19th Brazilian Congress of Thermal Sciences and Engineering
November 06th-10th, 2022, Bento Gonçalves - RS - Brazil

ENC-2022-0373
MODELING AND SIMULATION APPLIED TO THE THERMAL MANAGEMENT OF ELECTRONIC SYSTEMS

Luiz Fernando Rigatti
eng.rigatti@hotmail.com
José Viriato Coelho Vargas
Universidade Federal do Paraná (UFPR)
vargasjvcv3@gmail.com

Wellington Balmant
Universidade Federal do Paraná (UFPR)
wbalmant@gmail.com

André Bellin Mariano
Universidade Federal do Paraná (UFPR)
andrebmariano@gmail.com

Abstract. *Telecommunications systems, computers, server bases often operate inside cabinets. However, if the temperature inside the cabinet is not controlled, the efficiency and life of the equipment will be compromised. This study experimentally investigates the ability of a simplified computational simulation methodology to evaluate the thermal response of electronic packaging cabinets. Mathematical modeling describes a volume element model (MEV), which allows for different phases within the solution domain (eg solid and gas). The physical laws of conservation, empirical and theoretical correlations available, are the basis of the model. In this way, only a set of algebraic and time-dependent ordinary differential equations is needed to obtain the spatial variable of the process (eg temperature), spatial distribution and transient response. Laboratory experiments were performed to adjust the model by solving the inverse parameter estimation (IPPE) problem and to validate the model results. Subsequently, it is possible to simulate the variation in the height of the heat generating source. Fundamentally, it seeks to identify critical temperatures and thus find ideal positions for the heat source. The other important conclusion is that the accuracy and low computational time will ensure the reliability of the model for the design and optimization of the electronic packaging cabinet.*

Keywords: *Cabinets, Simulation, Mathematical Modeling, Temperature, Optimization*

1. INTRODUCTION

Telecommunications cabinets are metallic cabinets used to hold electronic equipment, responsible for the reception and transmission of telephone signals. They are responsible for protecting the components installed inside against any external threat, such as environmental weather and vandalism. Humidity and temperature control must also be maintained under the responsibility of these cabinets. However, these devices dissipate a large amount of heat by the Joule effect, which requires an efficient heat removal system from these metal cabinets, since these devices cannot operate at temperatures above 60 °C.

Currently there is a high demand for telephony services, so the amount of equipment per metal cabinet has increased considerably. This increase in the amount of equipment caused the Joule heat generation to increase significantly inside the case. This makes the cases demand increasingly efficient systems for heat removal, such as heat exchangers, exhaust fans and in extreme cases even air conditioning systems. The addition of these systems considerably increases the production costs of these cabinets. To reduce manufacturing costs when designing the heat removal system, the highest possible efficiency is prioritized. One of the ways to find a heat removal system as efficiently as possible is through mathematical modeling, simulation and optimization of the heat dissipation system. Commonly, these problems are approached in a complex way with methodologies that result in space- and time-dependent equations; for example the CFD, for this it is necessary computers of great hardware capacity. However, even in possession of high-potential computers, only a CFD simulation can take a few hours, so when the objective is the optimization which operates the comparison of the crossing of the various configurations of the design and process variables, there is a scientific problem, because the complete optimization can take days, making it unfeasible.

2. BIBLIOGRAPHIC REVIEW

In this chapter, the theoretical basis necessary to carry out this article will be presented.

2.1 Telecommunication offices and Systems engineering

Telecommunications cabinets are metallic cabinets used to hold electronic equipment, responsible for the reception and transmission of telephone signals. Therefore, they are also responsible for protecting the components installed inside against any external threat, such as climate change, rain, wind, animals, among others. Consequently, humidity and temperature control must also be maintained under the responsibility of these cabinets.

Meng et al. (2015) defines that outdoor cabinets are used to house many forms of electronic equipment, ranging from batteries to telecommunications equipment.

