rho$	1,127 Kg/m <sup>3</sup>
Hydraulic Perimeter	1,326 m
Thermal Perimeter	1,052 m
Section	$7,546 \cdot 10^{-3}$ m <sup>2</sup>
Hydraulic Diameter	0,023 m
Nusselt	35,221
$Cf$	$9,017 \cdot 10^{-3}$
Reynolds	6254,230
Air Speed	4,697 m/s

## 6. Fluidic model

This chapter will be a step by step resolution of the fluidic model calculations. The main goal is to obtain the pressure drop of each path between Raspberries and for all the cluster. These calculations will be based on the air characteristics results from the previous chapter.

First it will explain the equations considered for the calculations, secondly it will show the geometry of the path and lastly it will show the obtained results.

### 6.1. Pressure drop types

It will be considered four types of pressure drops (White, 2011) [15].

1. Singular pressure drops. They are caused by gratings or foams (see Equation 6.1).

$$H = k \cdot \left( \frac{Q}{A} \right)^2 \cdot \frac{1}{2 \cdot g} \quad (\text{Equation 6.1})$$

Where:

- $H$  [m air column] is the pressure drop in meters of air column.
- $k$  is a constant based on the obstacle.
- $Q$  [m<sup>3</sup>/s] is the air volume flow.
- $A$  [m<sup>2</sup>] is the section surface.
- $g$  [m/s<sup>2</sup>] is the gravity acceleration.

2. Pressure drops for sudden compression (see Equation 6.2). They are caused when the air goes from a section  $A_1$  to a smaller section  $A_2$ .

$$H = \left( \frac{A_2}{A_1} - 1 \right)^2 \cdot \frac{u_2^2}{2 \cdot g} \quad (\text{Equation 6.2})$$

Where:

- $A_1$  [m<sup>2</sup>] and  $A_2$  [m<sup>2</sup>] are the sections surfaces.

- $u_2$  [m/s<sup>2</sup>] is the air speed at the second section.
- 3. Pressure drops for sudden expansion (see Equation 6.3). They are caused when the air goes from a section  $A_1$  to a bigger section  $A_2$ .

$$H = \left(1 - \frac{A_1}{A_2}\right)^2 \cdot \frac{u_1^2}{2 \cdot g} \quad (\text{Equation 6.3})$$

Where:

- $A_1$  [m<sup>2</sup>] and  $A_2$  [m<sup>2</sup>] are the sections surfaces.
- $u_1$  [m/s<sup>2</sup>] is the air speed at the first section.
- 4. Lineal pressure drops (see Equation 6.4). They are caused because of the wall roughness.

$$H = f \cdot \frac{L \cdot u^2}{Dh \cdot 2 \cdot g} \quad (\text{Equation 6.4})$$

Where:

- $f$  is the friction coefficient.
- $u$  [m/s<sup>2</sup>] is the air speed at the section.
- $Dh$  [m] is the hydraulic diameter of the section.
- $L$  [m] is the section length.

For each section from the path will be considered an absolute roughness of 0,2mm. Each section will have different air speed, length and hydraulic diameter, so there will be a different friction coefficient for each section.

The friction coefficient will be determined with the Moody diagram (see Figure 6.1), knowing that the Reynolds number is around 6000.

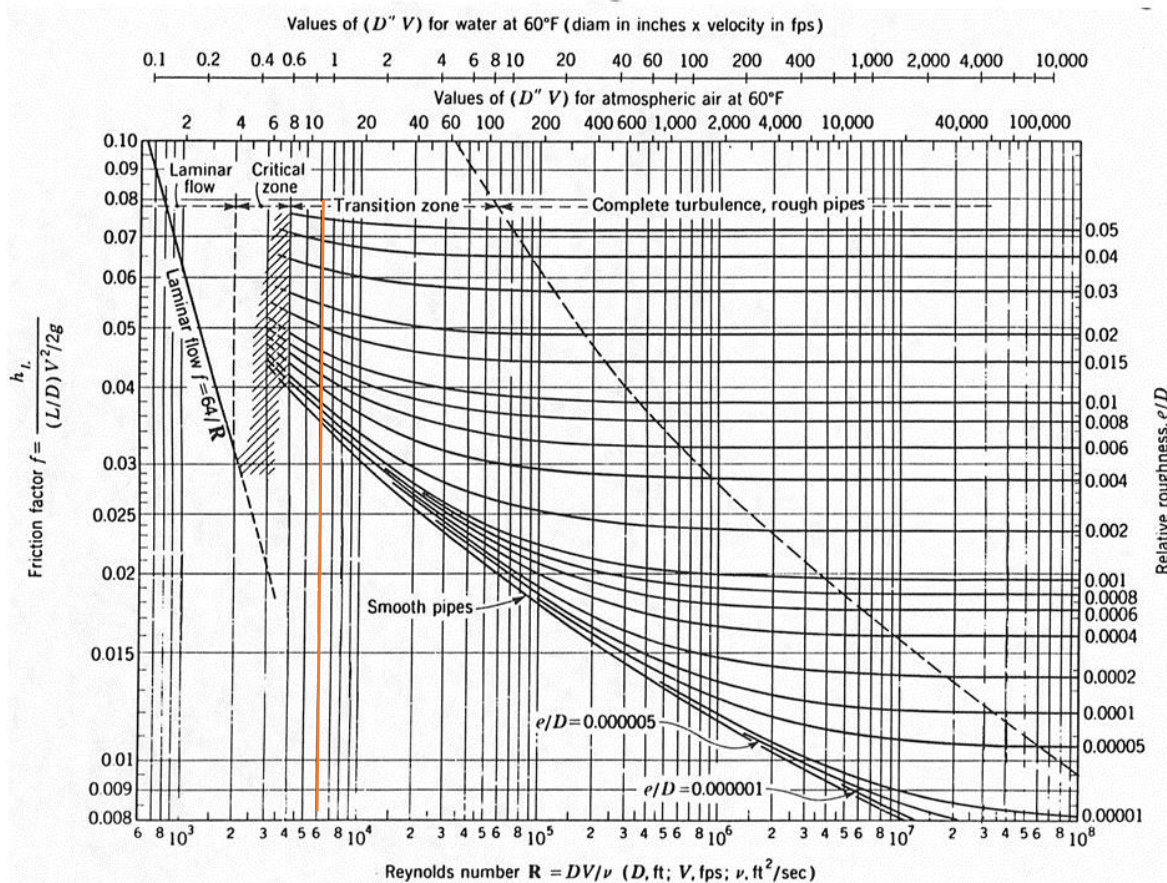


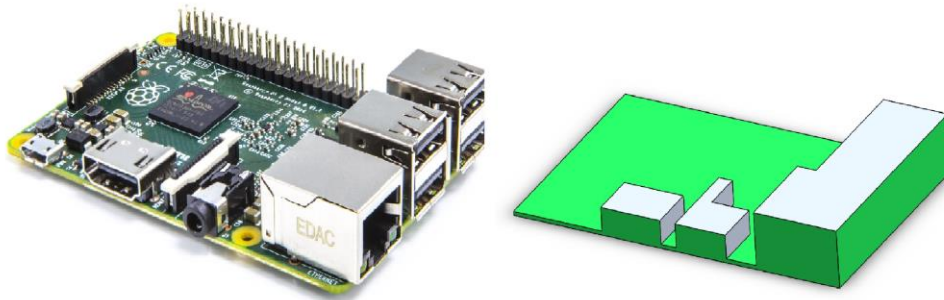
Figure 6.1 Moody Diagram [16].

## 6.2. Geometry considered

### 6.2.1. Raspberry Pi 2 simplification

In order to simplify the calculations, it will be considered the Raspberry geometry represented on the Figure 6.2.



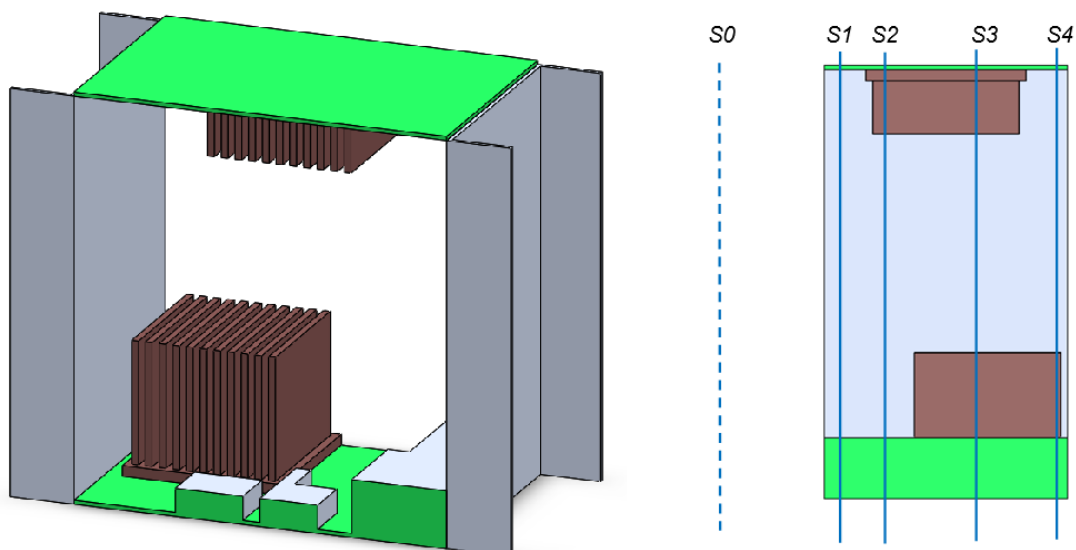


*Figure 6.2 Raspberry Pi 2 simplification.*

The biggest obstacles are represented but the smallest ones are dismissed. The pins at the left and behind the microprocessor should be disengaged. This should be done for fitting well the microprocessor heat sink.

