**Computational Thermo-Fluid Dynamics**
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# Forced Convection in Cooling Systems for Electronic Components

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**Abstract**
Cooling Systems play an important role in the development of electronic devices, by preventing the device itself from reaching high temperatures and generating so-called *hotspots*. Such systems mostly rely on forced convection - either via liquid or gaseous mean - to enhance the heat transfer, thus decreasing the temperature of the electronic components. To investigate such phenomena, the model of a multiphase domain consisting of a solid section and a fluid section is adopted - that is to say, the board where an electronic component is placed and the surrounding air. In particular, the effects of convection on the temperature distribution are evaluated with respect to a single electronic component placed within the board, which is modeled as a source at constant temperature. Together with this approach, the modeling of different velocity gradients is also considered. A real practical case for a LED is finally shown, in order to represent an application closer to reality both on the board and in the surrounding system.

**Keywords**
Forced Convection — Electronic Components — Multiphase Domain

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## 1. Introduction

One of the main issues when working with electronic devices is temperature. Temperature highly influences the materials' life span: depending on their function, electronic components are subjected to certain limits in terms of temperature range, in order to guarantee an adequate lifetime. Cooling Systems are what prevents an electronic device from reaching temperatures that would severely damage and impair its functioning. Typical examples of cooling units include Radiators, Thermally driven interfacial-radiators and Forced Convective Liquid cooling types [1]. These systems can be modelled from a thermodynamic point of view according to the basic heat transfer equations [2]. In order to accurately investigate the model it is first of all necessary to introduce the basic heat transfer mechanisms:

**Conduction** Modeled thanks to Fourier's Law and in particular to the *Heat Diffusion Equation* under the assumptions of incompressible medium and absence of convection:

$$\nabla \cdot k \nabla T + \dot{q} = \rho c \frac{\partial T}{\partial t} \tag{1}$$

**Convection** Occurring when a flow prevents heat from accumulating on a body's surface, thus highly dependent on the flow's parameters, it is modeled thanks to the introduction of the *Heat Transfer Coefficient*.

**Radiation** Process due to electromagnetic radiation, whose intensity highly depends on a body's temperature and surface.

The purpose of the present work is to present a tool to study the effects of a convective air flow on such devices, allowing to change the configuration and the characteristics of the flow in order to better represent this phenomenon.
Changing the flow's gradient can also have many other applications in other non-electronic fields, such as boundary layer heat energy transfer. Considering the board as a tiny section of an aerodynamic airfoil, the heat boundary layer could be noticed. For this reason, and although its final influence on electronics is not big, it has been considered of great interest to analyse the gradients' performance. Nevertheless, not in-depth investigation has been done, as it would be a completely different topic.

## 2. Physical Analysis

The most important phenomena to be considered in this work are Conduction in the board and Forced Convection in the fluid. Conduction is generated through the heat spread by the electronic component or source, while Forced Convection is imposed by the speed at which air is moving in the surroundings of the board.
Concerning the thermal behavior of the electronic devices, it is important to analyse the parameters that can influence it. The ones considered in the analysis are:

- Air Speed in Forced Convection
- Gradient of Velocity
- Distribution of the Sources

## 2.1 Physical Representation

A physical representation of the considered model is shown in Figure 1, from [1] In particular, the focus of the present work is on the surface where the device spreads localized heat flux. From a physical point of view, the reference device taken into account is the PCB - Printable Circuit Board.

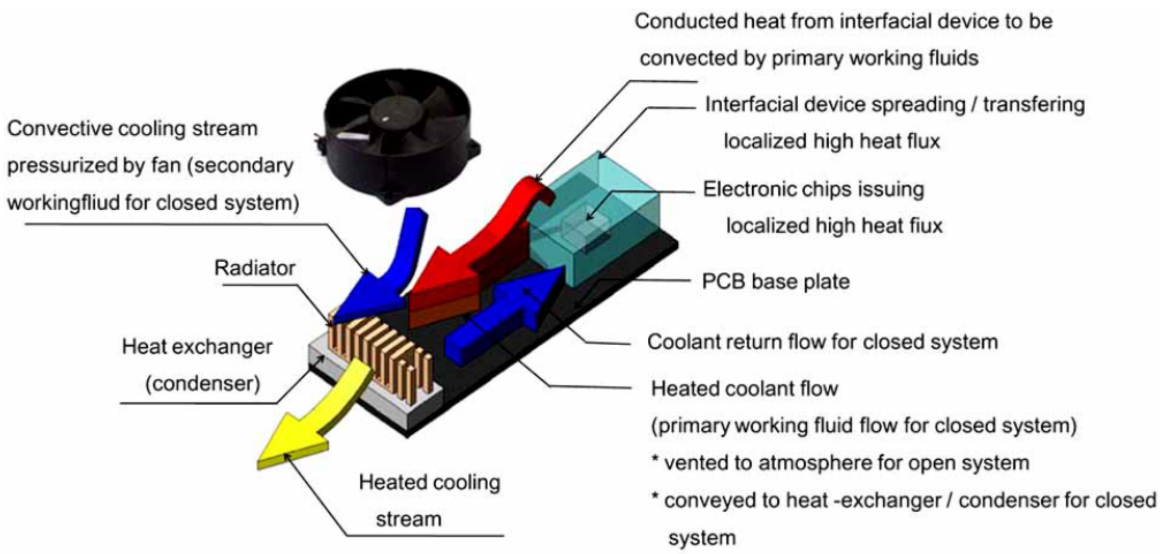


**Figure 1.** Physical Model of the considered phenomenon

## 2.2 Bi-dimensional Representation

The bi-dimensional model can be represented as in Figure 2. First a basic structure without convection and one source only is analysed. Secondly, the effects of convection are investigated, as well as the influence of its parameters on the system. Sources with different shapes are also evaluated in the further sections.

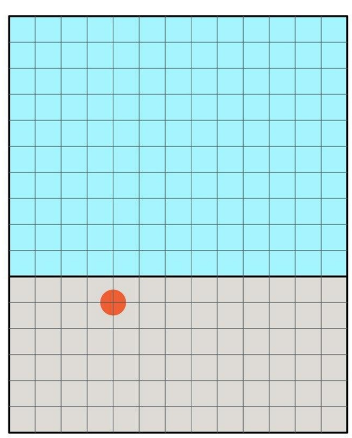

**Figure 2.** Bidimensional Model

# 3. Numerical Methods

The calculations used to build the model are performed via finite volumes (FV) and finite differences (FD), for what concerns spatial discretization of the equations, while for the temporal discretization the Runge Kutta (fourth order) algorithm is used. These methods are here briefly introduced. The final purpose of such discretization is to obtain two terms:

**Information Matrix *A*** : a matrix whose content includes the relations between every node and its surrounding nodes

**Known Vector *b*** : a vector built depending on Boundary Conditions and general conditions the system is subject to

## 3.1 Finite Volumes

To represent the heat diffusion differential equation 1 the finite volume numerical scheme can be adopted. According to this method, the Divergence Theorem can be applied to the integral solution of a second order differential equation, thus transforming a volume integral into a surface integral - or, in our specific case, a surface integral into a line integral [3]. The reference equation is the *Heat Diffusion Equation* for steady state, that is the same as Eq. 1, without the time - dependent term and without heat generation.

$$\lambda \nabla^2 T = 0 \tag{2}$$

The line integral is then evaluated according to any numerical integration technique - in our case, mid-point rule, for a generical point P:

$$\int_{S^P} \lambda \nabla^2 T dS = \oint_{\partial S^P} \lambda \nabla T \cdot \boldsymbol{n} dl = 0 \tag{3}$$