There are two purposes for using metal cabinets, being initially to provide physical storage space and secondly, to protect electronic equipment from adverse environmental conditions. As electronic equipment typically generates considerable amounts of heat when switched on, enclosures need an appropriate thermal management system to ensure acceptable operating temperature (MENG et al., 2015).

Traditionally, engineering problems are treated in a specialized way, where each piece of equipment that makes up a system is designed independently from the rest of the system. For example, on a ship the propulsion turbine is designed independently of the air conditioning system, but when these equipments are conditioned and operate together inside a ship, there is an interaction between these components, as both are operating close to each other and affecting up thermally. To more quickly evaluate the interaction between the components of a complex system, the systems engineering approach can be used.

In the preliminary development phase of a system, it is sought to relate the user's needs and specified functionalities that must be achieved, thus conceiving the project synthesis and the validation stage to address the problem as a whole simultaneously reporting requirements data in a systematic (HONOUR, 1998).

That is why it is worth highlighting that systems engineering uses a set of tools that include modeling and simulation (SAGE, 1992), thus helping to approach the set in an interdisciplinary way, using current tools and methods, making it possible to anticipate results for better understanding of the project already in the project phase. of planning.

2.2 Mathematical modeling and computational simulation

It is understood that mathematical modeling seeks to address the complexity of the system through an adequate mathematical equation that allows a satisfactory representation of the behavior of a physical system during its cycle, steady state, transient or both. Consequently, the mathematical modeling starts with computer simulation, 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 most closely match the established needs (DILAY, 2013).

Currently computers have evolved significantly, however the success of computer simulation still depends on mathematical modeling, in other words, even with excellent computers, the complexity of many systems far exceeds the computational processing capacity, when they are detailed in mathematical modeling. in detail the physical phenomena involved.

Complex systems contain a large number of components; and a mathematical model capable of faithfully representing the phenomena involved turns out to be also complex, thus making computer simulation unfeasible when the objective is to find quick answers (RIGATTI, 2018).

When the time required to evaluate only one configuration of the system under analysis is long, it is possible to conclude that the optimization process via modeling and simulation may be unfeasible. As already mentioned, even with high performance computers, forms of composite analysis in order to analyze physical phenomena within systems engineering, bring a qualitative form that requires less complex equations (VARGAS; ARAKI, 2016).

In view of this problem, whenever the system is too complex, a simplification of the equations of the mathematical model used in systems engineering is necessary, but this simplification must be able to result in adequate quantitative simulations for the system. Having established this, one can then classify types of mathematical models.

2.2.1 Classification of the mathematical 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 predicts response trends, but with low precision of variable locations and absolute values. The quantitative model, on the other hand, predicts response trends and high precision of local values of the variables (WOODS; LAWRENCE, 1997; VARGAS et al., 2001). Or a low or high order model (low order, high order) according to Shapiro (2003), which 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, there is greater precision in the results, but in a way that requires more computational time. Low-order models use partial or ordinary differential equations, the latter of lower order (VARGAS; ARAKI, 2016).

Also a satisfactory way to obtain a model of reduced order is through the estimation of parameters, when the physical system already exists it is possible to collect the experimental data and compare them with those obtained in simulation and from this point to adapt the mathematical model through the real responses, thus facilitating the consideration in the model only of the phenomena that most influence that system.

So reduced-order models combine good response accuracy with simpler mathematical equations than higher-order models. This type of model has been used frequently and with satisfactory results in systems engineering simulations. A reduced-order model reduces the simulation accuracy by only 5%, again compared to higher-order models.

Basically, higher-order models consider a greater number of physical phenomena, and as already reported, they normally use higher-order partial differential equations. Hence the high order name. Evidently, these models present the best accuracies in responses. On the other hand, low-order models are composed of lower-order partial or ordinary differential equations, naturally also from there arises the description of low-order models. Mesh generation and refinement is directly affected by this concept due to the discretization of the system in space. Where there may be dependence on space and time or just on time (DILAY, 2013).