### 6.2.2. Path geometry

In order to simplify the calculations, the heat sinks considered at the pressure drops calculations will be made with rectangular fins instead of needle fins.



*Figure 6.3 Path between two boards and sections.*

The heat sink from the microprocessor and the one from the RAM don't coincide at the same section in all their length because of the Raspberry geometry (see Figure 6.4). This means that there is a short section where is only the heat sink from the Ram and another section where is only the one from the microprocessor. However, the air speed differences between these sections are quite negligible, so the heat transfer results from the previous chapter are still valid. Moreover, this configuration guides better the air flow and decreases the pressure drops.

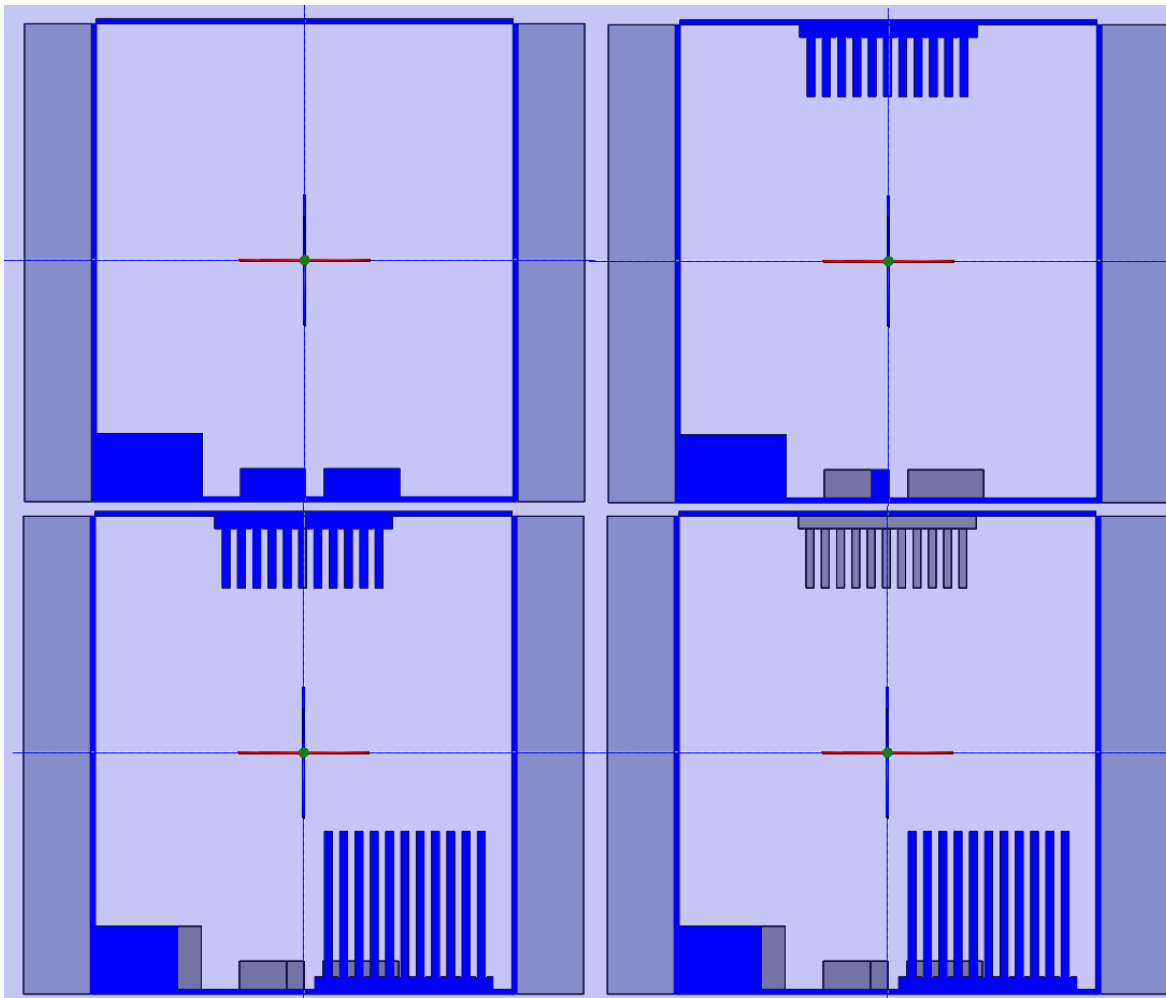


Figure 6.4 Path sections. From left to right and up to down S1, S2, S3 and S4.

At this path is represented the upper side of one board and the bottom of another. The air flow will pass through four different sections: S1, S2, S3 and S4 (see Figure 6.4). S0 is the surface that is in front of all the Raspberry Pi boards. It is the last section before the air passes between the boards, and it will be explained in detail in the next chapter.

Each section has a different surface. The ones that involve a heat sink are corrected. This correction is because the surface between fins has not the same ability to slow the air flow

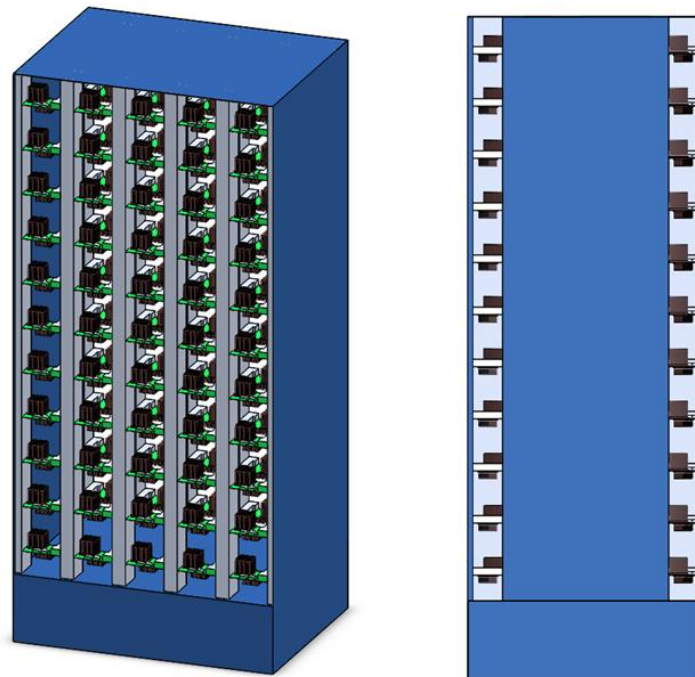
than the rest of the section surface. This correction means to calculate an adjusted hydraulic diameter. This adjusted hydraulic diameter is the average of the one considering the heat sink as a solid block and the one considering the fins of the heat sink. The final values for the surfaces are on the Table 6.1.

*Table 6.1 Surfaces values.*

Concept	Value
Surface S0	1,175 m <sup>2</sup>
Surface S1	8,196·10 <sup>-3</sup> m <sup>2</sup>
Surface S2	7,991·10 <sup>-3</sup> m <sup>2</sup>
Surface S3	7,129·10 <sup>-3</sup> m <sup>2</sup>
Surface S4	7,565·10 <sup>-3</sup> m <sup>2</sup>

### 6.2.3. Cluster case geometry

The proposed geometry for the cluster is the represented at the Figure 6.5.



*Figure 6.5 E-Nanocluster case geometry.*

The space between the blocks of 10 Raspberries is for the cables. It is not represented, but there will be fans at the case and there is a grating and a foam at the two first big sections of the cluster (called S0), in front of the Raspberries. The foam will prevent the cluster from the dust. At the chapter 8.3 the case design will be explained in detail.

### 6.3. Pressure drops results

On the Table 6.2 are the pressure drop results. They are calculated considering an air volume flow of 0,035 m<sup>3</sup>/s going through each path.

Table 6.2 Pressure drop results.

<b>Pressure drop type</b>	<b>Pressure drop value [mm air column]</b>
<b>1 Path pressure drops</b>	
Compression S1-S2	0,627
Compression S2-S3	14,654
Expansion S3-S4	4,176
Lineal S1	5,276
Lineal S2	6,839
Lineal S3	68,745
Lineal S4	10,531
<b>Total</b>	<b>110,850</b>
<b>Cluster</b>	
Singular pressure drops	463,771
Compression S0-S1	87,178
Expansion S4-S0	141,924
Total paths	11 085,032

---

**Total pressure drops****11 777,906**

---

The required power for the air to pass these pressure drops is calculated with the following equation (see Equation 6.5) (White, 2011) [15].

$$P = \rho \cdot V \cdot g \cdot H \quad (\text{Equation 6.5})$$

Where:

- $P$  [W] is the power required.
- $\rho$  [Kg/m<sup>3</sup>] is the air density, which is 1,127 Kg/m<sup>3</sup> at 40°C.
- $V$  [m<sup>3</sup>/s] is the air volume flow, which is 3,544 m<sup>3</sup>/s.
- $H$  [m air column] is the total pressure drops.

The total required power in these conditions is 461,656 W.

