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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 weather 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 useful life and efficient 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, which can be tools used to analyze this problem even in the design phases. Therefore, the objective of this work is the mathematical modeling and the simulation of a metal cabinet that holds 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), which generates a mesh with a system of first order ordinary differential equations, where the independent variable is time. The simulations of the model described the expected results in practice. The objective is to aggregate information to transform this methodology as a tool for simulation and optimization of the thermal profile of electronic packaging systems.*

Keywords: *Mathematical Modeling. Volume Element Method (Sem). Simulation. Cabinet. Electronic Equipment.*

1. INTRODUCTION

The telecommunications cabinets are metallic equipment, which include electronic devices responsible for the reception and transmission of telephone signals. Its objective is the electrostatic protection and also of the climatic intempéries where these systems are located. However, the electronic equipment in these cabinets dissipates energy in the thermal form due to the Joule effect, which is an aggravating factor for the useful life and efficiency of these equipments. Figure 1 shows the cabinet used in this study, with maximum dimensions of 2048x1974x850mm, the airflow is forced by two fans located at the top and with a unit capacity of 860m³h⁻¹.

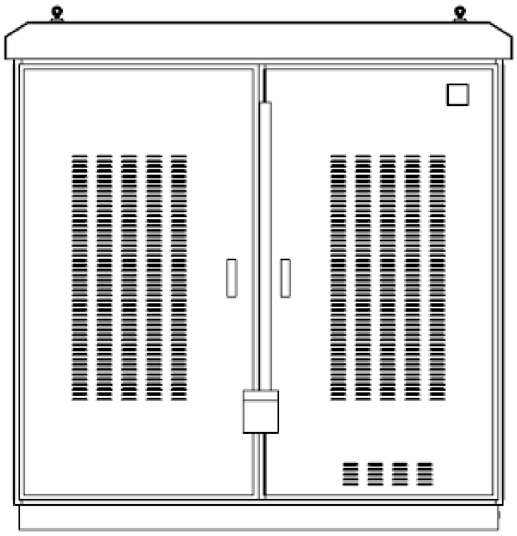

Figure 1 - Illustration of the Telecommunication cabinet - Front View. Source: The author (2017)

This generation of heat and consequent increase of temperature end up making difficult the maximum use of the physical space of the closet. Currently, the concept of telecommunications network management has been changing. Before, there were small groups of cabinet with a large number of users per cabinet, today the trend is to reduce the number of users per cabinet by increasing the number of cabinets (CAMPOS, 2004). Possibilitanto more personalization in the service offered to the client. Therefore, this higher number of cabinets requires high thermal efficiency so that they can have a smaller size and also operate closer to each other.

One way to approach the problem of heat dissipation and consequently the thermal efficiency of the cabinet is through mathematical modeling and computational simulation. This requires a correct understanding of the system's temperature profile. However, these problems are usually addressed in a complicated way with methodologies that result in complex partial differential equations, thus causing a demand for processing time when using software capable of solving such equations. This need for big times and high cost makes it difficult to use these methods.

With this, there is a need for more simplified simulation tools that provide answers with acceptable precision and small computational time allied, in the case of thermal systems, to a thermal management model with the objective of providing the temperature profile through a mathematical model.

However, the correct understanding of the particularities involving physical phenomena is essential for the modeler to achieve success. The precise knowledge of the temperature field of the equipment is also fundamental for the control of thermomechanical voltages, since the uncontrolled voltages are extremely damaging to the equipment (DILAY, 2013). It is also known that poor thermal management can, of course, lead the system to an unexpected response and even in the latter case mechanical or electrical failure (SOMAN, 2009).

In addition to temperature control, relative humidity control is essential. It is known that water is harmful to electronic equipment, for reasons already known as oxidation, more likely to short circuit, since water offers less electrical resistivity than air. It is also worth noting that heat transfer is analogous to electrical conductivity.

In high temperature environments coupled with high relative humidity (tropical countries), they require not only temperature control, but also the control and monitoring of the relative humility within these equipment, with smaller electronic packaging designs and low cost comes being studied (CAMPOS, 2004). It is always necessary to predict the conditions of operation of the equipment by calculating the temperature and relative humidity field, so that adequate parameters can be maintained (VARGAS; ARAKI, 2016).