Eventually, by applying the Green Theorem:

$$\left.\frac{\partial T}{\partial x}\right|_S \approx \frac{1}{S^S} \oint_{\partial S^S} T dy \qquad and \qquad \left.\frac{\partial T}{\partial y}\right|_S \approx \frac{1}{S^S} \oint_{\partial S^S} -T dx \tag{4}$$

The final expression of Equation 2 for a 3x3 grid, as shown in Figure 3 is [3]:

$$S^P = \frac{1}{2}|(x_n e y_s e - x_s e y_n e) + (x_s e Y_s w - x_s w y_s e) + (x_s w y_n w - x_n w y_s w) +$$
$$(x_n w y_n e - x_n e y_n w)| \tag{5}$$
$$S^s = \frac{1}{2}|(x_e y_{\mathbb{S}e} - x_{\mathbb{S}e} y_e) + (x_{\mathbb{S}e} y_{\mathbb{S}w} - x_{\mathbb{S}w} y_{\mathbb{S}e}) + (x_{\mathbb{S}w} y_w - x_w y_{\mathbb{S}w}) +$$
$$(x_w y_e - x_e y_w)| \tag{6}$$
$$S^e = \frac{1}{2}|(x_{n\mathbb{E}} y_{s\mathbb{E}} - x_{s\mathbb{E}} y_{n\mathbb{E}}) + (x_{s\mathbb{E}} y_s - x_s y_{s\mathbb{E}}) + (x_s y_n - x_n y_s) + (x_n y_{s\mathbb{E}} - x_{n\mathbb{E}} y_n)| \tag{7}$$
$$S^n = \frac{1}{2}|(x_{\mathbb{N}e} y_e - x_e y_{\mathbb{N}e}) + (x_e y_w - x_w y_e) + (x_w y_{\mathbb{N}w} - x_{\mathbb{N}w} y_w) + (x_{\mathbb{N}w} y_{\mathbb{N}e} -$$
$$x_{\mathbb{N}e} y_{\mathbb{N}w})| \tag{8}$$
$$S^w = \frac{1}{2}|(x_n y_s - x_s y_n) + (x_s y_{s\mathbb{W}} - x_{s\mathbb{W}} y_s) + (x_{s\mathbb{W}} y_{n\mathbb{W}} - x_{n\mathbb{W}} y_{s\mathbb{W}}) + (x_{\mathbb{N}w} y_n - x_n y_{\mathbb{N}w})| \tag{9}$$

While the inner nodes are evaluated by interpolation [3]:

$$T_{sw} = \frac{T_{\mathbb{S}\mathbb{W}} + T_{\mathbb{S}} + T_P + T_{\mathbb{W}}}{4} \tag{10}$$
$$T_{se} = \frac{T_{\mathbb{S}\mathbb{E}} + T_{\mathbb{S}} + T_P + T_{\mathbb{E}}}{4} \tag{11}$$
$$T_{ne} = \frac{T_{\mathbb{N}\mathbb{E}} + T_{\mathbb{N}} + T_P + T_{\mathbb{E}}}{4} \tag{12}$$
$$T_{se} = \frac{T_{\mathbb{N}\mathbb{W}} + T_{\mathbb{N}} + T_P + T_{\mathbb{W}}}{4} \tag{13}$$

Where the nodes are named after the scheme in Figure 3.

The coefficients obtained from Equations 5 to 9 and 10 to 13 are then used to build the so-called Information Matrix $A$, so that for a steady state the system 14 is obtained:

$$AT = B \tag{14}$$

Where $B$ is a vector built from the Boundary Conditions and $T$ is the vector representing the desired temperature distribution.

## 3.2 Finite Differences

Applying the Finite Difference method means replacing the differential terms of an equation with a linear combination of the same quantity's values, evaluated in different points, therefore the final expression obtained removing the $v_y$ term is:

$$\frac{\partial T}{\partial t} + v_x\left(\frac{T_{\mathbb{W}} - T_P}{\Delta x}\right) \tag{15}$$

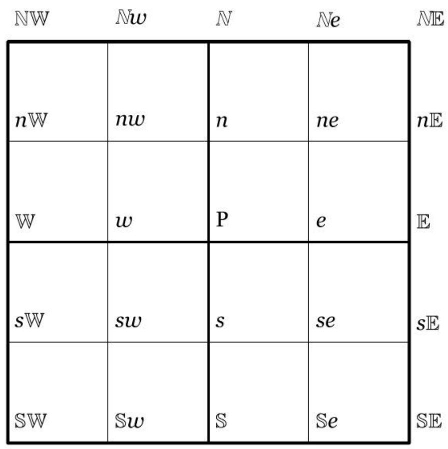


**Figure 3.** Representation of the 2-dimensional grid

In the considered case (Eq. 15) convection is assumed for a stream flowing from left to right, therefore heat exchange occurs at the right border. The coefficients obtained from 15 also contribute to building Equation 14, according to the Superposition Principle which, given the linearity of the problem, allows to mix two different discretization methods.

### 3.3 Runge Kutta Fourth Order

Concerning time discretization, the Runge Kutta fourth order *RK4* is used. According to this algorithm, a correction term is applied to every step of the time iteration, leading to the following expression [3]:

$$T^{n+1} = T^n + \frac{1}{6}\Delta t\left[AT^n + 2A\dot{T}^{n+1/2} + 2A\ddot{T}^{n+1/2} + A\dddot{T}^{n+1}\right] \tag{16}$$

Where:

$$\dot{T}^{n+1/2} = T^n + \frac{1}{2}\Delta t A T^n - b\delta t/2$$
$$\ddot{T}^{n+1/2} = T^n + \frac{1}{2}\Delta t A T^{n\dot{+}1/2} - b\Delta t/2$$
$$\dddot{T}^{n+1/2} = T^n + \frac{1}{2}\Delta t A T^{n\ddot{+}1/2} - b\Delta t/2$$

Special attention needs to be used when dealing with the time step and number of nodes regarding convergence. Not small enough values or few nodes could translate into divergence and thus to inconsistent results.

# 4. Modeling the Physical Process

To describe phenomena such as the distribution of a gas or the propagation of noise, partial differential equation (PDE) provide a general answer: such equations are here adapted to heat transfer models and are handled with the mathematical approach previously explained.
The physical reference model used throughout the study - for any number of sources - can be described as a multi-phase domain, composed of a solid section in the lower part and a fluid in the upper part. In the simulation, each section is firstly built as an independent grid and secondly connected to the other. Both domains (fluid and board) are firstly considered as an independent problem and secondly connected. The source - ideally a wire - is then inserted within the solid. Particularly significant for the construction of the entire model are the Boundary Conditions (BC) [3]:

- Dirichlet BC: a constant temperature is assumed known at the boundary
- Neumann BC: a certain heat flux term is assumed known
- Robin BC: a combination of Neumann and Dirichlet Boundary Conditions

While the starting point to model any heat transfer phenomenon is the following general transport equation, also called *convection-diffusion-reaction (CDR)*:

$$\frac{\partial}{\partial t}(\rho\phi) + \nabla\cdot(v\rho\phi) - \nabla\cdot(D\rho\nabla\phi) = s \tag{17}$$

It is to be noticed the presence of three important terms:

**Temporal Term** : $\frac{\partial}{\partial t}(\rho\phi)$

**Convective Term** : $\nabla\cdot(v\rho\phi)$

**Diffusion Term** : $\nabla\cdot(D\rho\nabla\phi)$

Where $\rho$ represents the density of the material, $D$ its thermal diffusivity and $s$ the source.