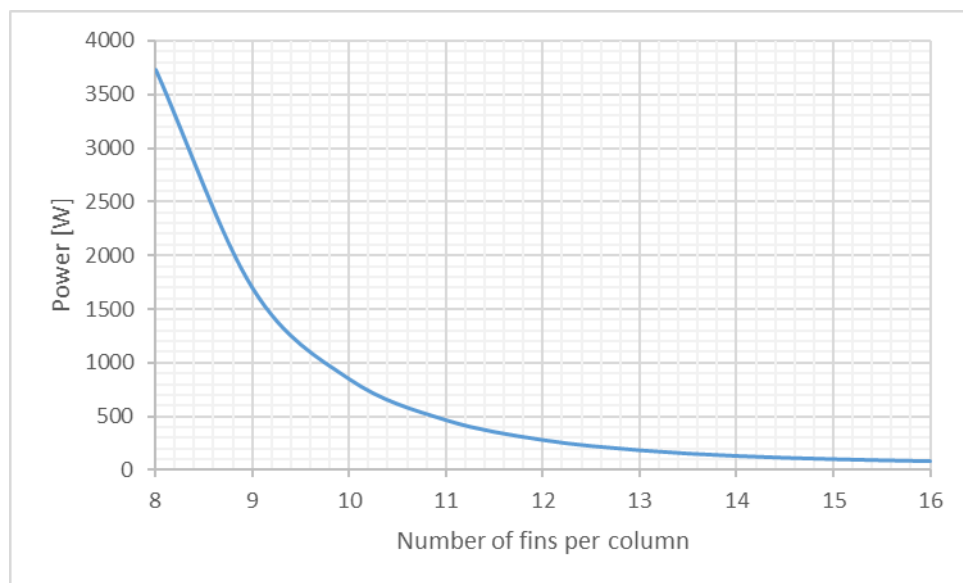
## 7. Sensitivity analysis

This chapter will show a sensitivity analysis considering some design factors. The main goal is to obtain the most relevant ones. These ones are the most related with the final required fan power.

### 7.1. Number of fins

The used heat sink for the RAM and microprocessor has 11 rows of 11 needle fins each one. This design is based on a real heat sink in the market [13]. The objective is to see the relationship between the number of fins and the fan power required (see Figure 7.1).

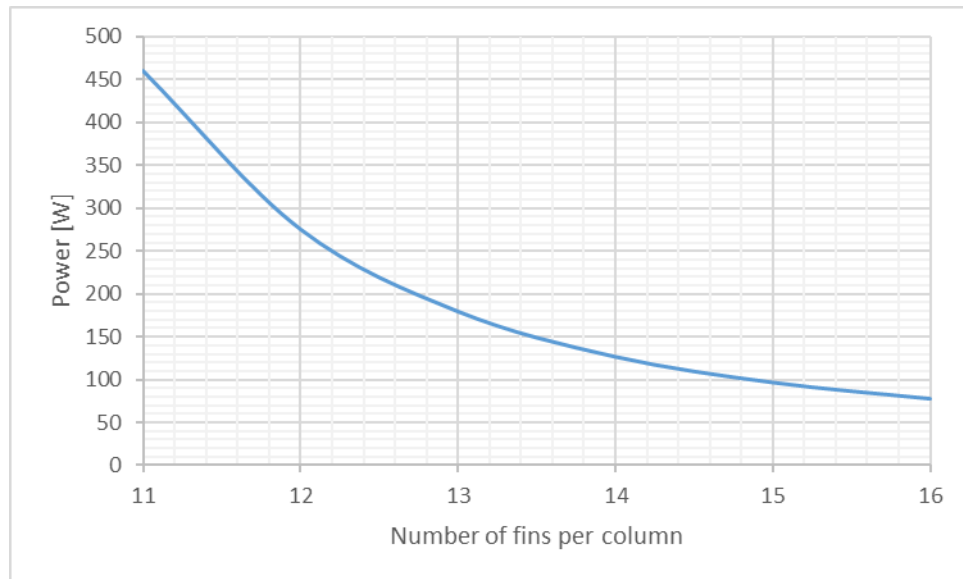
To have more fins means more surface for convection, but more fins means a bigger obstacle and more pressure drops.



*Figure 7.1 Power required vs number of fins per column.*

The analysis has been made by using the same number of fins per column and row. That means that in total it is used a square number of fins.

Using less than 11 fins per column (121 fins) makes the cluster unusable.



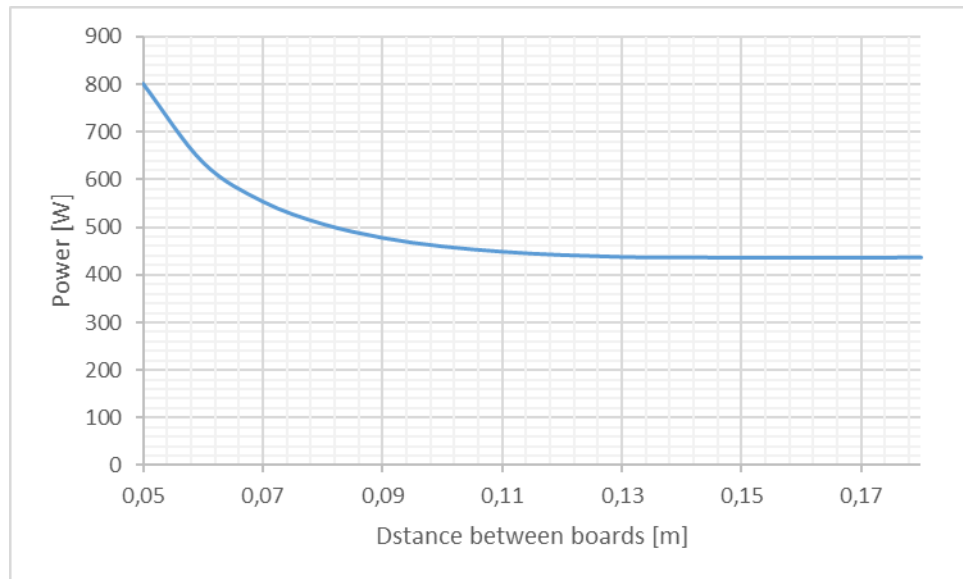
*Figure 7.2 Power required vs number of fins per column aggrandized.*

By using more fins, the required power decreases significantly (see Figure 7.2). However, as more fins are used, the space between fins decreases as well and the air has not the same capability to pass through the heat sink. So use more than 16 fins per column could not be realistic.

The optimal solution would be to use between 14 and 16 fins per column with a higher number of fins per row, and that could mean to buy customized heat sinks. By now, the design will continue using the heat sinks of 11 fins per column and row because they are already on the market.

## 7.2. Distance between boards

The minimum distance between two boards is 5 cm because of the heat sink sizes. As we increase this value, the required air volume flow increases but the pressure drops decrease. And the total volume of the cluster is closely related to this value too.



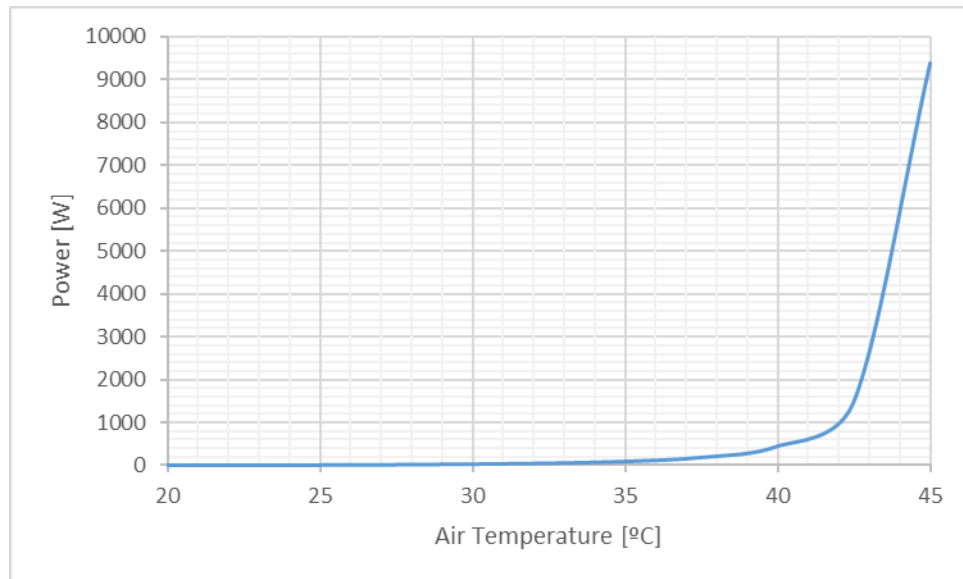
*Figure 7.3 Power required vs distance between boards.*

The Figure 7.3 shows that from 10 cm the required power is steady around 440 W. So the design will continue with a distance of 10 cm between boards in order to minimize the cluster final volume.

### 7.3. Air temperature

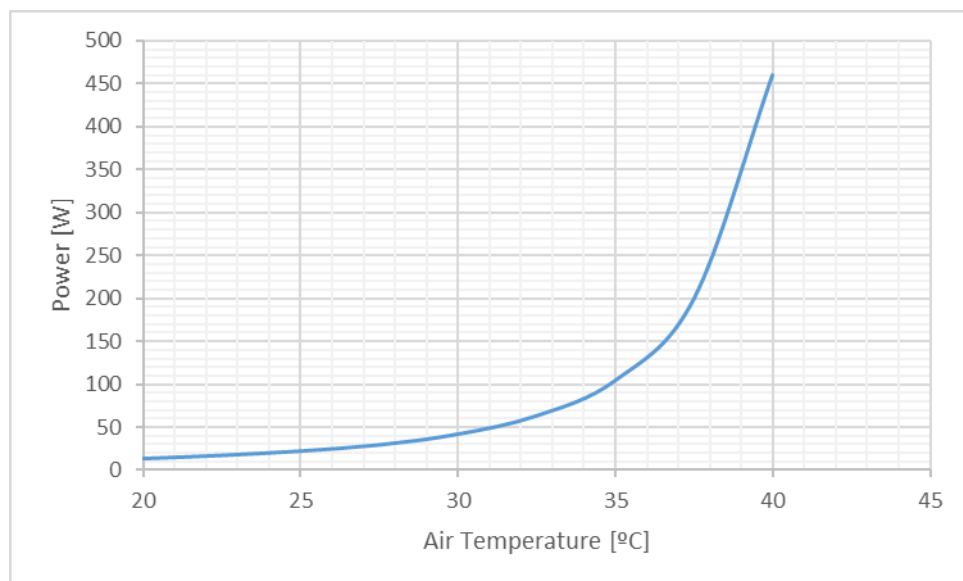
The air temperature is closely related to the heat transfer model. If the air is at an environmental temperature, the required power for extracting the heat would be very low (see Figure 7.4).