2. VOLUME ELEMENTS MODEL

For the development of mathematical modeling, the Volume Element Method (VEM) was used. This way of approaching the problem was characterized as a reduced order three-dimensional dynamic model and was called the Volume Element Method (VEM) proposed by (VARGAS et al., 2001).

Mathematically, it is necessary to obtain a simple model, which does not require much computational effort, but which is able to provide satisfactory answers with acceptable accuracy. One way to achieve this is through the Volume Element Method (VEM) (DILAY, 2013). In this method the system is discretized in volume elements with constant properties along every element. Thus, the objective of this work is to simulate the thermal dissipation of a telephony enclosure using the (VEM) through the energy balance of the system using the first law of thermodynamics.

However mathematical models can be approached according to their classification, they are classified as high order and low order. High order models provide good precision of response, but result in complex mathematical models that have dependence on two variables in their main equations. On the opposite side are the low order mathematical models, dependent on only one variable, which are simple but bad in the accuracy of the result. High order models are based on partial differential equations (SHAPIRO, 2003). The low order models are based on generally ordinary differential equations (VARGAS, ARAKI, 2016). It can be seen in Figure (2) the relationship between the accuracy that the mathematical model offers in relation to its size. It is evidenced that in high order models growth in relation to the size of the mathematical model is greater than the increase of precision. Reduced-order models have better efficiency compared to their size or complexity.

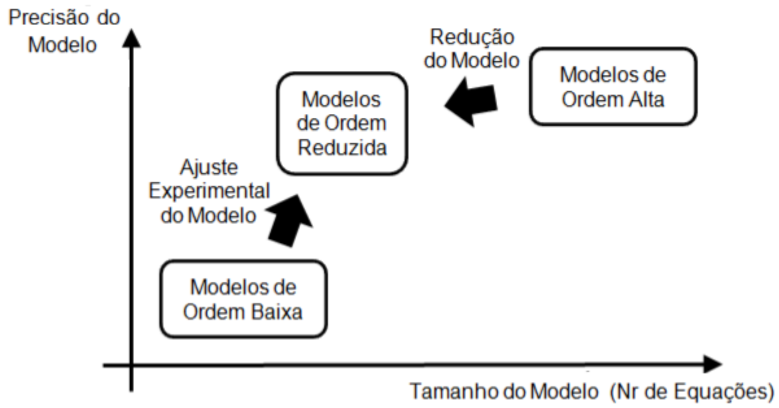

Figure 2 - Relation between Precision and Size of Mathematical Model. Source: Adapted from Shapiro (2003)

Therefore, a good way to approach the problem without great complexity, but with a satisfactory answer is to obtain mathematical models of reduced order, or intermediate, located between the high and low order.

The method discussed in this article makes use of reduced-order mathematical models. This method generates equations that depend only on one variable, however it is also considered the second variable, but it is pointed out manually and not disregarded as in simpler models. In this way, they obtain good precision together with a simplified model.

The volume element method (MEV) then proposes the realization of simulations through mathematical models with ordinary differential equations that do not depend on space. Among the important characteristics of the Volume Element Method, there is one of them that must be evidenced as well, it is the possibility of coexisting three (03) types of elements in the same computational domain, that is, it is possible to consider the EV as being solid, fluid and still the mixture of the two, and all EV interact within the same computational domain in use. Thus, it is possible to understand that three (03) types of E.V. can coexist. For the cabinet, only E.V. fluids and solids are considered, and E.V. is not considered as formed by the mixture of solid and fluid.

3. METHODOLOGICAL PROCEDURES

Seeking solution for thermal dissipation through modeling and simulation some tools were used. As a result of the modeling using the (VEM) it became necessary to find software for programming the computational code. In this paper, the software used was Fortran, which enabled the compilation and simulation of the physical system through computational mathematical modeling.

Specifically in Fortran programming, the fourth-order Runge-Kutta adaptive step method was used to simultaneously solve the transient ordinary differential equations resulting from the modeling formulated for each volume element (KINCAID and CHENEY, 1991).

As mentioned above, the set of equations obtained was simulated in the Fortran program code, but the result was only numerical, so to obtain the graphical visualization of temperature and relative humidity in the telecommunications cabinet, the VisIt 2 program was used. specific for transforming the files generated in .vtk format by Fortran into graphic images according to a mesh that was also defined through cabinet geometry.

The SolidWorks program was used to elaborate the 3D model, which assists in the geometric definition necessary for the VisIt 2 program. The resulting graph is generated by VisIt 2 very important for visualization and understanding of the dynamic response of temperature and relative humidity over time.

