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## MODELING AND SIMULATION OF THERMAL MANAGEMENT SYSTEMS OF ELECTRONIC EQUIPMENT

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**Abstract.** *Electronic devices are usually protected by cabinets, for electrostatic and climatic protection of the environment in which they are located, however such electronic equipment can dissipate a great amount of heat due to the Joule effect, which is an aggravating factor for the life and efficiency the equipment. Thus, there is a need for a heat dissipation system. One of the ways to improve the thermal efficiency of this system is mathematical modeling and computer simulation. Therefore, the objective of this work is the mathematical modeling and the simulation of a metal cabinet containing electronic equipment. The mathematical model consists of the transient energy balance of the system using the first law of thermodynamics. The system was discretized using the Volume Element Method (VEM). The objective was to obtain a tool for simulating the thermal profile of electronic packaging systems.*

**Keywords:** *Mathematical Modeling, Simulation, Volume Element Method (VEM), Telecommunication Cabinets.*

## 1. INTRODUCTION

Electronic telecommunication equipment such as modems and telephone exchanges need to be installed in regions close to the end user. In this way, such equipment must be placed in metal enclosures for protection against environmental hazards and vandalism. However, such equipment dissipates a large amount of heat by Joule effect, which requires an efficient system of heat removal from these metal cabinets, since these equipment can not operate in temperatures above 60 ° C.

Currently a high demand for telephony services, and this increase in the amount of equipment has caused the Joule heat generation to increase significantly within the cabinet. So cabinets demand more and more efficient systems for heat removal. However the addition of these systems greatly increases the final cost of these cabinets.

One way to reduce the manufacturing costs of these cabinets is to design a heat removal system with the highest possible efficiency. One of the ways to find a heat removal system with the highest possible efficiency is through the mathematical modeling and simulation of the heat dissipation system.

Commonly these problems are addressed in a complex way with methodologies that result in space and time dependent equations; with this it is necessary of computers of great capacity of hardware to solve them and high time of processing, often unfeasible the simulation in this way. The need for more simplified simulation tools emerges, but with answers that add precision and low computational time.

The volume element method (MEV) proposes to be able to perform simulations through mathematical models with ordinary differential equations that do not depend on space, being only time dependent or algebraic equations. This does not use partial differential equations, differentiating it from traditional methods.

As the name suggests (MEV) brings as a philosophy to divide the system into elements of volume, where each volume is analyzed separately, being considered the communication between neighboring volumes through the transfer of energy and / or mass. It is for this reason that the (MEV) does not need spatial dependence (each EV has its defined location).

## 2. MATHEMATICAL MODELING AND COMPUTATIONAL SIMULATION

In advance of the use of computer simulation tools, mathematical modeling is necessary. It is understood that mathematical modeling seeks to address the complexity of the system by means of a mathematical equation suitable to represent satisfactorily the behavior of the physical system during its cycle, steady state, transient or both. Consequently, mathematical modeling starts with simulation in computers, thus reducing expenses in the design phases, because in this way it is possible to obtain answers from various types of project configurations, choosing what will be closer to the established needs (DILAY , 2013).

The concept of computer simulation has already been used since the 1960s, initially addressing problems related to meteorology. With the gain of knowledge in these areas, in the 1970s and 1980s there was a significant increase in suppliers of computer systems, but it was only around 1990 that the computer simulation tools gained strength and significant relevance. The fact that this happened was due to the large increase in the number of personal computers manufactured by IBM (DILAY, 2013).

If it is the mathematical modeling itself, it is possible to classify the type of model.

The models can be classified according to their degree, preliminarily one can fit two categories in order to approach the degree of complexity, called qualitative models and quantitative models. The qualitative model, which predicts trends of responses, but with low precision of variable locations and absolute values. The quantitative model predicts trends of responses and high precision of local values of the variables (WOODS and LAWRENCE, 1997; VARGAS et al., 2001). Or a model of low or high order according to Shapiro (2003), can also be presented as a concentrated or distributed model (TRIVELATO, 2003; KAISER, 2004).

High-order model uses partial differential equations (SHAPIRO, 2003), with this one has a greater precision in the results, however in order to require more computational time. Low order models use partial or ordinary differential equations, the latter of lower order (VARGAS; ARAKI, 2016).