*Figure 7.4 Power required vs air temperature.*

This is the main factor of the sensitivity analysis. If the room air is above 40°C, the cluster cannot work. But if it is at less than 35°C, the required power is very low (see Figure 7.5).



*Figure 7.5 Power required vs air temperature aggrandized.*

If the cluster is used in a room where air temperature is regulable (very common in the industry), the power consumption and the price decreases significantly.

From now on, the design for the fans will consider a controlled room with an air temperature of 25°C.

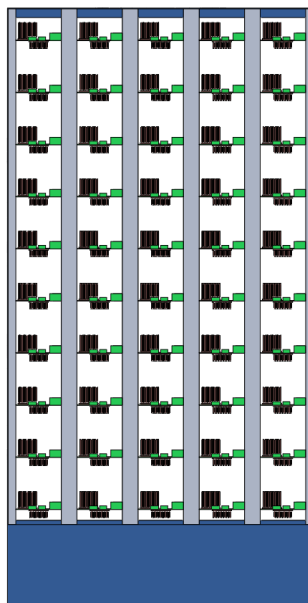
## 8. Final design

This chapter will show a proposed design for the cluster. The main goal is to obtain the case with the best performance for getting the highest reliability. That means that all the Raspberry Pi 2 boards must be cooled homogeneously.

### 8.1. Top and bottom boards

The top and bottom boards have a different path from the rest. It has been included an obstacle at the end of the top and bottom paths in order to have the same pressure drop as the rest of the paths (see Figure 8.1).

The power that requires the air flow to pass through the top and the bottom paths is the same as in one of the rest of the paths.



*Figure 8.1 Top and bottom obstacles.*

### 8.2. Fans

It has been decided to work with 5 fans. The model has been chosen by crossing the working function of the fan [17] and of the system (see Figure 8.2). The common point is the working point.

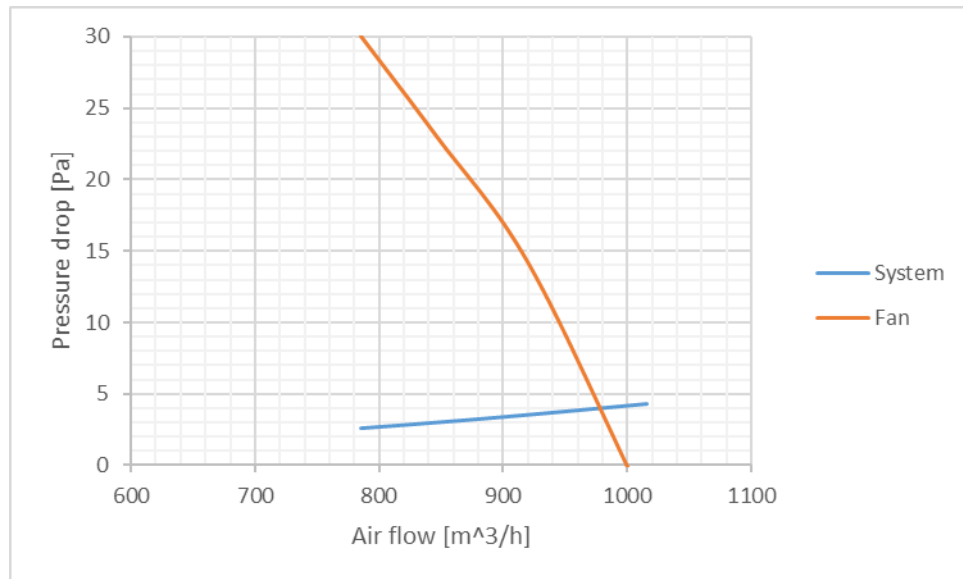


Figure 8.2 Fan vs System working functions

The working point is at 980 m³/h which means a pressure drop of 4 Pa per fan. This working point makes the system steady until an air temperature of 27°C.

The main characteristics are on the Table 8.1.

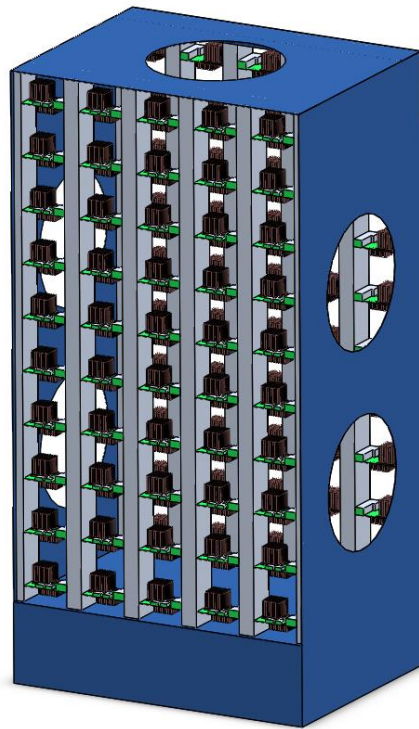
Table 8.1 Fan characteristics [17].

Concept	1 Fan
Diameter	230 mm
Depth	78,5 mm
Bearing type	Ball
Air Flow	970 m³/h
Noise Level	53 dB
Power consumption	34 W

## 8.3. Case designs

### 8.3.1. Original case design

The original design had 10 columns with 10 Raspberries each one. After installing the fans, the E-NanoCluster would look like at the Figure 8.3. The sizes are 588 mm width, 450 mm length and 1143 mm height.



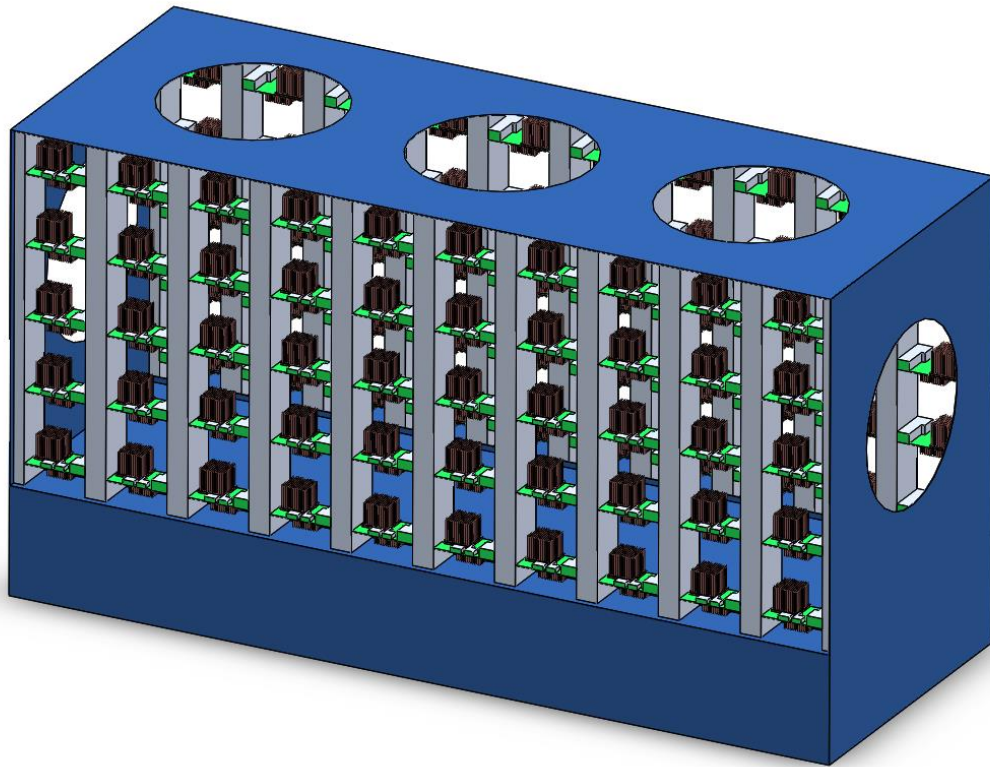
*Figure 8.3 E-Nanocluster first design.*

At the bottom of the cluster there is a box. In this box will be located all the supply system and the connections between boards. There are two fans at each side and one on the top. However, this case has two disadvantages:

- The structure is very vertical. It can be unstable and it has risk of falling down.
- The height difference between the top and the bottom Raspberries is big. These height differences can make the system inhomogeneous.

### 8.3.2. Final case design

It is decided to use 10 columns of 5 Raspberries in each side of the cluster (see Figure 8.4). Then the system is more stable and more homogeneous because the height differences between boards are lower. The sizes are 1174 mm width, 450 mm length and 643 mm height.



*Figure 8.4 E-Nanocluster final design.*

## 9. Computational Fluid Dynamics simulations

This chapter will show some CFD (Computational Fluid Dynamics) simulations in order to verify the model and to predict what would be the real performance and the most critical points of the cluster.

To make these simulations it will be used the *Flow Simulation* software from SolidWorks. First it will be explained the model that this software use and then it will be shown the results from the simulations.

### 9.1. Flow simulation software

There are different CFD programs on the market. At the beginning of the project the decision was between OpenFoam and the *Flow Simulation* pack from SolidWorks. OpenFoam is free and open source but it has two several disadvantages: the difficulty of importing the geometries and creating the mesh [18]. Conversely, the Flow Simulation software was able to import the geometry from the pieces already formed with SolidWorks and to create a refined mesh automatically [19]. This was the reason why the chosen CFD program was *Flow Simulation*.