## 4.1 Diffusion

The first step in the implementation of the desired model is to locate a random source in the board and analyse how the heat is spread into the surrounding domain. For this purpose, only diffusion is considered at first. Since the aim of this report is to analyse the influence of some sources inside an electronic component *(board)* and find a way of cooling the system by applying an air flow, the focus is on temperature distributions. Therefore it is at first necessary to see how the temperature evolves in a system where there is no cooling agent. In other words, the convective flux is in the first place neglected:

$$\frac{\partial}{\partial t}(\rho\phi) + \nabla\cdot(D\rho\nabla\phi) = s \tag{18}$$

By replacing $\phi = cT, R = \lambda, s = \dot{\omega}$ and assuming constant both density $\rho$ and heat capacity c for the fluid and for the board, Equation 18 results in:

$$\rho c\frac{\partial T}{\partial t} - \nabla\cdot(\lambda\nabla T) = \dot{\omega}, \tag{19}$$

being $\lambda$ the thermal conductivity and $\dot{\omega}$ the heat release source term. Eq. 20 is the so-called *Heat Equation*.
Finally, considering $\lambda$ as constant the Eq.20 is obtained:

$$\rho c\frac{\partial T}{\partial t} - \lambda\frac{\partial}{\partial x}(\frac{\partial T}{\partial x}) - \lambda\frac{\partial}{\partial y}(\frac{\partial T}{\partial y}) = \dot{\omega} \tag{20}$$

## 4.2 Convection

Once this first step is completed, convection can be considered. While in the first case Finite Volumes method was chosen, Forced Convection is implemented by Finite Differences. Logically, the fluid is the material affected by convection. Convection's effects are thus added as a part of the information matrix for the inner nodes of the fluid. Especially important is the fluid's speed, which is assumed in one dimension only, that is to say any turbulence effect is neglected and the particles are all considered to move in the same direction at the same speed.
The mathematical expression for convection is:

$$\rho c\frac{\partial T}{\partial t} + v\nabla\cdot T - \nabla\cdot(\lambda\nabla T) = \dot{\omega} \tag{21}$$

It is clear that both convective flux and diffusion influence the result. The ratio of diffusion terms to convective terms is given by the *Peclet Number*:

$$Pe = \frac{\ni_0 L_0}{D_0} \tag{22}$$

Where $\ni_0, L_0, D_0$ respectively stand for reference Velocity, reference Length and reference Diffusion coefficient. This expression allows to identify the behaviour the fluid will have. For example, having a significant $Pe$ number, implies $\ni >> D$, therefore the diffusive term could be neglected. This tool will be useful to predict the behaviour of the fluid over the electronic component in further sections.

# 5. Analysis of the Model's Components

## 5.1 Board Model

For the evaluation of the temperatures on the board the information matrix has to be built according to the process explained in the previous sections, therefore it is necessary to make some assumptions concerning the Boundary Conditions. Those are assumed to be Robin at the interface with the fluid and Dirichlet at all other borders.

Dirichlet BC can be so defined:

$$T_P = T_D(y) \qquad \forall P \in \Gamma_D \tag{23}$$

Where $\Gamma_D$ represents the border of the domain itself. At the juncture between the two domains Robin Boundary Condition is applied:

$$\alpha * (T_P - T_\infty) + \lambda_P \frac{\partial T}{\partial y}\Big|_P = 0 \qquad \forall P \in \Gamma_R \tag{24}$$

Robin BC Eq.24 allows to model the heat flux occurring between the two domains. The heat exchange modeled through Eq.24 occurs between $T_P$ and $T_\infty$: $T_P$ is the temperature of the current point, which in this case is equal to the upper part of the board; while $T_\infty$ is the temperature of the ambient, here assumed constant. The possibility of constantly updating $T_\infty$ according to the changes in the fluid's temperature was proposed, nevertheless, being the difference in the final result not significant, this option is not presented.

## 5.2 Fluid Model

To model the fluid's temperature distribution the same approach as before is followed. The Fluid domain is characterized by Dirichlet BCs on all its borders but the right one, where Robin is applied. This is necessary because when convection is considered it is necessary to allow heat exchange: the flowing fluid enters through the left side of the domain, pushing some of the generated heat from the control volume (accumulated on board's surface and fluid surroundings) to the right. Therefore, the condition at the border in the direction of the flowing fluid (also called East) is imposed to be Robin 24.

Furthermore, at the interface with the solid temperature, the temperature is assumed known but not constant: for every time step, the temperature distribution calculated in the

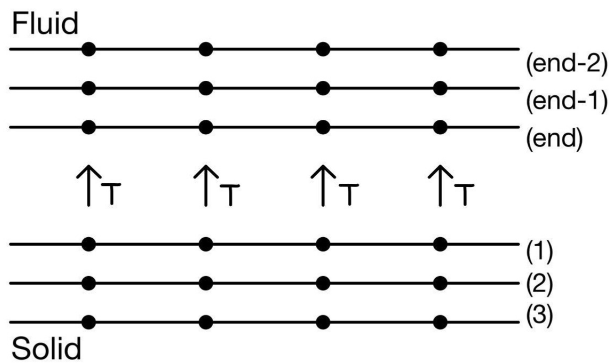


**Figure 4.** Grid at the solid-fluid interface

board is assumed as a reference for the Dirichlet condition in the fluid. As a consequence, condition 23 becomes:

$$T_P, board(k) = T_P, fluid(k) \qquad \forall P \in \Gamma_{border} \tag{25}$$

where $\Gamma_{border}$ represents the line of nodes of the two domains in contact with each other and k defines the column index of every node belonging to the border. The board-fluid relation is therefore implemented by setting the last line of nodes of the fluid to the same temperature of the upper nodes of the board, as shown in Figure 4. Moreover, this assumption makes it possible to highlight how heat is spread in different ways in the two different means, a phenomenon which is particularly evident when convection is involved.

## 5.3 Source Model

The source is modeled by imposing one of the nodes in the solid domain to be constant. In particular, the following assumption needs to be remembered:

$$Bi = \frac{\bar{h}L}{k_{\mathrm{b}}} << 1 \tag{26}$$

Where $\bar{h}$ represents the convective heat transfer coefficient, L is a characteristic representation for size of the body (e.g. the diameter) and $k_b$ represents the device's heat capacity. Biot number thus represents the ratio between the capacity for convection heat exchange from the body's surface and the body's heat capacity. In this case, Convective effects are negligible when compared to the heat stored within the device. The meaning of such assumption is that the temperature can be assumed constant within the device and consequently on the considered nodes.

# 6. Results

A very important objective of project is to achieve enough versatility to be applied to real world problems: from a general approach, many different application possibilities can be generated. For this reason, in the first part only a one-source model is displayed. This is thought as a general case where the evaluation of different parameters, such as velocity, takes place in order to observe their effects.In further sections more sources acting at the same time will also be considered. The reference values assumed for the simulations are represented in Table 6. The numbers here presented do not necessarily reflect those that can be found in real cases, they serve as a reference in order to better display the desired phenomena.

| Property | Value | Units |
|---|---|---|
| Source Temperature | 398 | K |
| Thermal Conductivity - air [4] | 0.1068 | W/mK |
| Thermal Conductivity - board [5] | 1.059 | W/mK |
| Density - air [4] | 1.335 | $kg/m^3$ |
| Density - board [5] | 1.850 | $kg/m^3$ |
| Heat Capacity - air [4] | 1000 | J/kgK |
| Heat Capacity - board [5] | 396 | J/kgK |
| Diffusivity - air [4] | 0.08 | $m^2/s$ |
| Diffusivity - board [6] | 1.446 | $m^2/s$ |
| Convective Heat Transfer Coefficient | 1 | $W/m^2K$ |

## 6.1 Effects of convection: Velocity's influence

A mesh of 40x20 nodes has been selected for the analysis of the results, that is to say 20x20 nodes for each domain. Furthermore, all Dirichlet Boundaries are sharing an ambient temperature of 298K. It is also important to remark that in all the graphs a red line separating board and fluid is placed at the interface between the domains.
To begin with, a single source is located in the middle of the board and its temperature is set to $398K$, at the same time, convective velocity has a value of $v_x$= 1m/s. Figure 5 represents the location of the source, and in both Figs. 5 and 6 the heat expanding through the board reaches the fluid and heats its lower side. The higher the temperature of the source, the larger the area of the fluid affected by the heat flux. In these images, the simulation reaches an equilibrium state, where heat is concentrated on the surface of the board. This phenomenon could damage the electronic component if the device is exposed to the heat for a certain period of time. In this case, convection is not severely affecting the system.