Next, two articles in the literature were analyzed with the objective of verifying the time used during the computer simulation with different types of mathematical model.

With the low-order model, Pasquier and Marcotte (2012) worked with a heat exchanger buried in the ground that was based on a resistance and heat capacity model. In this case, the software used outside of MATLAB and 3000 was the number of interactions made using the Runge-Kutta method. However, due to simplicity, the fluid flow inside the tubes and the variation of the internal convection coefficient were not considered for this model. However, the time required for simulation on a desktop computer was only one second.

More complex for using a high-order model was the work of Tsuzuki, Kato and Ishiduka (2007) who studied high performance heat exchangers in printed circuits. In this case, the number of interactions was also out of 3000. The software used was FLUENT, and the mesh was generated by the GAMBIT software. The κ-ε turbulence model and the SIMPLE algorithm synchronizing pressure and velocity. However, the time required was one and a half days, or approximately 129,600 seconds.

The difference between the time used in the simulation is much greater in the more complex model. So the challenge in this regard is to find a model that is sufficiently capable of presenting satisfactory answers and at the same time simple to the point of not requiring so much computational effort. As previously shown, it is known that it is possible through reduced-order models to achieve this objective, i.e., much shorter processing times and responses with acceptable accuracy with a margin of only 5% of error compared to high-order models.

Among the reduced-order models, the mathematical models that use MEV can be highlighted. Following this methodology in the thermal field 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 investigated simplified physical models in packaged electronic circuits, in which case the domain of interest was discretized in three spatial dimensions. Making use of a finite volume scheme with centered cells as a base, then analyzes governed by the principles of classical thermodynamics and heat transfer were duly applied.

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

This way of approaching the problem was characterized as a reduced-order three-dimensional dynamic model and was named volume element model (MEV) proposed by Vargas et al. (2001).

The (MEV) seeks to combine interdisciplinary methodologies already mastered to form an intermediate, reduced-order model, while maintaining satisfactory reliability and precision to assist in the initial development of the project, contributing to preliminary analyzes without large computational capabilities or high processing time (VARGAS; ARAKI, 2016).

Subsequently, a correct methodology must be approached to start the modeling itself. Fig. 1 represents a logical and temporal way that has been adopted by several researchers in the field of systems engineering (WOODS; LAWRENCE, 1997; VARGAS et al., 2001).

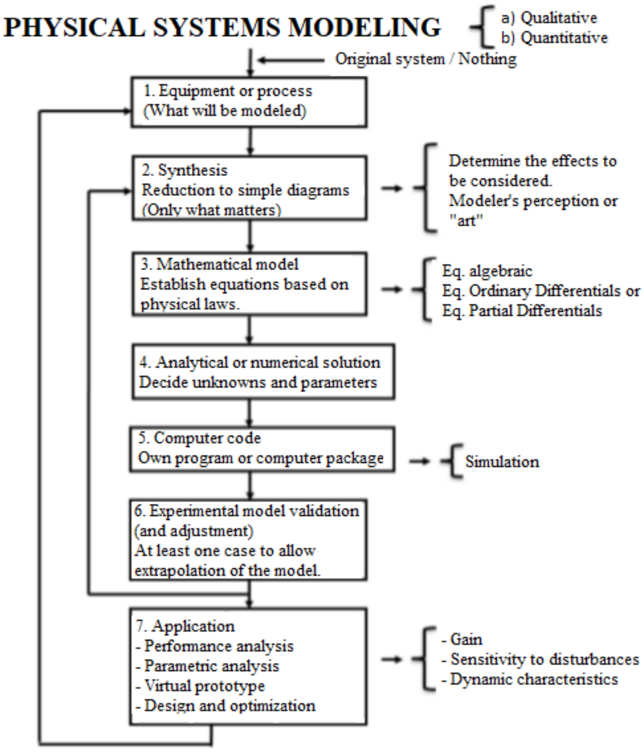


Figure 1. Flowchart for modeling and simulation of physical systems – Source: Adapted Woods; Lawrence, (1997); Vargas et al., (2001)

Understanding that the mathematical model will be solved numerically, it is necessary to choose the computational code by the modeler.