The equations that the *Flow Simulation* software uses are the ones explained in this chapter. The main equations are the Reynolds equations for incompressible flows. These ones involve the conservation of mass, momentum and energy. It is included a term  $\nu_T$  for including the effects of the turbulence of the flow based on Boussinesq hypothesis. The equation can be represented in differential form for a velocity vector  $\vec{u} = (x, y, z)$  (see Equation 9.1).

$$\begin{cases} \nabla \vec{u} = 0 \\ \frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \nabla) \cdot \vec{u} = -\frac{\nabla P}{\rho} + (\nu + \nu_T) \cdot \Delta \vec{u} + g \end{cases} \quad (\text{Equation 9.1})$$

Where  $P$  [Pa] is the pressure,  $u$  the speed [m/s],  $\rho$  [Kg/m<sup>3</sup>] the density,  $\nu$  and  $\nu_T$  [m<sup>2</sup>/s] are the kinematic viscosity and the turbulent viscosity and  $g$  is the gravity acceleration [m/s<sup>2</sup>].

The turbulent viscosity represents the effect of the turbulences in the flow. The turbulence model used is a  $k$ - $\epsilon$  model (see Equation 9.2) (Launder and Spalding, 1973) [20]. This model calculates the turbulent viscosity with a constant  $C$ , the turbulent kinetic energy  $k$ , which evaluates the energy of the turbulence (see Equation 9.3), and the turbulent

dissipation  $\varepsilon$ , which represents the dissipation of the turbulence (see Equation 9.4).

$$\nu = C \frac{k^2}{\varepsilon} \quad (\text{Equation 9.2})$$

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \vec{u}) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k + P_b - \rho \varepsilon - Y_M + S_k \quad (\text{Equation 9.3})$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \varepsilon \vec{u}) = \nabla \cdot \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (P_k + C_{3\varepsilon} P_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (\text{Equation 9.4})$$

The equations relate the coefficients with the density, the speed vector, the dynamic viscosity, collision diameter and pressures. This model has a low accuracy when appear boundary layer detachments, so it could affect the calculation of pressure drops.

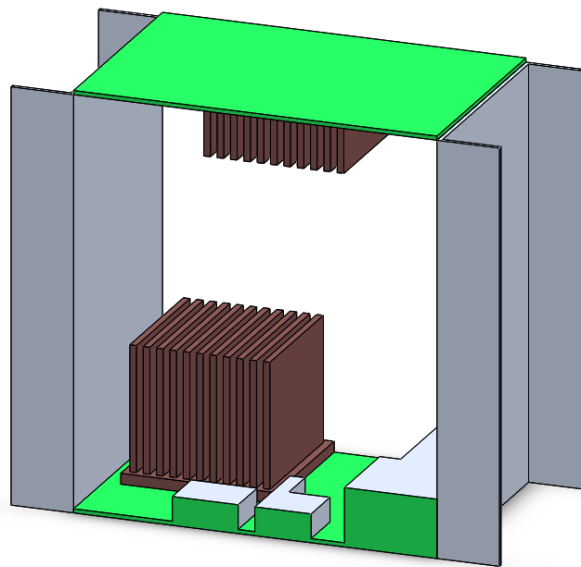
For the heat transfer calculations at the flow, the *Flow Simulation* software solves the energy equation (see Equation 9.5).

$$\frac{\partial}{\partial t}(\rho C_p T) + \nabla \cdot (\rho C_p T \vec{u}) = \nabla \cdot \left[ \left( \alpha + \frac{\mu_t}{\sigma_k} \right) \nabla (C_p T) \right] + \rho \varepsilon \quad (\text{Equation 9.5})$$

Where  $u$  [m/s] is the speed,  $\rho$  [Kg/m<sup>3</sup>] the density,  $C_p$  [J/(Kg·K)] the specific heat,  $T$  [K] the temperature,  $\alpha$  [m<sup>2</sup>/s] the thermal diffusivity,  $\mu$  [Pa·s] the dynamic viscosity and  $\sigma$  [Å] the collision diameter.

## 9.2. Simplified model simulation

This simulation will be a representation of the model conditions analysed in the previous chapters (see Figure 9.1).



*Figure 9.1 Path simulated.*

### 9.2.1. Boundary conditions

The boundary conditions will be the following:

- The Raspberry and the aluminium sides will be considered adiabatic.
- The heat sink base from the microprocessor and from the RAM will generate 7 and 3 W respectively.
- It will enter 0,03544 m<sup>3</sup>/s of air at 40°C and at environmental pressure.
- The analysis will consider heat transfer but it won't consider radiation.
- The external surfaces from the control volume will be considered adiabatic.
- The roughness from the walls will be considered of 200 micrometres.
- The mesh resolution will be of 6/8. The computer used for doing the simulations could not afford highest resolutions.

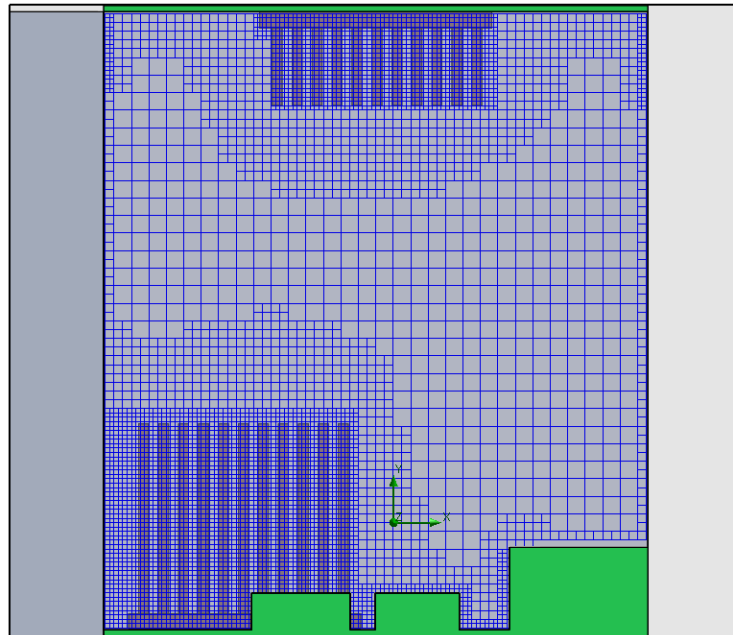
### 9.2.2. Results

- Mesh.

The final mesh is refined around the heat sinks (see Figure 9.2). This gives better resolution in these positions. There are cells inside and between the heat sink fins, so there will be a

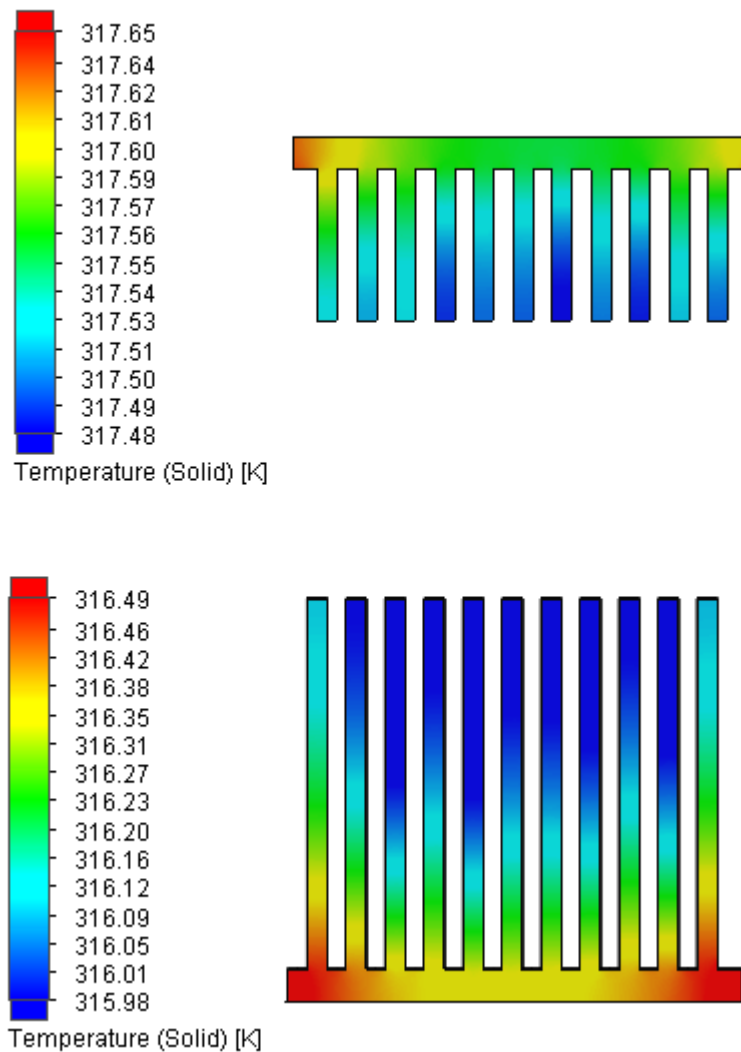


good precision at the calculations around the heat sinks.



*Figure 9.2 The refined mesh.*

- Heat sinks temperature.



*Figure 9.3 Cut plot of the heat sinks temperature.*

The Figure 9.3 shows that the heatsink from the RAM is one degree hotter than the microprocessor heat sink. That does not mean that the power that the RAM is extracting is higher, because they have different surfaces and thermal resistances.

The coolest zone from the heatsink is the top of the central fins (see Figure 9.4 and Figure 9.5). This is because in this zone the air goes faster and has a higher convection coefficient than at the rest of the heat sink.