The next step is to investigate the influence of velocity, so that the effects of heat are considerably reduced. By experimentally changing the value of the velocity, such correlation can be analysed. Increasing the velocity, convection starts gaining in importance. It is important to remember that int the present work the the phenomena occurring in the

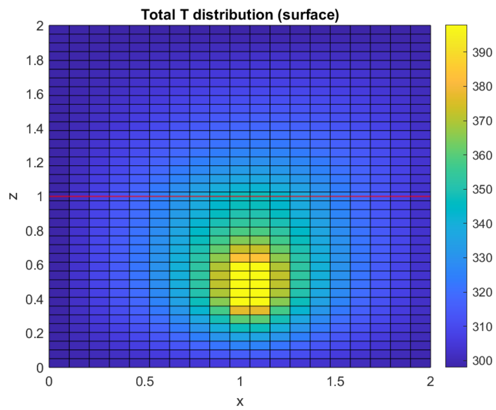


**Figure 5.** Temperature Distribution, low convection velocity

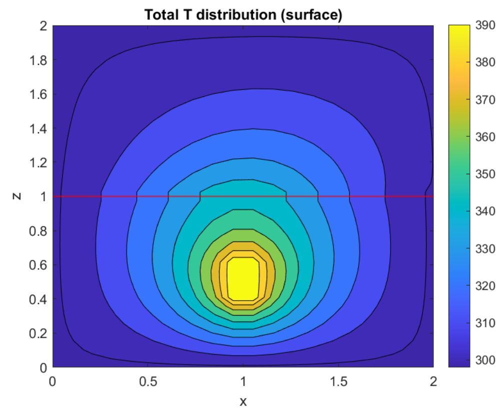


**Figure 6.** Temperature Distribution, low convection velocity

thermal boundary layer, as well as the ones related to turbulence theory are neglected, also because velocity is only considered in one direction. In Figs. 7, 8, 9, 10 the velocity is thus incremented to $v_x = 10 m/s$.

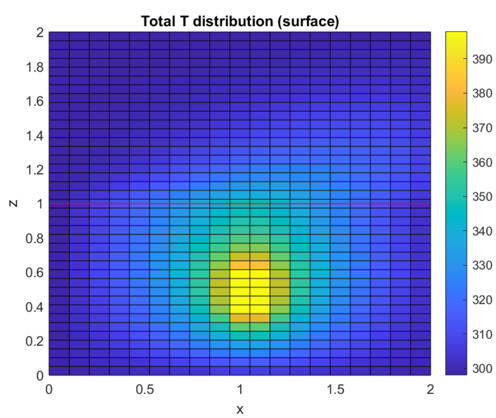


**Figure 7.** Temperature Distribution, medium convection velocity

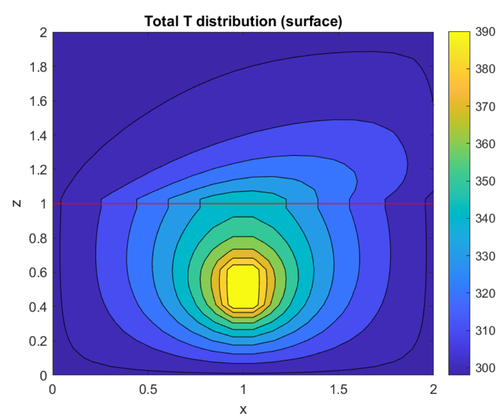


**Figure 8.** Temperature Distribution, medium convection velocity

With this increase, the heat removal is highly efficient, its accumulation is thus avoided. In Figure 10 a closer look at the fluid is taken: isotherms are bending towards the right side of the plot, being the left region hardly influenced. However, it can be said that the right half could be subjected to slightly more damage than in Figures 5 and 6, being all the heat accumulated on the right side of the domain.
When the velocity is brought to $v_x = 100 m/s$ an important change occurs as a consequence of the increasing speed: heat is successfully removed, as shown in Figures 11 and 12. Being velocity highly significant, this solution extracts air and might not be the best one, from an efficiency point of view.

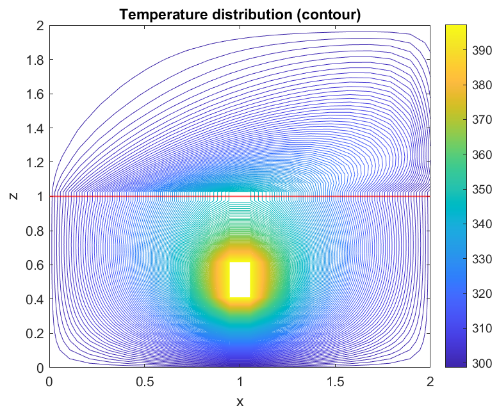


**Figure 9.** Isotherms Distribution with medium convection velocity

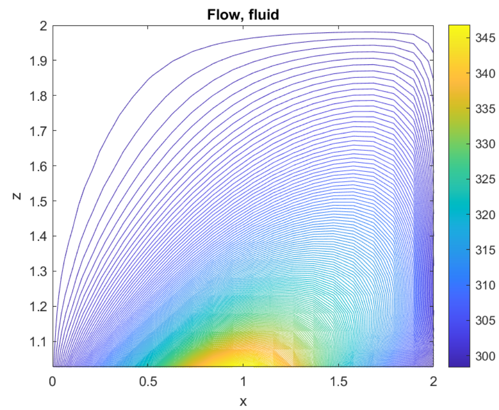


**Figure 10.** Zoom: isotherm distribution in fluid with medium convection velocity

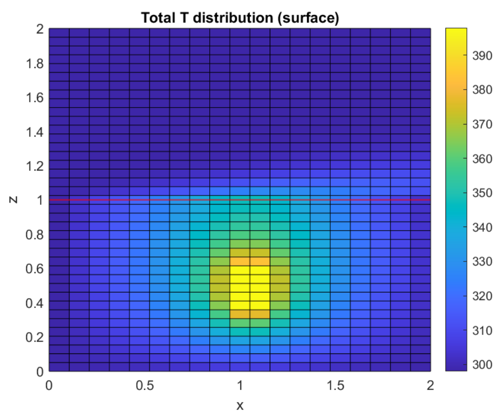


**Figure 11.** Temperature Distribution with high convection velocity

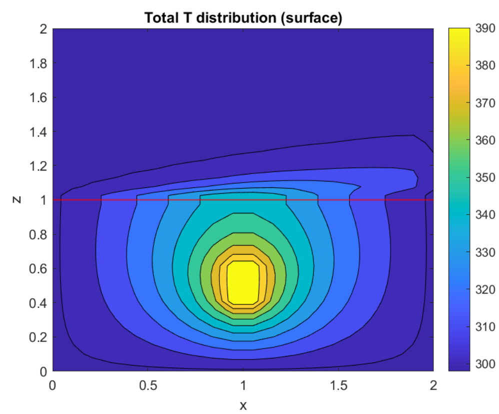


**Figure 12.** Temperature Distribution with high convection velocity

On the economical side, the more powerful the flow is, the more it costs. Therefore, finding the minimal velocity that allows the maximal reduction in heat exchange can be useful for companies applying this system.
Furthermore, as previously mentioned, the air flows from the left border in all its extension, which means higher costs for companies. Since the heat generated by the source does not reach the upper boundary of the fluid, another approach to reduce costs is now investigated: an air stream flowing in the lower half of the domain only. Velocity flows in the $z \in [1, 1.5]$ interval with a constant value of $100 m/s$. The result is practically the same as for introducing velocity in the whole fluid span. As a consequence, it is stated that velocity has only a positive influence when it directly affects the generated heat. In other words, as far as the heat ascends through the fluid, convection will be confined to its height, in terms of cost minimization. Of course, this consequence is only valid for this model, where $v_y$ has not been taken into consideration. A final consideration concerning the board-fluid interface

must be taken into account: since the adopted model imposes the same temperature on two rows (one within the board's domain, one within the fluid's domain) the temperature distribution in this area does not properly reflect the effects of convection. In fact, it might seem from the graphs that heat is accumulated at the interface region, while this is in fact just a graphical effect depending on the computational process.