With the transient ODEs formulated for each specific EV, the integration of the equations is then performed simultaneously. At this point, using known initial conditions for the integration variables, the system of transient equations is explicitly time integrated using the fourth-fifth-order Runge-Kutta adaptive step method for solving (KINCAID; CHENEY, 1991).

The time step is automatically adjusted, according to the local truncation error, which must be below the specified tolerance delimited for the case (CAMPOS, 2004).

Subsequently, according to the flowchart presented, and with the model solved, the adjustment and validation phase begins. At this stage, the aim is to verify the accuracy of the results and later the practical use (VARGAS; ARAKI, 2016). Without practical application, the mathematical model would have no use in approaching this thesis.

2.3 Model for thermal management

The problem comes down to calculating the temperature and relative humidity field inside this cabinet (DILAY, 2013). In order to maximize heat transfer to reduce the internal temperature of the cabinet, using the volume elements method (RIGATTI et al., 2017).

For systems where thermal management is involved, the approach shown in topic 2.3 is equally valid to find a model capable of providing the temperature profile, showing again the great variability of application of this type of method. However, the correct understanding of the particularities involving physical phenomena is also no different, only in this way is it possible for the modeler to achieve his goals in any area that he wishes to apply this methodology.

In order to find the maximum global efficiency of an electronics packaging system through computer simulations, reliable thermal models are needed, which allow coherent optimization. Since these types of equipment (eg electronic cabinets) dissipate significant amounts of heat, therefore, system performance is also dependent on these large thermal transients. Therefore, satisfactory thermal management strategies are sought in order to avoid failures resulting from excessive temperature. The correct knowledge of the temperature field of the equipment is essential for the control of thermomechanical tensions, since these are extremely deleterious to the equipment as a whole (DILAY, 2013).

3. METHODOLOGY

The following exposed methodology is necessary to achieve the objective of this article

3.1 Thermal management strategies and production of experimental measurement set in electronic packaging cabinets

The experimental temperature measurements in the telecommunications cabinet were carried out through thermal tests at the Hydraulic Machines Laboratory – LMH. The LMH thermal chamber has dimensions of 3600 mm in length by 1650 mm in width and 2650 mm in height and can operate with a range between 5 °C to 100 °C, national and international standards for such tests will be considered (ETS 300753 , IEC 61587-3, IEC 60068-2-11, ETSI EN 300 019-2-4, EN 300 019-1-4). The standard in the control of the internal temperature of the chamber is guaranteed through the thermal insulation and antechamber, this equipment is also equipped with two air conditioners, one for each environment (chamber and antechamber). In the upper inner part of the chamber, incandescent lamps are installed, which are responsible for simulating the incidence of radiation and also helping to increase the temperature, in addition to electrical resistors responsible for increasing the temperature both outside and inside the telecommunications cabinet, at the coordinates (987.0 mm; 425.0 mm; 615.0 mm), electrical resistances capable of simulating the internal heat generation that electronic equipment generates when energized are installed. View Fig. 2.

The instrumentation is composed of thermal sensors – high precision NTC thermistors $\pm 0.005\ °C$ which work sensitively through the temperature variation, changing the electrical resistance offered at their terminals, NTC thermistors decrease the electrical resistance as the temperature increases.

About the cabinet, which is the object of the test, it was instrumented with 17 thermal sensors - thermistors, enabling the collection of data at specific points of interest.