It is possible to change the order of the model, so for a low order model, simply adjust it in order to transform it into a reduced order model, to a high order model, just simplify it or in other words , reduce it, that then a reduced model will emerge. Reduced order model falls within the range of low and high order models. Reduced order models have good accuracy characteristics with reasonable size, ie a model adjusted to offer the best possible results within a smaller set of mathematical equations when compared to high order models, thus aiming for better results within shorter times of processing (VARGAS; ARAKI, 2016).

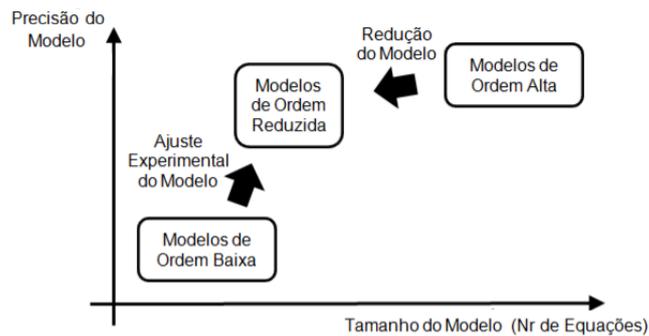


Figure 1 - Relationship between precision and size of mathematical model. Source: Vargas; Araki (2016)

Within reduced-order models, we have mathematical models that use the MEV. Interesting methodology to use in the thermal area in order to obtain true answers with the models, Vargas et al. (2001), Ordonez et al. (2008), Dias et al. (2009), Vargas et al. (2012) and Dilay et al. (2013) previously studied this methodology for simplified physical models in packaged electronic circuits, considering the domain of discretized interest in three spatial dimensions. A finite volume scheme with centered cells was used, all analyzes governed by the principles of classical thermodynamics and heat transfer were appropriately applied.

Thus, with these physical analyzes it is possible to elaborate a model with ordinary differential equations in relation to time. Thus allowing quantification of the energetic interactions between cells in relation to time and space, observing temperatures and relative humidity to delimit the mesh existing empirical and analytical correlations are used to obtain physical quantities necessary for the model to converge.

Then this form described to address these types of problems was characterized as a reduced order three-dimensional dynamic model, which was called the volume element model (MEV) proposed by Vargas et al. (2001).

Sage (1992) already mentioned that the commonly used design tools do not consistently meet the need, so there are methods that can only address the most relevant factors of the project and that will have the greatest impact on the final result.

The MEV seeks to combine interdisciplinary methodologies already dominated in order to design a model of reduced order, intermediate, maintaining a reliability and satisfactory accuracy to assist in the initial development of projects, in this way it is possible to obtain preliminary analyzes without the need of large computational capacities or high processing time (VARGAS; ARAKI, 2016).

### 3. METHODOLOGICAL PROCEDURES

Initially it is important to know the functioning of the system under analysis, to understand the physical phenomena involved in order to be able to relate in the mathematical model only the factors that really affect the result. The dimensions of the telecommunications cabinet were measured and later modeled using SolidWorks software, the generated file was converted to .vtk, thus allowing computational mastery. Figure 2 demonstrates SolidWorks modeling of the system being analyzed.

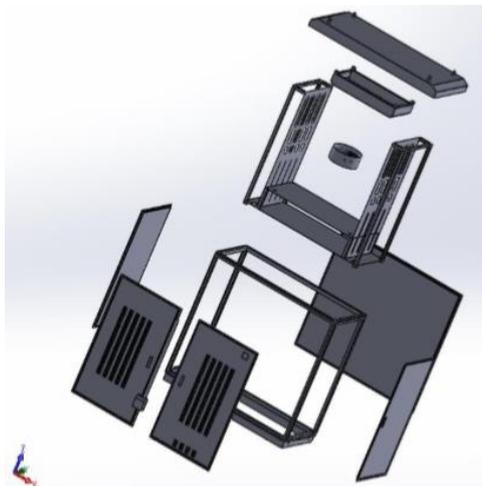


Figure 2 - Telecommunications cabinet - Exploded view. Source: The author (2017)

In the cabinet used, the cooling system basically consists of controlling an air flow coming from the outside of the cabinet, where due to the suction of two fans, it comes in contact with the faces of the heated electronic components, thus occurring the exchange of heat by convection predominantly. Then the air is blown out. The fans each have a flow of  $860\text{m}^3/\text{h}$  and a power of  $56\text{W}$   $48\text{V}$ , and dimensions of  $190\text{mm}$  in diameter and  $69\text{mm}$  in height.