## 6.2 Gradients of velocity

In this section, simulations ran with different velocity gradients are shown, as well as the results obtained. It is again important to remark that such simulations do not rely on real data, they are only representative of the effects of convection on the considered systems, even in extreme conditions. Three different velocity variations are considered in the following sections:

- Speed proportionally decreasing with z
- Speed proportionally increasing with z
- Speed varying as a sine wave

### 6.2.1 Decreasing Gradient of Velocity

For this section the variation of velocity is so defined:

$$v_x = (k/2)z - k \qquad \forall z \in [1;2] \tag{27}$$

Where $k$ represents the maximal speed and is different in the considered cases. The outcome of the simulation for an increasing velocity gradient is shown in Figures from 13 to 24. While in Fig. 13 and 14 the maximum speed is $v_x = 20m/s$, in Fig. 15 and 16 it is $v_x = 200m/s$. In these cases the magnitude of velocity is not enough to act as a cooling agent, since the heat is not completely removed. Instead, for 17 and 18 the maximal speed is $v_x = 2000m/s$. Although it is certainly not plausible to reach such a speed in a small system, it is interesting to notice how this would almost entirely remove any heat accumulation.

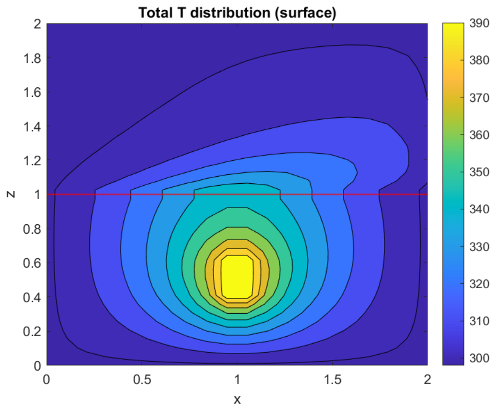


**Figure 13.** k=20 m/s

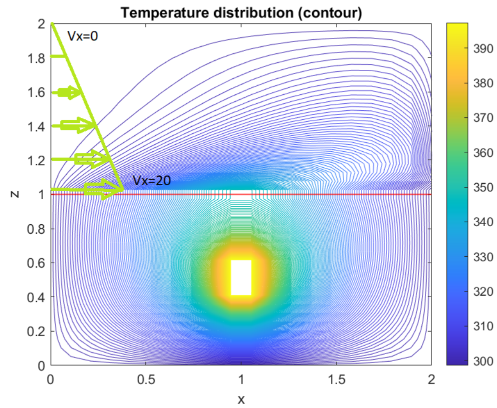


**Figure 14.** k = 20 m/s

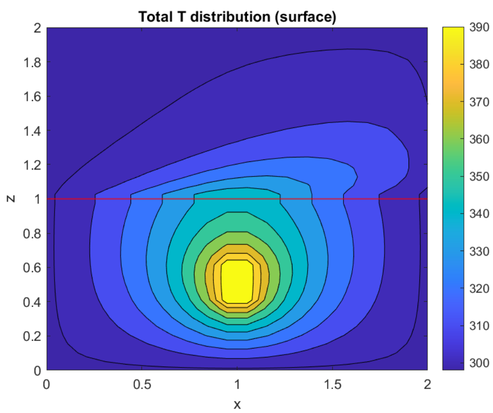


**Figure 15.** k= 200 m/s

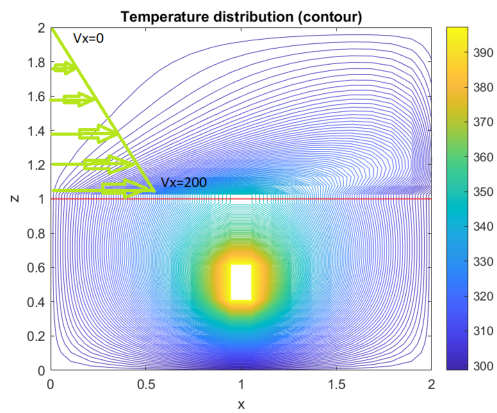


**Figure 16.** k=200 m/s

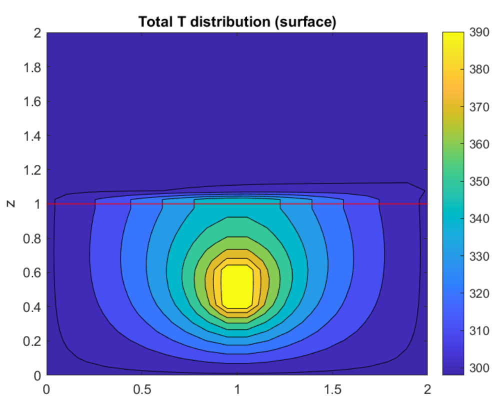


**Figure 17.** k= 2000 m/s

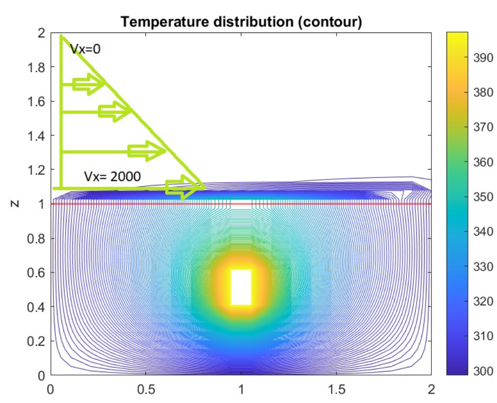


**Figure 18.** k=2000 m/s

### 6.2.2 Increasing Gradient of Velocity

In this case the Velocity increases according to the following:

$$v_x = kz - k \qquad \forall z \in [1;2] \tag{28}$$

As for the previous case, three different values of k are considered.
In this section, Figures 19 and 20 reach the speed $v_x = 20m/s$, Figures 21 and 22 reach $v_x = 200m/s$ and Figures 23 and 24 reac a final speed $v_x = 2000m/s$. In this case an important movement of the isotherms is highlighted: they appear to be more inclined over the board and totally absent in the upper part of the domain.
In comparison with the previous results, this configuration is worse in terms of cooling, since all the heat is accumulated in a layer covering the board. Not even velocities near $2000m/s$ totally remove the heat, since at the interface the speed is always $v_x = 0m/s$, therefore no heat is removed in this area.