4. MATHEMATICAL MODEL

For the mathematical model it is important to make some initial considerations that facilitate the elaboration of the same one. As already mentioned, the methodology used is that of the (VEM) that addresses the problem according to the first Law of Thermodynamics and empirical correlations if necessary. Some terms of the first Law of Thermodynamics can be disregarded already in the initial hypotheses, for example, it was not considered the potential energy variation in the system because the cabinet has a small size and therefore the height variation is insignificant, also it is observed the velocities are low, then zero kinetic energy is assumed. When it comes to the physical system, there is no change of heat between the cabinet and the external surroundings since the walls of the cabinet are doubled to provide the insulation.

With some hypotheses already assumed, the mass and energy balance is initially executed:

$$\frac{dm_{vc}}{dt} = \dot{m}_e - \dot{m}_s \tag{1}$$

In equation (1) we have the mass balance, the term (dm_{vc}/dt) on the left side represents the mass accumulation according to the mass variation that occurs on the right side of the same equation. Specifically ($\dot{m}_e$) represents the rate of mass entering the system and ($\dot{m}_s$) the mass rate that is coming out of the system.

After correlating the mass balance the energy balance is elaborated, but before starting the modeling for energy it is interesting to make the consideration where the enthalpy is represented by the following equation:

$$h = cp.T \tag{2}$$

Where the term (h) of enthalpy can be written by the product of specific heat at constant pressure (cp) and temperature (T), thus, the following energy balance is written:

$$\frac{dE_{vc}}{dt} = \dot{Q}_{ger} + \dot{m}_e.cp.T_e - \dot{m}_s.cp.T_s \tag{3}$$

Where in equation (3) the term (dE_{vc}/dt) represents the accumulation of energy and ($\dot{Q}_{ger}$) is the rate of heat generation.

The accumulated energy can still be considered as in the following equation:

$$E_{vc} = m.T.c \tag{4}$$

The accumulated energy being represented by the product of the mass (m) by temperature (T) and specific heat (c). In this way, we rewrite equation (3) as a function of temperature, which is the main objective.

$$\frac{dT_1}{dt} = \frac{\dot{Q}_{ger} + \dot{m}_{1e}.cp.T_{amb} - \dot{m}_{1s}.cp.T_1}{m.cv} \tag{5}$$

This results in equation (5), already defined (dT_1/dt) as the variation of temperature in time and the term (cv) represents the specific heat at constant volume, since there is no change in volume inside the cabinet. We can even detail the term of generation, it can be replaced, since it is already known the mechanism of generation, in this electric case, then:

$$\dot{Q}_{ger} = \frac{V^2}{R} \tag{6}$$

(V) depicts the electrical voltage and (R) the electrical resistance offered by the component. Rewriting (3):

$$\frac{dT}{dt} = \frac{\frac{V^2}{R} + \dot{m}_{1e}.cp.T_{amb} - \dot{m}_{1s}.cp.T_1}{m.cv} \tag{7}$$

Equation (7) is ready to be applied to fluid (air) type volume elements, the most common in this type of system.

For solid E.V., there is no mass transfer, so the mass balance equation is zero. In the same way, the energy balance equation will not have the mass terms, leaving only the generation term that will also represent the heat transfer, as follows:

$$\frac{dE}{dt} = \dot{Q} \tag{8}$$

Rewriting equation (8) by observing the heat transfer rates by convection and conduction has the following equation:

$$\frac{dT}{dt} = \frac{\{[h_{ar1}.A(T_{ar1} - T_{sólido}) - h_{ar2}.A(T_{sólido} - T_{ar2})] - [K.A(T_{sólido} - T_{sólido2})/L - K.A(T_{sólido3} - T_{sólido})/L]\}}{m.c} \tag{9}$$

Equation (9) finally writes elements of solid volumes. (h_{ev}) is the convection term that can vary from E.V. (K) the conduction term, (A) expresses the related area and (L) the length of the analyzed object. It is possible to notice that the temperature of the element of volume "solid" is also objective, since all equation is in function of (dT/dt). As is characteristic of the method, each E.V. in question is in contact with other E.V. being they solid or air. The adjustment must be made according to the neighborhood of each E.V. under analysis.