The air flow can be controlled from 30% to 100% by changing the momentary flow rate of the fans. The flow of air is shown in Figure 3, where cold air enters the front cabinet doors (blue arrows) and hot air is evacuated from the upper side (red arrows).

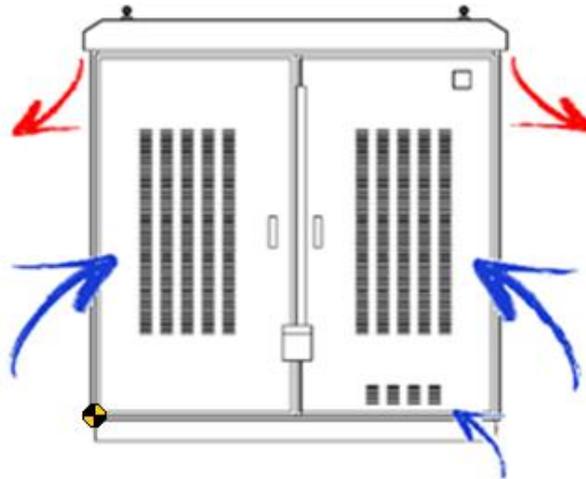


Figure 3 – Cabinet airflow. Source: The author (2017)

In order to obtain a mathematical model, the volume elements method was used. Then the telecommunications cabinet was divided into volume elements, with the purpose of applying the 1st Law of Thermodynamics with mass and energy equations for each volume element, and also, if necessary, other algebraic equations. In this way obtaining a thermal and psychometric response of the system.

#### 4. MATHEMATICAL MODEL

Initially it is important to understand the separation of the system into volume elements. For this, Figure 4 expresses a volume element with square geometry (DILAY et al., 2014), can also be rectangular if necessary, this depends on the analysis of the modeler, however in both situations each volume element contains six faces of interaction.

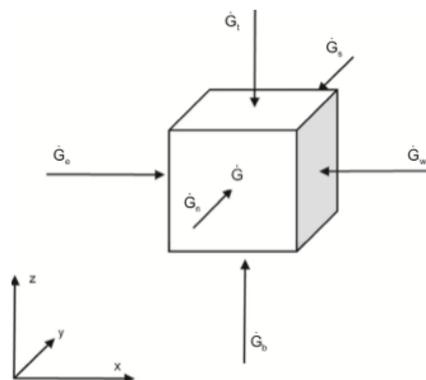


Figure 4 – Typical volume element with interaction rates with neighborhood. Source: Dilay et. Al., (2014)

Then, based on the first law of thermodynamics.

Modeling for a single volume element and taking into account the term source  $G$ , we obtain the following conservation equation of mass, energy, species, etc. (DILAY, 2014).

$$\frac{d(\rho VT)_i}{dt} = \sum_{j=e,w,t,b,n,s} \dot{G}_{j,i} + \dot{G}_i \quad (1)$$

The left side of the equation represents the accumulation, which is responsible for advancing the solution in time, in transient cases, then the term  $t$  represents the time,  $\rho$  expresses the density,  $V$  the volume. The term  $G$  can refer to other contributions as shown below.

$$\dot{G}_{j,i} = \dot{G}_{adv,j,i} + \dot{G}_{dif,j,i} \quad (2)$$

The first contribution  $G_{adv}$  represents advective terms, ie, convection, and  $G_{dif}$  expresses the diffusive terms, being this, conduction. There is still the possibility of other types of interaction as the example of radiation, in this case, this portion of energy must be represented together with the term of diffusive.

Rearranging equation (1) with the considerations of (2):

$$\dot{G}_{adv,j,i} = \alpha_{j,i}(\dot{m}_{E,j}T_j - \dot{m}_{S,j}T_i) \quad (3)$$

Equation (4) is the balance of the diffusive flows:

$$\dot{G}_{dif,j,i} = \dot{G}_{other,j,i} + A_j \Gamma_j^0 (T_j - T_i) \quad (4)$$

If radiation interaction is required, equation (5) represents this term. Where  $A$  represents the area in this equation. It is enough to replace the term "other" source of equation (4) with equation (5).

$$\dot{Q}_{rad,i,j} = A_{i,j} \{ \alpha_j I - \varepsilon_j \sigma (T_{i,j}^4 - T_{ext}^4) \}, \quad j = e, w, n, s, t, b \quad (5)$$

The first term in the brackets represents the portion of the average solar radiation absorbed by the face of the EV in this case where there is solar incidence,  $\alpha$  and  $\varepsilon$  are consecutively the absorptivity and emissivity of the EV face under analysis,  $\sigma$  represents the Stefan-Boltzmann constant, and to the area on the face of EV  $A_{i,j}$ . It is considered that  $I = 0$  in cases where the face of the EV is in contact with some material that blocks the transfer of heat by radiation.