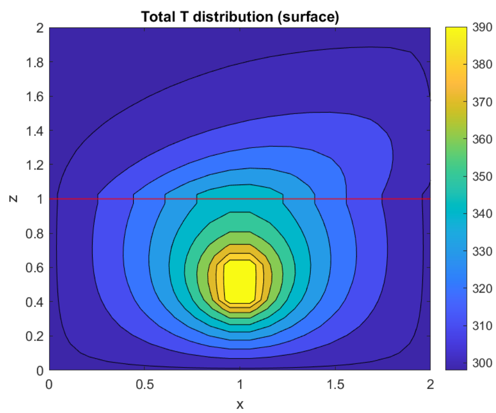


**Figure 19.** k=20 m/s

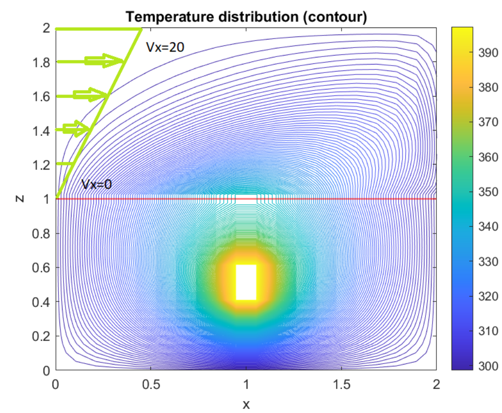


**Figure 20.** k = 20 m/s

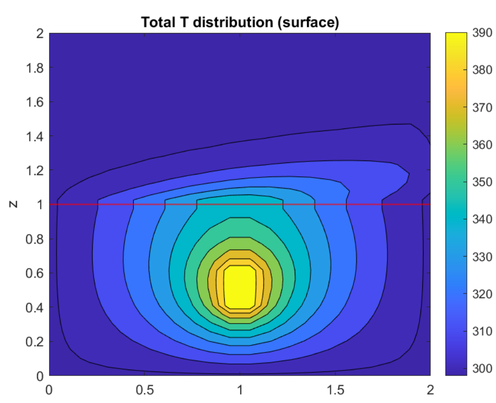


**Figure 21.** k= 200 m/s

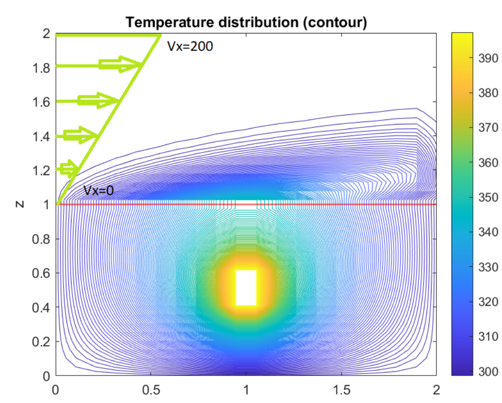


**Figure 22.** k=200 m/s

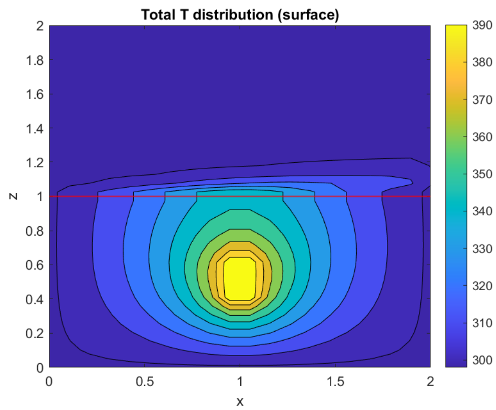


**Figure 23.** k= 2000 m/s

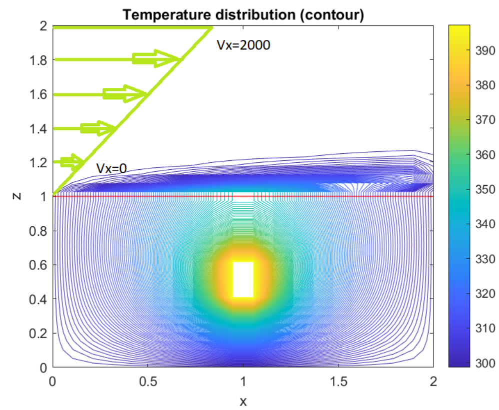


**Figure 24.** k=2000 m/s

### 6.2.3 Sine-varying Speed

Finally, a case with speed varying according to the sine function is considered:

$$v_x = -k \cdot sin(\pi z) \qquad \forall z \in [1;2] \tag{29}$$

Where $k$ represents the maximum amplitude of the sine wave and, thus, the maximal velocity reached within the domain.

Figures 25 and 26 are again the ones where the lowest velocity $v_x = 10m/s$ is reached, in Figures 27 and 28 $v_x = 100m/s$ is considered and finally in Figures 29 and 30 the speed value reaches $v_x = 1000m/s$.

The obtained results are very similar to the second case: a layer of heat remains between board and fluid, therefore the final purpose of the report - to evacuate heat - is not properly achieved. The reason of this, as for the previous case, lies in the fact that the speed at the interface is null.