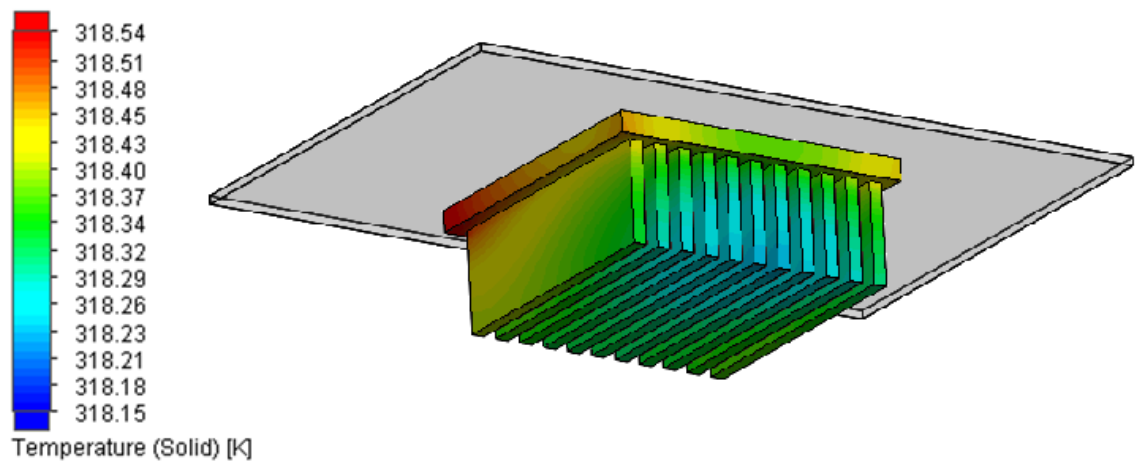


Figure 9.4 Surface plot of the RAM heat sink temperature.

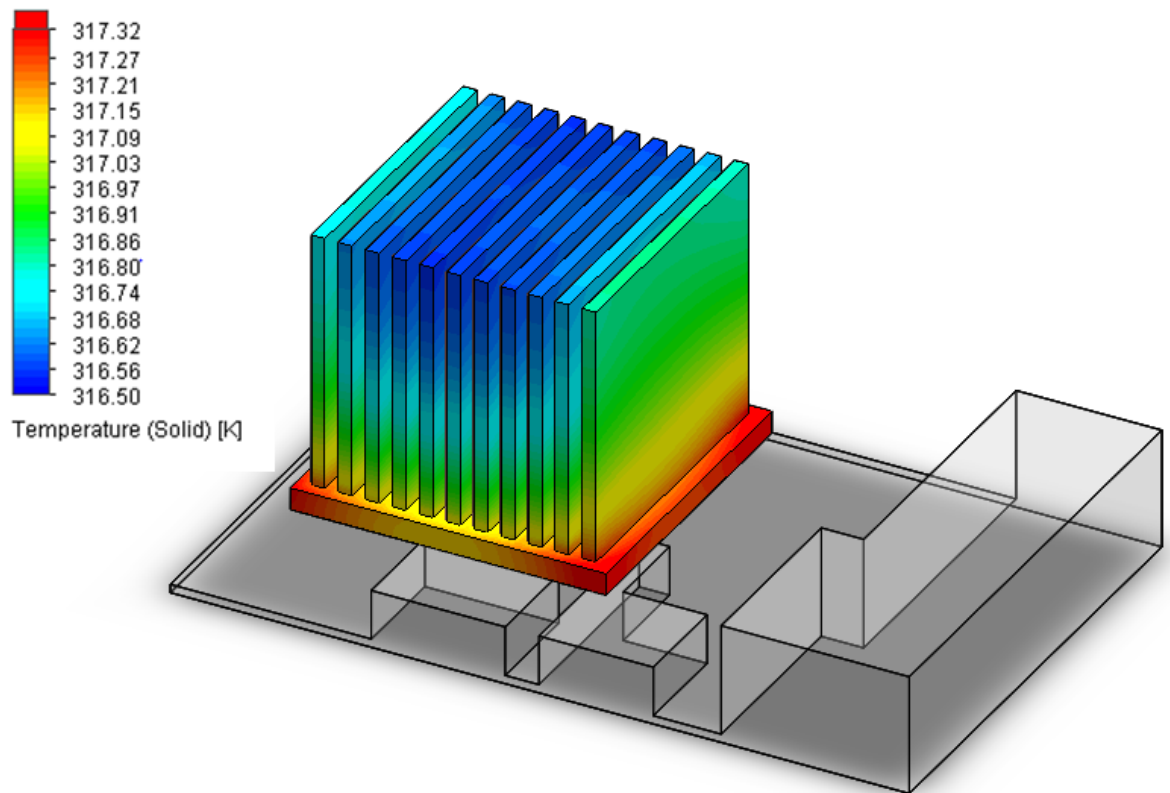
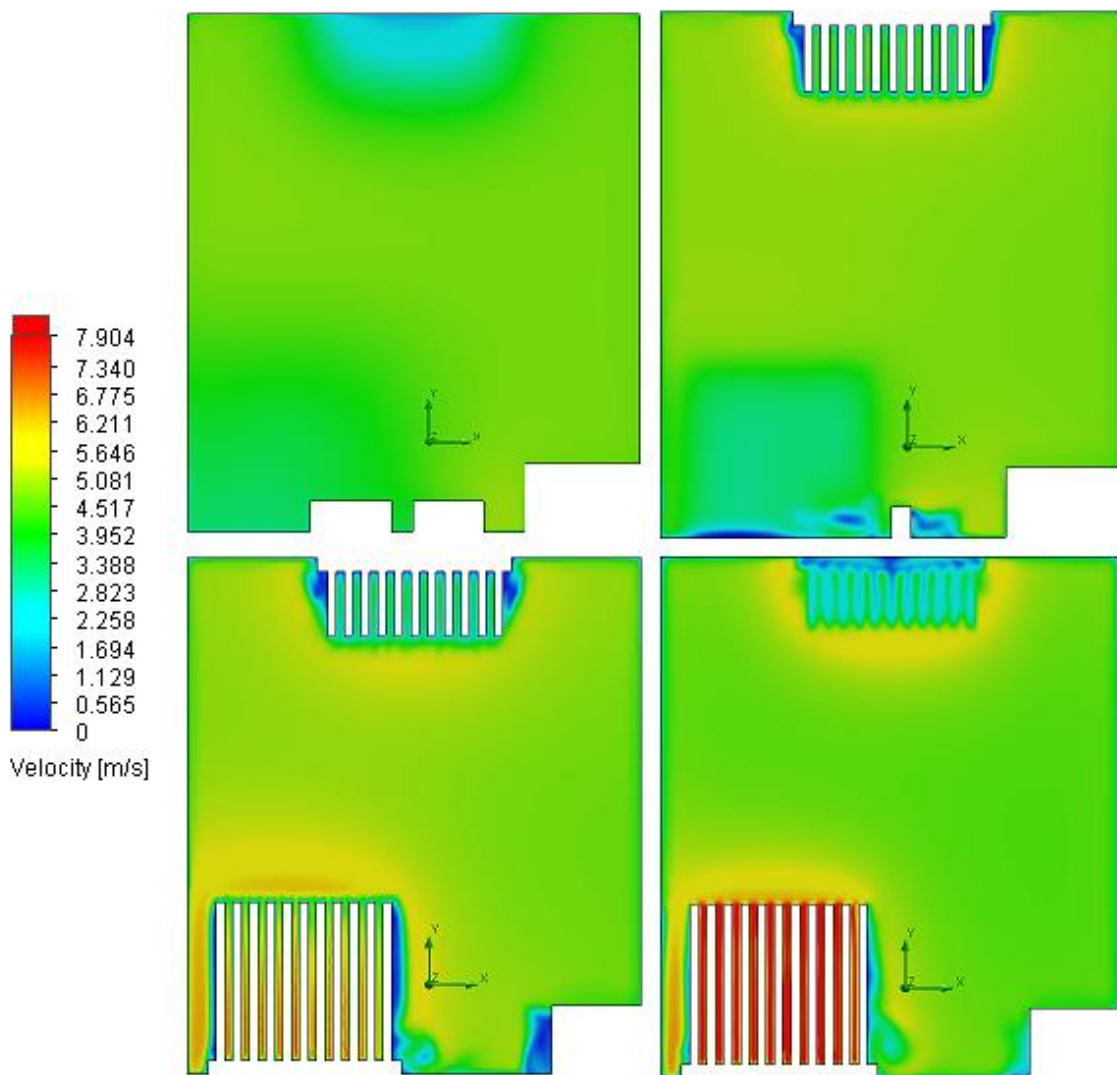


Figure 9.5 Surface plot of the microprocessor heat sink temperature.

- Air speed.