It is important to highlight one more characteristic of the volume elements method, it consists in the possibility of coexisting three types of elements in a same computational domain, thus allowing to consider the EV as solid, fluid or even the mixture of the two, with all interacting within of the same computational domain. Therefore it is possible to understand that there may be three types of volume elements, which result in up to six possible interactions between the elements, and there are still three other interactions expressing EV. with the border. Figure 5 illustrates this.

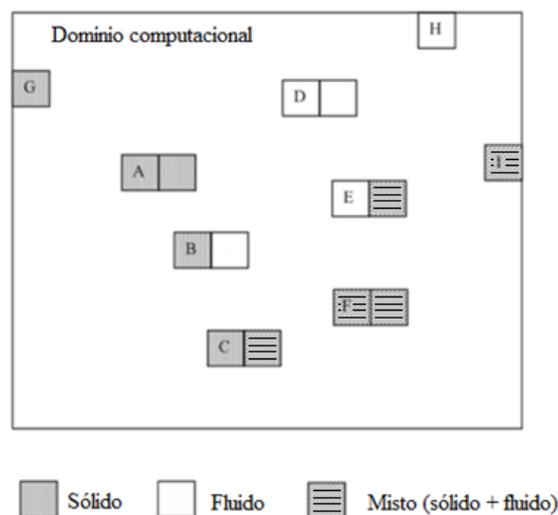


Figure 5 – Types of ev. and its possible interactions. Source: Adapted from Dilay et. Al., (2014)

To refine the mesh, we use equation (6), this equation the term  $var_i$  sets up each unknown of the system (DILAY, 2013). This equation makes it possible to create a mesh capable of converging with greater accuracy. This equation provides a form of refinement, basically after the modeler defines the first mesh, it must generate an even more refined

second mesh so that it is possible through the equation to observe if the tolerance was less than or equal to 1%, when it does not reach, it is enough to continue refining the mesh and analyze the results through equation (6).

$$\varepsilon_{\text{mesh},i} = \frac{|\|\text{var}_i\|_{\text{mesh1}} - \|\text{var}_i\|_{\text{mesh2}}|}{\|\text{var}_i\|_{\text{mesh1}}} \leq 0.01 \quad (6)$$

Observed more specifically the mathematical model for the proposed theme, it is known that the model is based on the first Law of Thermodynamics. So in this case it is necessary to satisfy mass conservation, so the flow is determined by the flow rate of the fans. Then it is also necessary to calculate the initial vapor pressure in the EV, for this we have the equation (7) below:

$$p_{V,i} = \varphi_{i0} \cdot p_{VS}(T_{i0}) \quad (7)$$

$p_{VS}(T_{i0})$  represents the saturation pressure of water at temperature ( $T_{i0}$ ). For the absolute humidity in each volume element it is assumed that it remains approximately constant. However the relative humidity in the EV is described according to the following equation (8):

$$p_{V,i} = \varphi_{i0} \cdot p_{VS}(T_{i0}) \quad (8)$$

In equation (8)  $p_{VS}(T_i)$  indicates the water saturation pressure in the EV at the temperature  $T_i$ . For solid EVs, fluids, or a mixture of both, relative humidity is set to zero, that is,  $\varphi_i = 0$ .