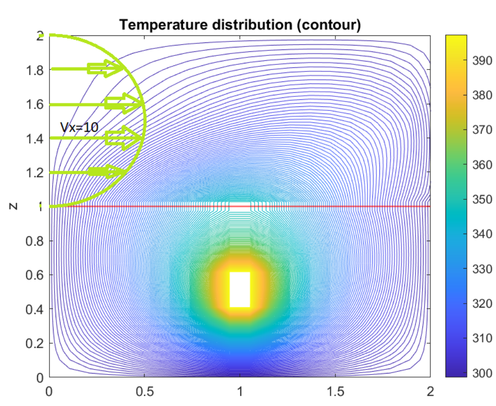


**Figure 25.** k=10 m/s

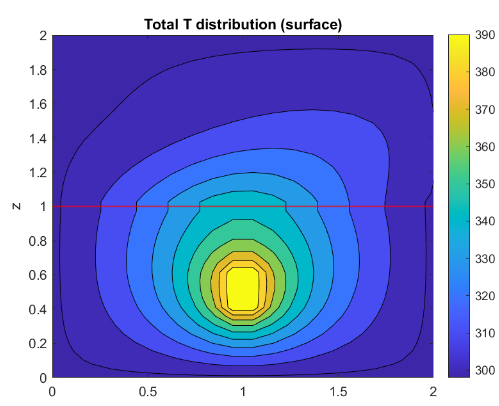


**Figure 26.** k = 10 m/s

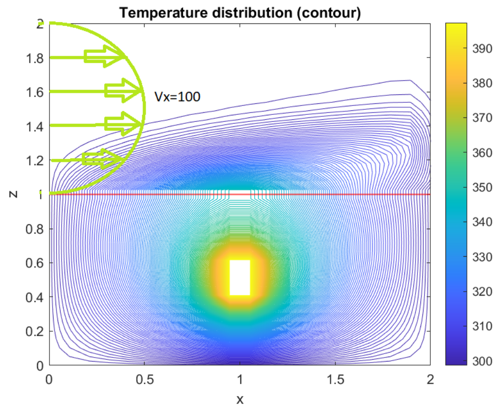


**Figure 27.** k= 100 m/s

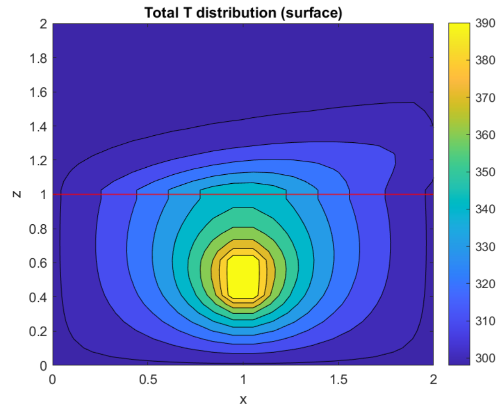


**Figure 28.** k=100 m/s

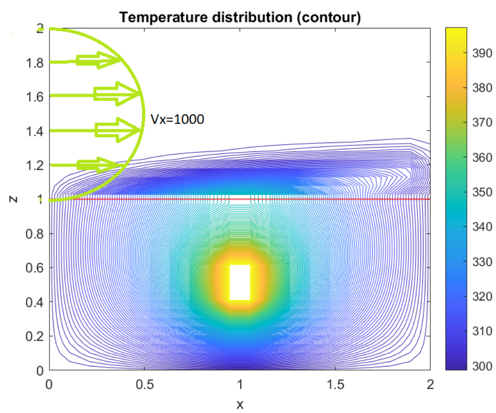


**Figure 29.** k= 1000 m/s

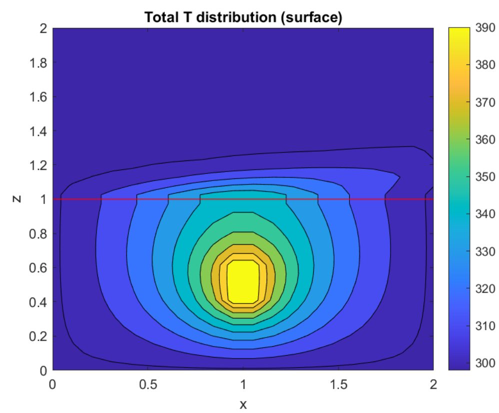


**Figure 30.** k=1000 m/s

In conclusion, altering the gradient does not vary considerably the heat transport. However, it is again observed the influence of the magnitude of velocity. All the configurations give similar results that resemble the same outputs reached with a constant velocity. Nonetheless, if the best one has to be chosen, it is the proportionally decreasing one. The reason is clear when looking at extreme cases (velocities of order $\approx 10^3$), where this particular configuration makes the heat layer look flatter.

## 6.3 Multi-source modeling

In addition to this analysis, the effects of different sources can also be studied. The code developed is thought to allow to introduce multi-shape sources, in order to better imitate real electronic components. This analysis will be done in the following section for a Light Emitting Diode (LED). In fact, the simulated electronic components could be resistors, transistors, batteries, or any other component whose thermal behavior can be modeled through a time-dependent law. The only difference with the already analysed sources would be in shape and temperature, which is this report always assumed constant.

## 6.4 A practical example: LED Model

### 6.4.1 One Source LED Model

In this section a real-life case is investigated: the temperature distribution generated by the presence of a LED within a PCB board. As suggested from [7], the source is placed in the upper section of the PCB model. In this peculiar case the reference temperature of the diode is assumed T=333 K, as suggested in [8]. According to [9], the convective heat transfer coefficient is assumed equal to $\alpha = 20\frac{kW}{m^2K}$

| Property | Value | Units |
|---|---|---|
| Source Temperature [8] | 333 | K |
| Thermal Conductivity - air [4] | 0.02509 | W/mK |
| Thermal Conductivity - board [5] | 1.059 | W/mK |
| Density - air [4] | 1.225 | $kg/m^3$ |
| Density - board [5] | 1.850 | $kg/m^3$ |
| Heat Capacity - air [4] | 1000 | J/kgK |
| Heat Capacity - board [5] | 396 | J/kgK |
| Diffusivity - air [4] | 0.08 | $m^2/s$ |
| Diffusivity - board [6] | 1.446 | $m^2/s$ |
| Convective Heat Transfer Coefficient [9] | 20 | $W/m^2K$ |

**One source, No Convection** In Figures 31 and 32 the temperature distribution obtained in absence of convection are represented. The highest temperature reached is that of the LED itself, but the heat is widely spread in the surrounding as well, leading to a higher temperature at the interface with the fluid.

**One source, Slow speed Convection** In Figures 33 and 34 the temperature distribution does not show big differences with respect to the previous case. Convection speed is here set to $v_x$= 0.01 m/s. Neverthless, the effects of convection are more evident in the Contour Plot 34, where the contours slightly deviate in the direction of the flow, namely where the heat is being transported.

**One Source, High speed Convection** In Figures 35 and 36 the effects of convection are clear. The considered speed of convection is $v_x$= 4 m/s. In Figure 36 the heat transport phenomenon is particularly evident: apart from the considerably lower temperatures reached all over the graph, the heat flow is particularly noticeable.

Once more the importance of Convection in cooling systems for electronic devices is highlighted: the temperature distribution at the interface with the fluid goes from covering the range 298 K -325 K to almost entirely being at 298 K, that is to say ambient temperature. Independently of the temperature reached by the device, convection provides an efficient method to prevent electronic components from overheating.