As well as in cases of radiation incidence, the radiation term by the incidence area should be considered, in this case we would have equation (9) rewritten below to be able to carry heat transfer also by radiation:

$$\frac{dT}{dt} = \frac{\{I_0.A - [h_{ar1}.A(T_{ar1} - T_{sólido}) - h_{ar2}.A(T_{sólido} - T_{ar2})] - [K.A(T_{sólido} - T_{sólido2})/L - K.A(T_{sólido3} - T_{sólido})/L]\}}{m.c} \tag{10}$$

The term (I_0) expressing the radiation that is incident.

However, fan flow can be calculated by dividing the total volume (V) by the total free area of the flow.

Table (1) brings together the terms and their respective definitions of the equations quoted above, in order to facilitate interpretation.

Table 1. Definition of the terms of the equations.

Term	Definition
$\frac{dM_{vc}}{dt}$	Total Mass Variation Time
$\frac{dE_{vc}}{dt}$	Total Energy Variation Time
$\frac{dT}{dt}$	Temperature Variation in Time
$\dot{m}_e$	Entering Mass Flow, kg/s
$\dot{m}_s$	Outgoing Mass Flow, kg/s
H	Enthalpy, KJ
c	Specific Heat, J/kg.K
cp	Constant Pressure Specific Heat, J/kg.K
cv	Constant Volume Specific Heat, J/kg.K
T	Temperature, K
$\dot{Q}_{ger}$	Heat Transfer Rate, W
V	Electric tension, Volts
R	Electrical Resistance, W
h	Coefficient of Convection Heat Transfer, W/(m².K)
A	Area, m²
K	Thermal Conductivity of Material
L	Length
I_o	Radiation Incidence

The following figures demonstrate the main parameters used during programming, these data define the necessary conditions for the physical system, that is, design parameters and also the parameters of operation of the equipment. Below figure (3) relates the environmental variables and initial conditions.

Table 2 - Environmental variables and initial conditions. Source: Vargas J.V.C. (2016)

ENVIRONMENT VARIABLES------------------------------------		
0	! vair = external air velocity	[m/s]
293.15	! tground = groud temperature	[K]
293.15	! tpair = external air temperature	[K]

INITIAL CONDITIONS--		
293.15	! tp0 = Initial temperature	[K]
293.15	! tpoute = Initial temperature of the external wall EAST	[K]
293.15	! tpouts = Initial temperature of the external wall WEST	[K]
293.15	! tpouts = Initial temperature of the external wall SOUTH	[K]
293.15	! tpoutn = Initial temperature of the external wall NORTH	[K]
293.15	! tpoutt = Initial temperature of the external wall TOP [K]	
0.8	! hum0 = initial relative humidity	

Table (3) then expresses the physical properties determined for this system:

Table 3 - Physical properties of the system. Source: Vargas J.V.C. (2016)

PHYSICAL PROPERTIES---------------------------------------		
1.165	! rhoair = air density	[kg/m^3]
9.07e+07	! gban = air property combination for natural convection (DO NOT CHANGE)	
700	! cvair = Specific heat at constant volume for air	[J/kg.K]
1000	! cpair = Specific heat at constant pressure for air	[J/kg.K]
0.026	! rkair = Thermal conductivity of air	[W/m.K]
100	! rkwall = Thermal conductivity of the wall	[W/m.K]
2e-05	! visair = dynamic viscosity of air	[Pa.s]
0.72	! pr = Prandtl number for air (momentum/thermal)	
0.9	! alf = wall absorptance (entre 0 e 1)	
0.9	! epsi = wall emittance (entre 0 e 1)	
2700.	! rhoal = Wall material density	[kg/m^3]
910	! cal = Wall material specific heat	[J/kg.K]

5. RESULT AND DISCUSSION

The mathematical model elaborated through the (VEM) was constituted by 27000 elements of volume, each E.V. interacts with its neighborhood, that is, it interacts with the E.V. that are around it, this is a characteristic of the (VEM). The purpose is to obtain several elements delimited by the modeler that can interact with the neighboring elements in contact with their faces (DILAY, 2015).

The responses of the temperature gradient and relative humidity demonstration within the telecommunication enclosure, resulted in simulations with features equitably the actual response.

The figure (3) shows in blue all the air inlets that provide the mass flow inside the cabinet. Note that all entries respect the dimensional coordinates of the filters located on the cabinet doors. In the red color there are the areas of exit of the mass of air, which occurs at the top of the cabinet, also called "hat", at the same time, the mass of air coming out, carries with it a portion of energy released by heating inside the so the mass of air in the outlet has a higher temperature than in the inlet.