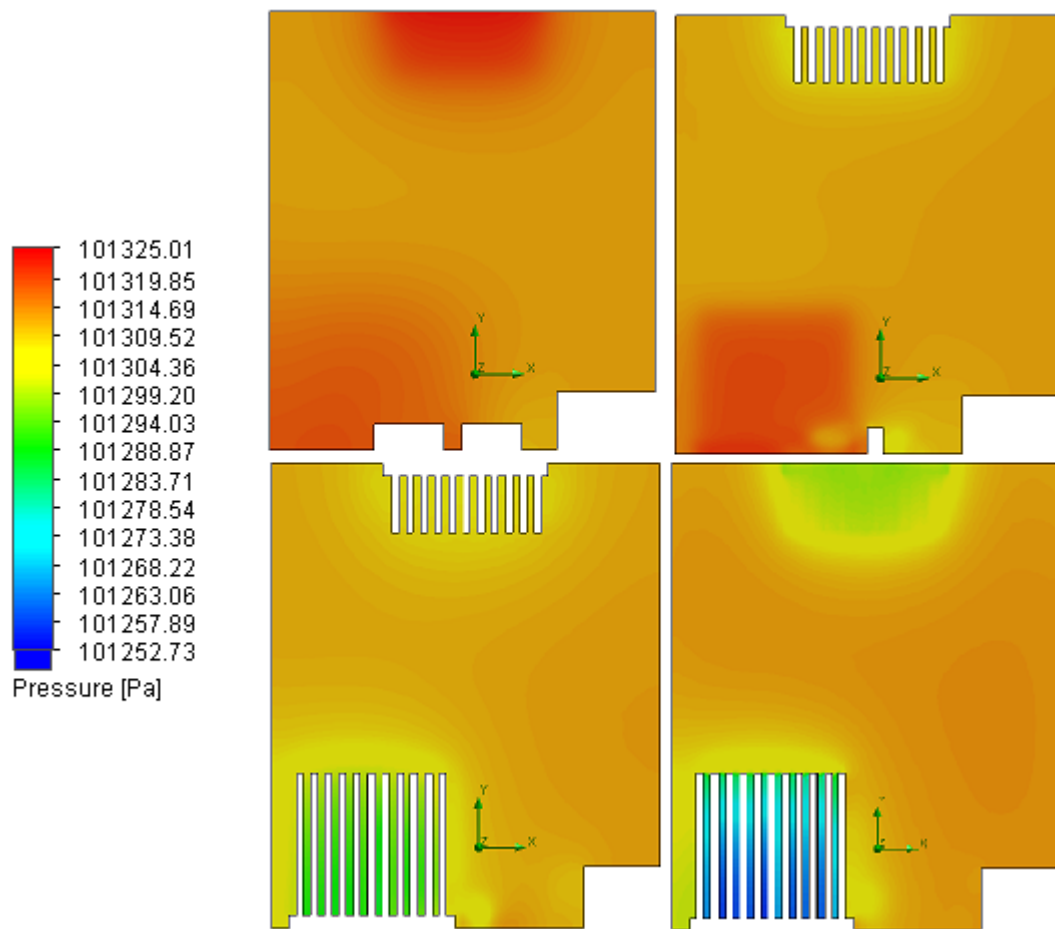
At the Figure 9.6 is represented the air speed at the four different sections of the path.



*Figure 9.6 Air speed at the four main sections of the path.*

The air speed at the main path is around 4,5 m/s. Around the heat sinks appears the boundary layer, where the air speed is reduced until values near to 0 because of the friction. Just after an obstacle appears the boundary layer detachment, where the air speed is suddenly reduced. The fastest zone is between the fins of the microprocessor heat sink.

- Air pressure.



*Figure 9.7 Air pressure at the four main sections of the path.*

The air pressure is always close the environmental pressure but near the heat sinks (see Figure 9.7). The zones where the air pressure is higher are the same where the air speed is lower and vice versa. This is because the air tries to keep its energy at the zones where it has low pressure with high speed and where it has low speed with high pressure. This phenomenon does not happen where the boundary layer is detached.

At the Figure 9.8 appears a longitudinal section between two fins from both heat sinks where is shown this phenomenon.

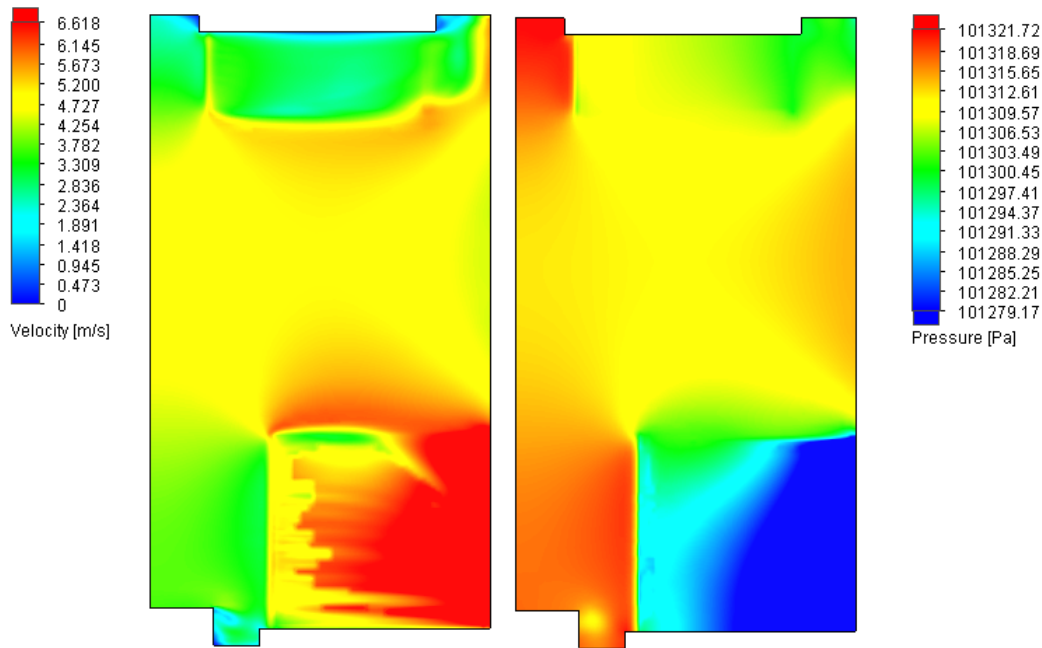


Figure 9.8 Longitudinal cut plot of the air pressure and speed between fins.

Between the fins from the RAM heat sink the model has a lower precision. But it is shown that at the heat sink from the microprocessor the phenomenon between pressure and speed happens.

The simulation pressure drop is calculated by using the data results (see Equation 9.6) (White, 2011) [15] and computing the energy drop.

$$AE = \left( \frac{\bar{u}_1^2}{2 \cdot g} + P_1 \right) - \left( \frac{\bar{u}_2^2}{2 \cdot g} + P_2 \right) \quad (\text{Equation 9.6})$$

Where:

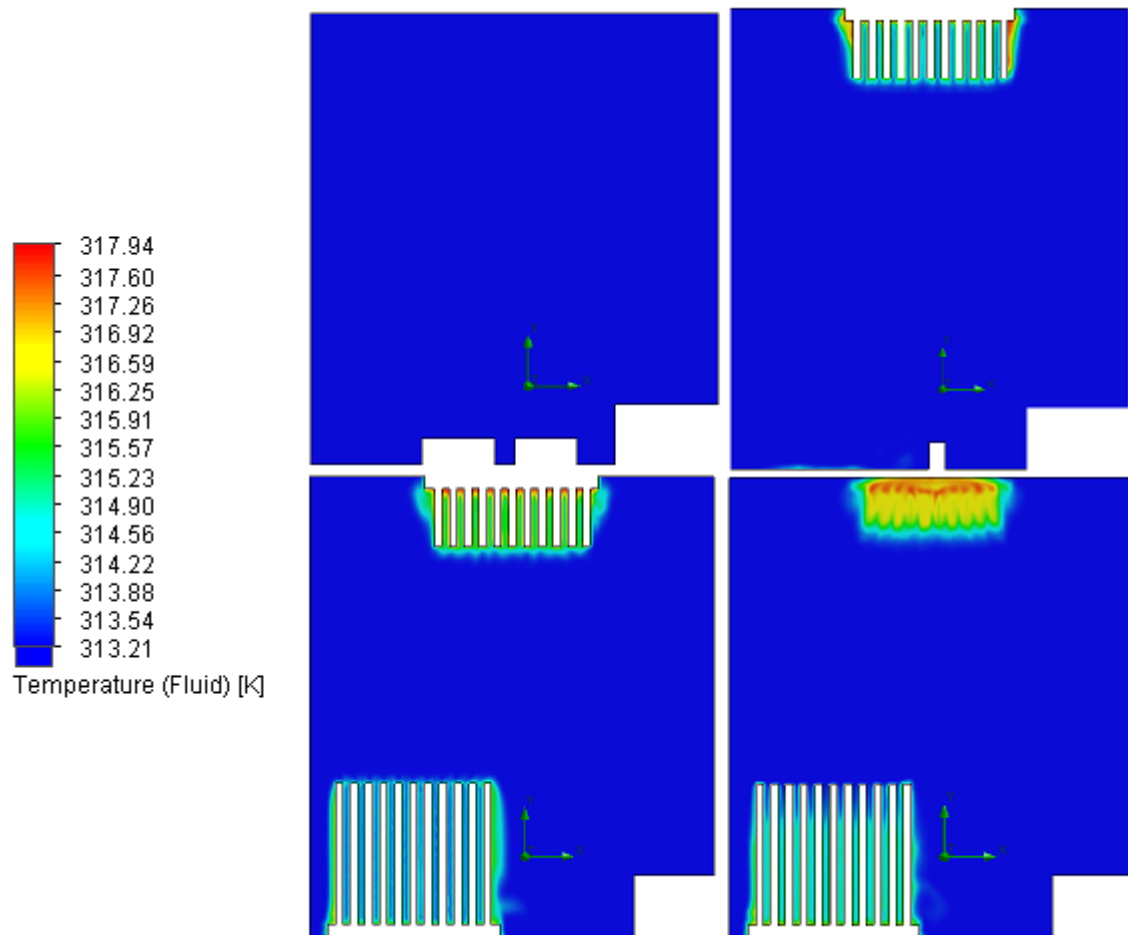
- $AE$  [meters of air column] is the pressure drop.
- $\bar{u}_x$  [m/s] is the average air speed.
- $g$  [m/s<sup>2</sup>] is the gravity acceleration.
- $P_x$  [meters of air column] is the air pressure.

The expected pressure drop is less than the half of the obtained result (see Table 9.1). This could be associated to the low resolution of the mesh and the turbulence model of the software.