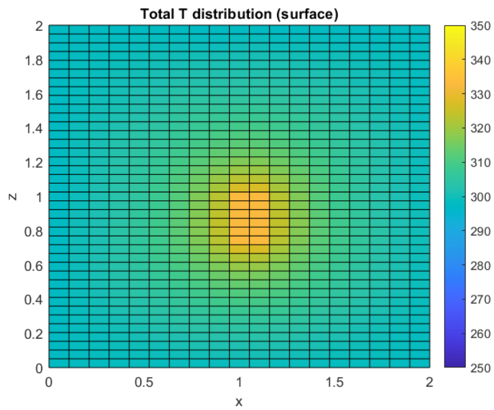


**Figure 31.** Temperature Distribution around a LED without convection

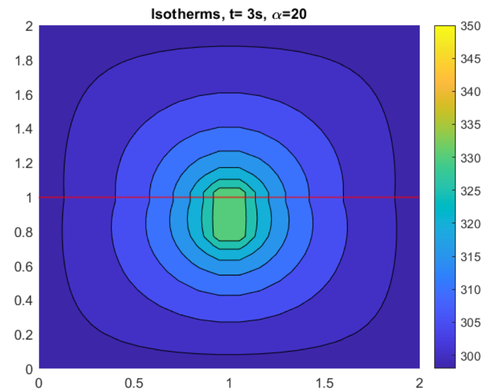


**Figure 32.** Temperature Distribution around a LED without convection

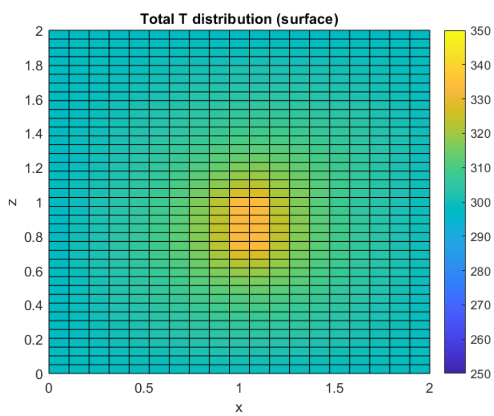


**Figure 33.** Temperature Distribution around a LED with low convection

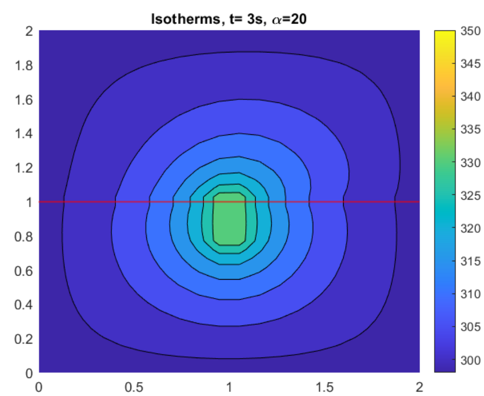


**Figure 34.** Temperature Distribution around a LED with low convection

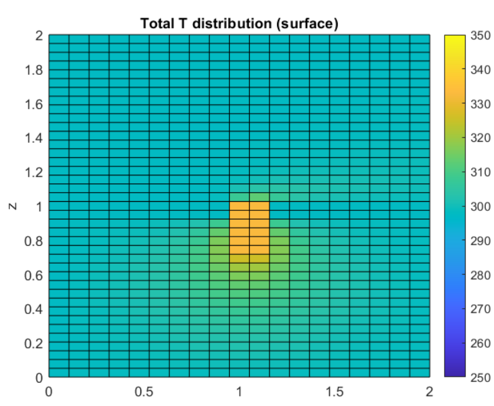


**Figure 35.** Temperature Distribution around a LED with high convection

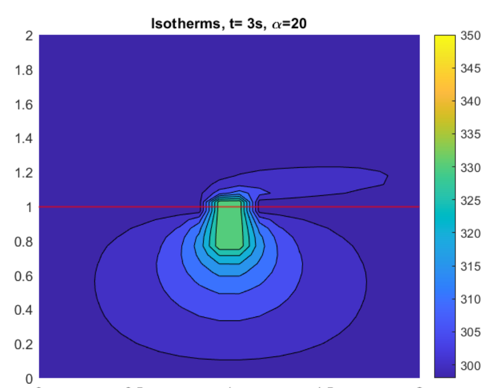


**Figure 36.** Temperature Distribution around a LED with high convection

### 6.4.2 Two Sources LED and Wire Model

Another example of real-case thermal behavior is presented in the present chapter. The physical reference is in this case a PCB with two LED sources connected by a wire and affected by mild conduction ($v_x$= 2m/s). The wire connecting the two boards is set to 333 K ≈ 60°C, which is the highest temperature that can be reached with the lightest insulation type (TW), according to Wire Temperature Ratings[10]. All other parameters are the same as the ones assumed in 6.4.1.

Figure 37 highlights the presence of the wire between the sources, while in Figure **??** the final effect on the surroundings is represented. The overall generated heat is considerably higher, despite the convection's velocity. The heat clearly accumulates at the interface between the two domains, leading to considerably higher temperatures in this region.

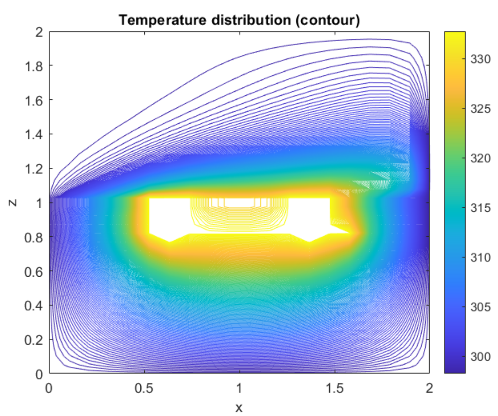


**Figure 37.** Temperature Distribution, 2 LEDs and a wire with mild convection

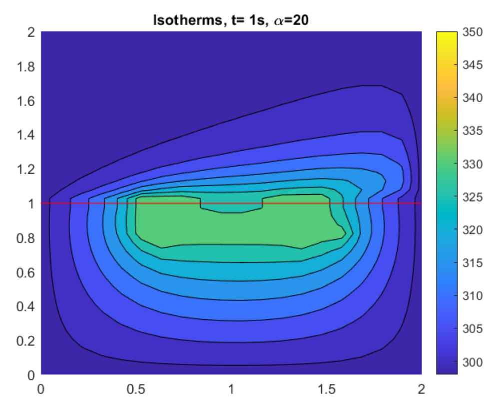


**Figure 38.** Temperature Distribution, 2 LEDs and a wire with mild convection

## 6.5 Temporal Evolution

An example of the temporal evolution of the considered systems is here represented. Once again, the reference values are those from Table 6.4.1 and the system consists of a LED source within a PCB board. In order to better represent the phenomenon of heat diffusion, the case with no convection is shown in Figures from 39 to 42. With $dt = 7.3492e-06$, Figure 39 represents the system after 10 iterations, Figure 40 after 50000 iterations, Figure 41 after 10000 and Figure 42 after 400000 iterations, that is to say at the end of the time interval considered t=3 s. It is immediately clear that the system reaches the equilibrium state shortly after the first iterations: in fact no real difference is noticeable between Figures 40 and 42.

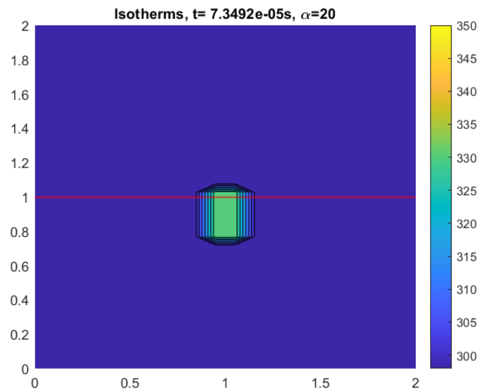


**Figure 39.** iterations = 10

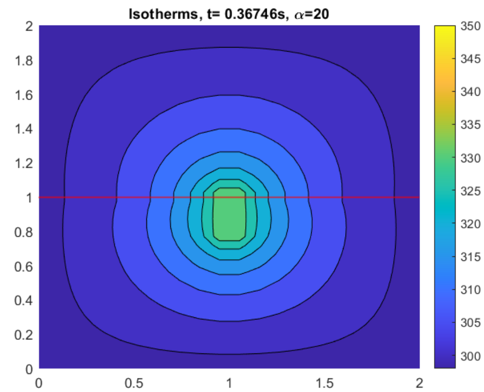


**Figure 40.** iterations = 50000

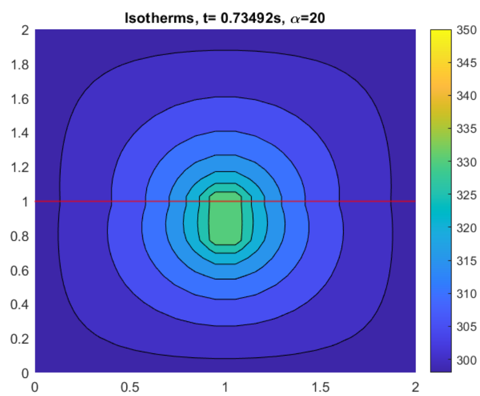


**Figure 41.** iterations = 100000

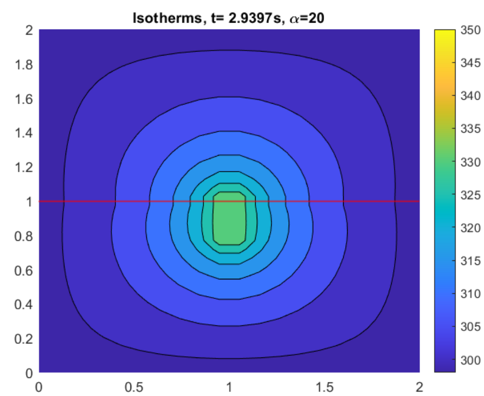


**Figure 42.** iterations = 400000

## 7. Conclusions

In conclusion, this report presents a tool to effectively model the thermal behavior of electronic components within a board, e.g. a PCB. The results are particularly relevant concerning convection: not only is in this case possible to highlight its importance, but the effects of speed's distribution and intensity are also investigated. Particular emphasis should be placed on the speed distribution, whose importance might be underrated with respect to the final value of the velocity. In fact, lower speed in a convenient distribution such as in Figure 13, lead to the same or usually better results when compared to non-convenient distributions (see Fig. 23) where the maximal speed is considerably higher. Furthermore, velocity only influences the area affected by the heat. If the heat spread reaches a certain height, the velocity is only needed until that point.
Concerning the real-life LED case, it is been possible to see a practical case and the possibilities that this project could open in real life applications.

## Acknowledgments

In the first place we want to thank Professor Silva for all the patience and attention dedicated to us during the elaboration of this project and, most important, the course.
We also feel the need to dedicate some words to our classmates, who - knowing that we had not worked with MatLab or CFD before - offered themselves to help us and acted like second teachers.
Finally, we are very proud of having taken this course, although it required a certain effort, it allowed us to learn a lot. Being able to finally present the results of such work is something we are very proud of.


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