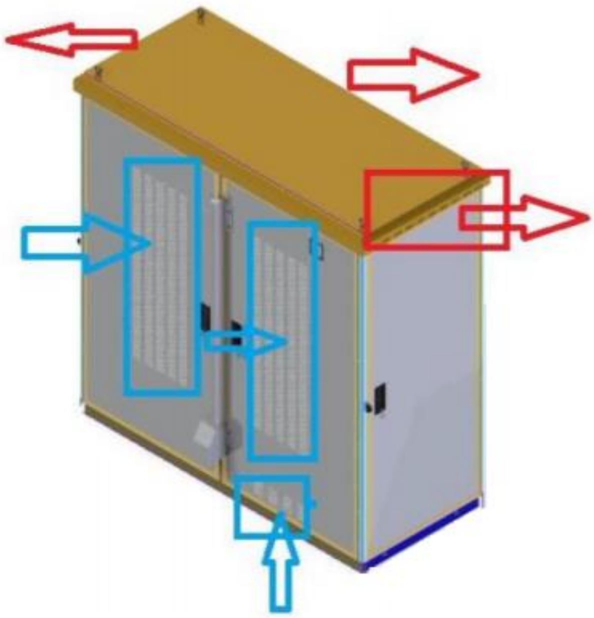

Figure 3 - Location of cooling air inlets and outlets. Source: Peixoto P.H.R., Rigatti L.F. (2016)

The temperature inside the cabinet can be seen graphically below in figure (4). The thermal progression occurs from the center of the electrical resistance to its surroundings, with the highest rate being drawn by the fans to the top, from which heated air leaves the cabinet. Just as found in the real model.

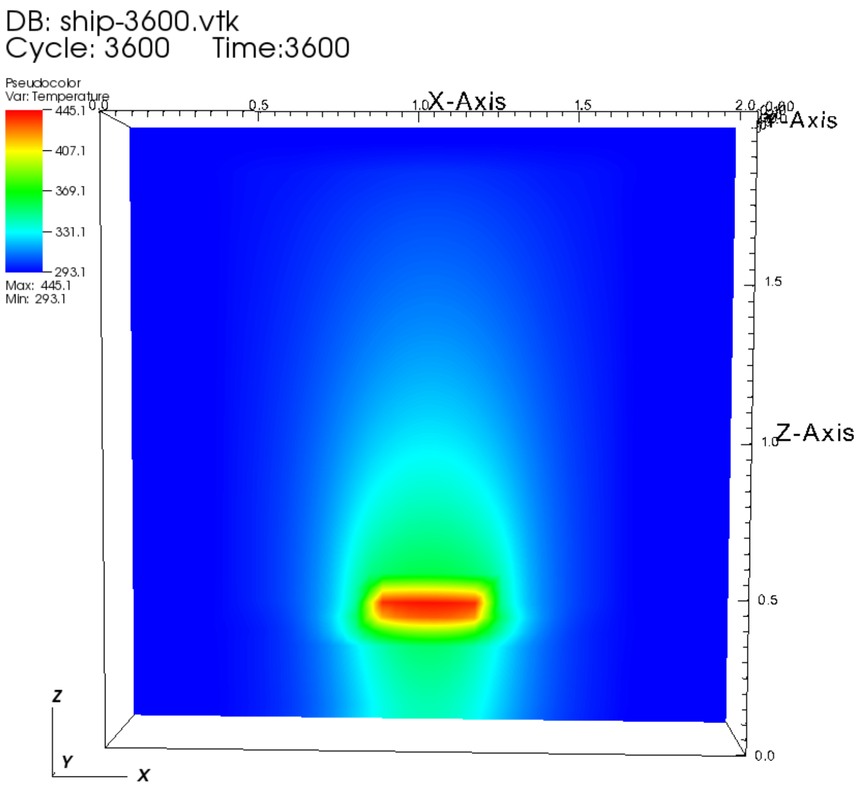

Figure 4 - Thermal Simulation - Temperature Data. Source: The author (2017)

The simulation expressed in figure (5), refers to the relative humidity inside the cabinet. It can be observed that in the center of the "x" axis and shifted below the center of the "y" axis we have the point of less relative humidity and also higher temperature, this is because it is exactly where the Cartesian coordinates of the source of heat. The heat source is shown in figure (6), which shows the exploded view of the cabinet, in this way it is possible to observe the internal components, the electric resistance has a circular geometric shape and is marked in red in figure (6), such is the heating element.