*Table 9.1 Pressure drop results.*

Concept	Model	Simulation
Pressure Drop	1,3 Pa	6,46 Pa

### 1. Air temperature



*Figure 9.9 Air temperature at the four main sections of the path.*

The air temperature vary only near the heat sinks (see Figure 9.9). This happens because the rest of the components are considered adiabatic. However, the average heating of the air is exactly the value that was expected in the model (see Table 9.2).

*Table 9.2 Temperature increment results.*

<i>Concept</i>	<i>Model</i>	<i>Simulation</i>
<i>Temp. Increment</i>	0,25 °C	0,25 °C



## 10. Temporal planning

### 10.1. Thermal design project planning

The activities for making this project were initially planned in order to ensure the goals and finish the project successfully in time.

At the Figure 10.1 is shown the Gantt chart. At the middle of the semester the design changed and some activities had to be remade. This redesign meant a delay in the entire project, but it simplified the model and improved the structure of the E-Nanocluster.

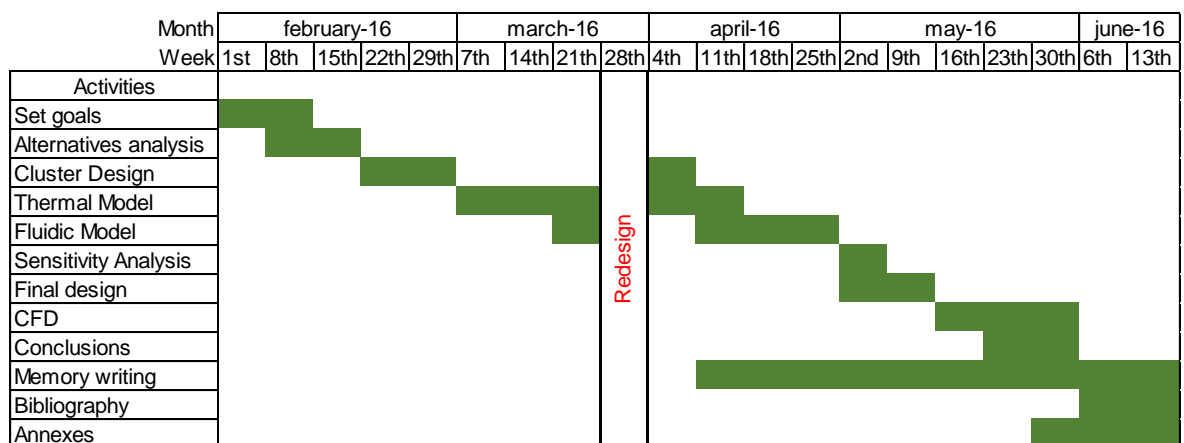


Figure 10.1 Gantt chart.

### 10.2. Next projects

It will be required a series of future end of bachelor degree projects in order to finish the design of the E-Nanocluster. They are structured in 3 phases.

- Phase 0
  - Thermal design.

This is the actual project. It provides an adjustable model and the preliminary design of the E-Nanocluster.

- Raspberry Pi 2 heat generation.

This project should research about the real heat generation of a Raspberry Pi 2 working at its maximum performance.

- Phase 1
- Adjusted thermal design.

This project should unify the first thermal design with the project of the Raspberry Pi 2 heat generation. It should provide the final heat sinks and fans for the cluster.

- Network connection.

This project should develop the network between the Raspberry Pi 2 boards in order to work as a computer cluster. It should provide also the power supply design.

- Phase 2
- Manufacturing process design.

This project should unify the data from the last two projects and develop the final design of the cluster. It should include the manufacturing process and the final budget of the E-Nanocluster.

After this phase, the E-Nanocluster will need just some investors to be finally developed and hit the market.

## 11. Environmental impact

The environmental impact of the project relies on how the E-Nanocluster affects the environment and what will happen with its components after its useful life.

The main effects of the E-Nanocluster are its power consumption, the space that requires, the heat that extracts and the noise that makes. All this effects are the ones related with a regular cluster and they cannot be cancelled, only reduced. The required space is the most reduced effect, because a regular cluster requires a big room but the E-Nanocluster can be installed in a smaller controlled area.

The materials used have also a small environmental impact. The aluminium is a recyclable material [21]. The same happens with the copper from the heat sinks. The electronics such as the Raspberry Pi 2 boards can be disassembled and separated in little components and different materials such plastics or metals that can be re-used [22].

The design of the E-Nanocluster has considered that the Raspberry Pi boards or the fans that fail can be replaced by new ones. The case has an open structure that helps the access to all the boards. That means that if one Raspberry or one fan fails, the entire system doesn't fail, because it can be replaced by a new one. So the useful life of the system is longer than the useful life of a single Raspberry or fan.

## 12. Budget

This chapter aims to give a first number or a magnitude order for the budget of the E-Nanocluster. The total project aims to develop the E-Nanocluster as a product manufactured in series, but it does not include the marketing and management costs (see Table 12.1). The concepts considered on the budget are the following:

- Physical components. They give a magnitude order for a first prototype. It involves:
  - The cost of the Raspberry Pi 2 boards.
  - The cost of the aluminium case.
  - The cost of the copper heat sinks.
  - The cost of the cables network.
  - The cost of the assembling parts such as screws, washers...
  - The cost of the fans
- Manpower. The estimated cost of assembling and building the components.
- Time of engineering. It will be used the total time of all the end of bachelor final degree projects and the average wage of industrial engineers.

Table 12.1 E-Nanocluster budget.

Concept	Units	Prize/Unit (EUR)	Total Prize (EUR)
<i>Raspberry Pi 2</i>	100	40	4000
<i>Aluminum Case</i>	1	100	100
<i>Processor heat sinks</i>	100	15	1500
<i>RAM heat sinks</i>	100	15	1500
<i>Cables network</i>	100	5	500
<i>Assembling parts</i>	1	5	5
<i>Fans</i>	5	50	250
Total prototype			7855
Manpower	10 hours	20 EUR/hour	200
Engineering	1500 hours	10 EUR/hour	15000
<b>Total budget</b>			<b>23055</b>

## Conclusions

This project aimed to launch the idea of the E-Nanocluster: a computer cluster made with a hundred Raspberry Pi 2 boards.

This project focused on the design of the structure and the heat extraction from the cluster.

Firstly, it has been made an alternatives analysis of all the cooling systems used on computers nowadays. It involved heat sinks for convection with air, liquid cooling and immersion in a dielectric liquid. The chosen system has been forced convection with air because it was the cheapest, the simplest and the easier one for doing the calculations. So the case has some fans and there is implemented a heat sink on the main heat generators of the Raspberry Pi 2 boards.

The main hypothesis for the work conditions were:

- The heat transfer is considered unidirectional and at a steady state. Radiation is not considered.
- The body of the Raspberry Pi 2 boards is adiabatic except the volume that is under each heat generator.
- The power generated for each board is 10 W, which is their maximum consumption.
- The main generators are the microprocessor (on the top of the board), and the RAM (at the bottom of the board). They generate the 70 % and the 30 % of all the heat generation respectively.
- The environmental conditions are the worst possible. The air from the room is at 40°C and the boards at a maximum admissible temperature of 50°C.

The first design had the boards in couples. One upside up and the other upside down. There was a heat sink only on the microprocessor from the boards. With the first calculations this design became unusable. It was required a high air flow for cooling the path between the RAMs without any heat sink. The design was modified by setting all the boards upside up and separating 10 cm one from another. This change represented a delay on the temporal planning but it simplified the model and the calculations.

It was made a model using a spreadsheet from Microsoft Office Excel and using tools such as Solver and Macros. The model was based on the second design and it included the thermal and the fluidic part. The actual model is at the Annex 2.

In this model was introduced the work conditions for each generator and the real characteristics of two heat sinks from the market. The thermal part calculates the minimum air convection coefficient for extracting all the power from each heat generator. This value was  $37,985 \text{ W}/(\text{m}^2\cdot\text{K})$ . Then it calculates the air speed for reaching this coefficient, which was of  $4,697 \text{ m/s}$  at the heat transfer zone. The fluidic part from the model calculates the pressure drop of each path between two Raspberry Pi 2 boards and the final power that the air requires for going through all the cluster. The pressure drop for each path is  $1,225 \text{ Pa}$  and the power required is  $461,656 \text{ W}$ .

After that, it was realized a sensitive analysis for optimizing the design. The main conclusion of the analysis was that if the air temperature was at less of  $30^\circ\text{C}$ , the required power was much lower. So it was decided to assume that the temperature of air of the room can be controlled and be always at  $25^\circ\text{C}$ . Then, the required power was only  $22,812 \text{ W}$  instead of  $461,656 \text{ W}$ . The design was finally completed by using five fans from the market. They were chosen by crossing their work function with the system work function. The planes of the pieces used for the final design are at the Annex 1.

Moreover, it has been done a CFD simulation at the path between two Raspberry Pi 2 boards. It was used the SolidWorks Flow simulation software. The boundary conditions represented the model conditions. This simulation provided a temperature map of each heat sink and the air characteristics (such as speed, temperature and pressure) at the main sections of the path. The simulation was also used for verifying the calculations of the model. The increase of the air temperature was exactly the same as the expected, but the pressure drop was of  $8 \text{ Pa}$  instead of  $1,2 \text{ Pa}$ . The reason could be that the mesh was not refined enough and that the turbulence model from this software was not the most appropriate for this geometry conditions.

This document also included a Gantt chart with the temporal planning of the project and a chapter that explains which ones should be the following projects for ending the total design of the E-Nanocluster.

Finally, it has been provided an environmental impact analysis of the cluster and a budget for the whole project, considering all the projects that should be done in the future and the estimated cost of one prototype.

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