Following more in depth equation (9) represents the total heat transfer rate (radiation (if any), conduction and convection) in each face element.

$$\dot{Q}_{i,j} = \dot{Q}_{\text{rad } i,j} + U_{i,j} A_{i,j} (T_{\text{ext}} - T)_i, \quad j = e, w, n, s, t, b \quad (9)$$

Equation (10) is used to find the global heat transfer coefficient  $U_{i,j}$ .

$$U_{i,j} = \frac{1}{R_{i,j}} \quad (10)$$

With the  $R_{i,j}$  for solid element given by equation (11),

$$R_{i,j} = \frac{l_{i,j} / 2}{k_i} + \frac{t_w}{k_w} + \frac{1}{h_{\text{ext}}} \quad (11)$$

E in Equation (12) for fluid element:

$$R_{1,i} = \frac{1}{h_{\text{int}}} + \frac{t_w}{k_w} + \frac{1}{h_{\text{ext}}} \quad (12)$$

Where  $l_{i,j}$  expresses the width or length of the EV,  $k_i$  represents the thermal conductivity cell,  $t_w$  and  $k_w$  is the wall thickness and the thermal conductivity, respectively,  $h_{\text{int}}$  and  $h_{\text{ext}}$  indicate the convective heat transfer coefficient by convection internal and external.

The coefficient  $h$  of heat transfer is written in the equation below:

$$h = \frac{k_f}{H} \left\{ 0.825 + \frac{0.387 \cdot Ra_H^{1/6}}{[1 + (0.492 / Pr)^{9/16}]^{8/27}} \right\}^2 \quad (13)$$

Where  $k_f$  represents the thermal conductivity of the fluid,  $Pr$  is the Prandtl number of the fluid,  $Ra_H = (g\beta / \alpha_T \nu) H^3 |T_{\text{neigh}, i} - T_i|$ ,  $g$  indicates the acceleration of gravity,  $\beta$  the coefficient of volumetric expansion of the fluid,  $\alpha_T$  represents the thermal diffusivity of the fluid, since  $\nu$  is the kinematic viscosity of the fluid;  $T_{\text{neigh}, i}$  is the temperature of the neighboring EV or the temperature at the boundary with the exterior of the system,  $H$  is the total height of the solid EV under analysis. Equation (13) is valid for all lamellar, transition Rayleigh number ranges, and for turbulent fluid properties as evaluated at film temperature, has:  $T_{\text{film}} = (T_{\text{neigh}, i} + T_i) / 2$ .

However when the EV is in contact with another EV, there are other considerations. In thermal systems the absence of flow at a fluid / fluid boundary in the horizontal direction is assumed when it is only natural convection, thus, flow is only in the vertical direction. With forced convection, the possibility of cooling through a transverse flow is admitted in

the model, being in the direction of the forced flow, estimated approximately by a velocity field. For forced convection the following equations are used:

$$h = \frac{k_f}{L} (0.064 \text{Pr}^{1/3} \text{Re}_L^{1/2}), \text{ para } \text{Re}_L < 5 \times 10^5 \quad (14)$$

$$h = \frac{k_f}{L} \{0.037 \text{Pr}^{1/3} (\text{Re}_L^{4/5} - 23,550)\}, \text{ para } \text{Re}_L < 5 \times 10^5 \quad (15)$$

Having  $\text{Re}_L = v_f L / \nu$ , where  $v_f$  is the fluid velocity,  $L$  is the length of the EV under analysis.

## 5. RESULT AND DISCUSSION

Some data packets have been developed. One with heat dissipation at 1600 W and airflow velocity in the cabinet cross-section was 0.142 m / s. Another with 3000 W and air velocity of 0.284 m / s, plus one with power set at 4225 W and air flow velocity was 0.569 m / s.

In the figure below the telecommunications cabinet is divided into four symmetrical parts that gave rise to three cut points, after the cuts made in the x axis the resulting image is folded (1st dihedral) next to the front image of the cabinet, allowing a greater detailed view two thermal gradients. In Figure (6), the measured data package at 1600W and air flow velocity of 0.142 m / s are shown.

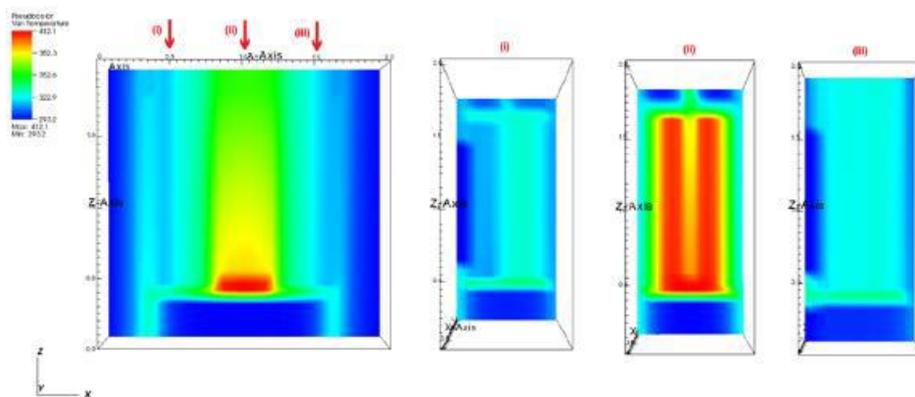


Figure 6 - Computational simulation 1600 w (x cuts). Source: The author (2018)