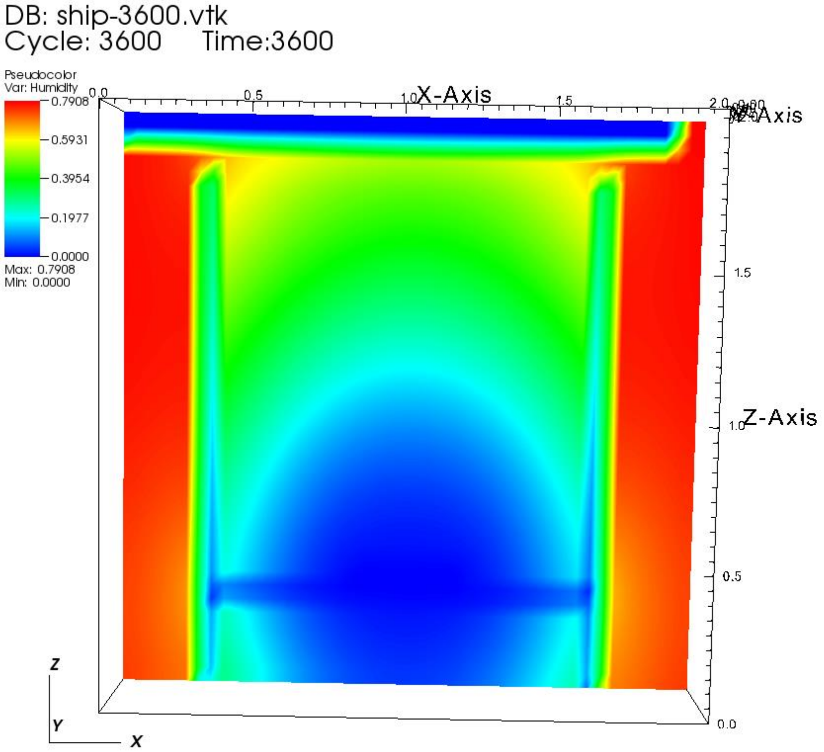

Figure 5 - Thermal Simulation - Relative Humidity Data. Source: The author (2017)

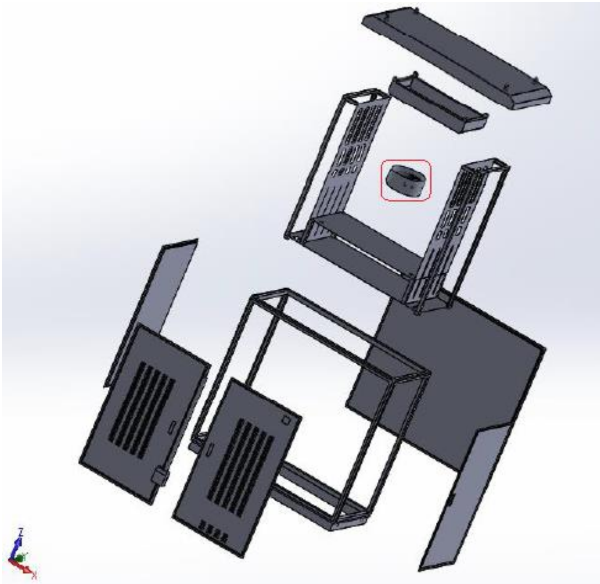

Figure 6 - 3D Modeling of the Telecommunication Cabinet - Exploded View. Source: The author (2017)

6. CONCLUSION

It has been presented in this article a way to approach problems of thermal dissipation in telecommunications cabinets, in order to maximize the heat transference in order to reduce the internal temperature of the cabinet, using the method of volume elements.

With this methodology was obtained ordinary mathematical equations facilitating the simulation in computers. It was possible to observe that the mathematical model obtained satisfactory answers according to the experimental validation. Making this type of approach a strong candidate for simulations in the early stages of projects where time is a determining factor for the success of the product and often the investment is still a decisive factor, yet it can be said that the method is also satisfactory in later applications, where a fast approach is required and with acceptable accuracy.

In compiling the simulations and relating the facts mentioned above, it is concluded that this method can be applied in telecommunications cabinets in both the design and the operation phases.

7. ACKNOWLEDGEMENTS

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