All the air intakes in the filters and the exits by the fans meet the law of conservation of mass, they are five points of entrance of air defined in the mathematical model, also it is physical system. Finally, it is possible to verify in the figure the air flow and the thermal gradients in a satisfactory manner, respecting in a similar way the one found in the real model. However the thermal propagation on the x-axis did not occur as expected.

As expected, temperatures near the ends of the system are lower than the temperatures in the center of the cabinet (MENG et al., 2015).

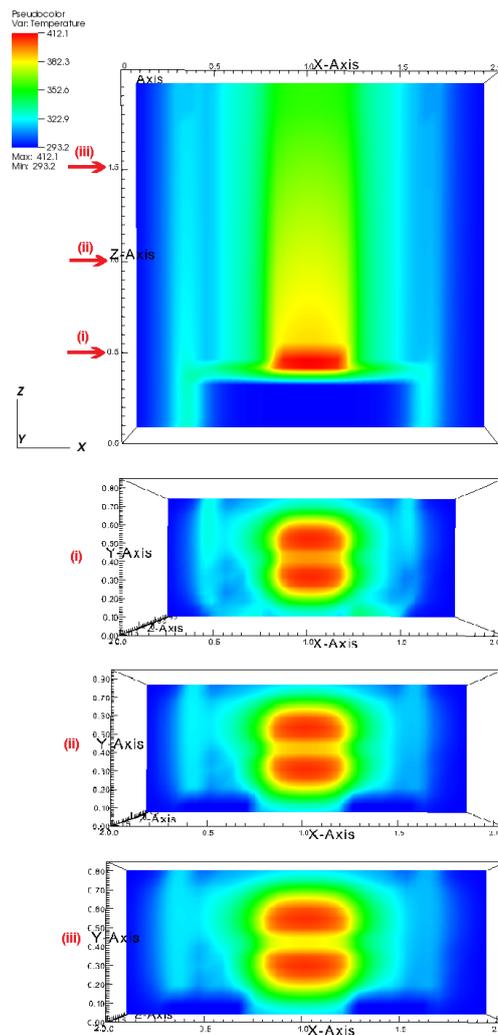


Figure 7 - Computational simulation 1600 w (y cuts). Source: The author (2018)

On the sides where there are metal plates that prevent the flow of hot air, the temperature does not change significantly.

The thermal progression occurs from the center of the electric resistance to its surroundings, with the highest rate being attracted by the fans at the top (RIGATTI; VARGAS; BALMANT, 2017).

## 6. CONCLUSION

In this work, a numerical study was carried out to obtain a computational tool for simulation of thermal management capable of providing fast answers with satisfactory accuracy for studies in systems engineering.

It is concluded that the proposed mathematical model can be used as a solution for the simulation of thermal management in refrigerated telecommunications cabinets with forced ventilation, guaranteeing precision and low computational time. However the model still needs to be improved to contemplate the thermal propagation in the x axis in relation to the displacement in the y axis, thus reducing the error between the answers that were above the 5% considered ideal.

Correcting the propagation in the x-axis, it will be possible to contemplate the highest temperature in the region of the top of the telecommunication cabinet, which is expected, since the heated air undergoes expansion thus becoming in less density than the cold air thus remaining in the higher regions, phenomenon of heat accumulation. One way to adjust this point is to define  $u_x = u_x(z)$ , where  $u_x$  is the velocity in the direction perpendicular to the telecommunications cabinet depending on the vertical component  $z$ . The same is being prepared for future work.

Finally, this tool was effective for the proposed study, it is possible to take advantage of it even more, to the example of performing optimizations in the system, an example is to find the best physical geometry of the telecommunications cabinet aiming maximum transfer of heat due to its design.

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