Figure 2. Thermal chamber (LMH) – Components: (a) Internal air conditioning - (b) Incandescent lamp - (c) Chamber thermistor - (d) Electrical resistance. Source: RIGATTI (2017)

3.2 Mathematical model based on the first law of thermodynamics

The dimensions of the telecommunications cabinet were measured and then modeled with the help of SolidWorks software, the generated file was converted to .vtk, thus enabling the computational domain.
Next, Fig. 3 presents the 3D modeling in an exploded view of the cabinet used to define the mathematical model and limit of the computational domain.

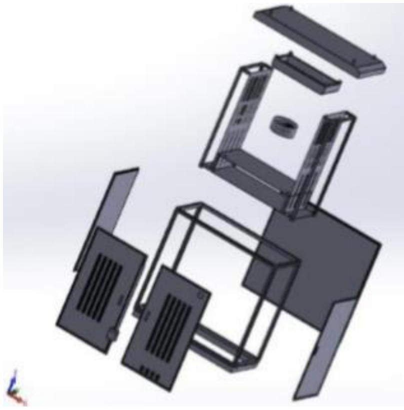
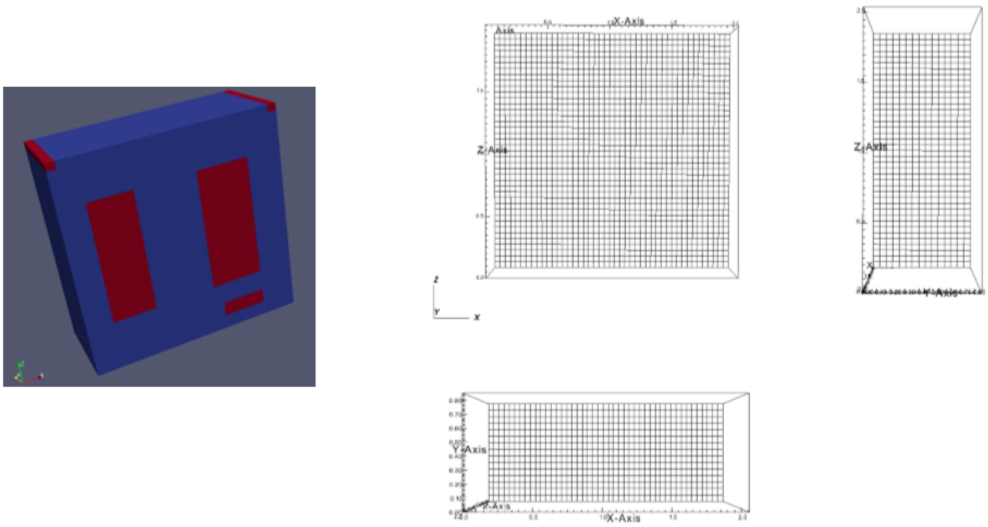


Figure 3. Telecommunications cabinet - exploded view. Source: RIGATTI (2017)

In the aforementioned cabinet, the cooling system consists of maintaining a flow of air coming from the outside of the cabinet, where, due to the suction of two fans, it comes into contact with the faces of the heated electronic components, thus exchanging heat for part of the heated part towards the air, which until then is at a lower temperature. Then the air is expelled out. Each fan has a flow rate of 860 m^3/h, and a power of 56 W 48 V with dimensions of 190 mm in diameter and 69 mm in height, the left fan is located at the coordinates (629.5 mm; 425.0 mm; 1800, 0 mm) and the right fan (1344.5 mm; 425.0 mm, 1800.0 mm) from the point (0.0 mm; 0.0 mm; 0.0 mm) which is located on the front of the case at the bottom left.

It is possible to computationally observe the air inlets and outlets by the generated mesh, as in Fig. 4 the representation of the telecommunications cabinet in blue (a), and in red the air inlet and outlet elements. On the right, of the same figure, we have the computational mesh generation for system (b).



(a) (b)

Figure 4. Telecommunications cabinet - mesh: RIGATTI (2017)

In view of the volume element method, one of its characteristics should be highlighted, which consists of the possibility of coexisting in the same computational domain three types of elements, that is, it is possible to consider the EV as being solid, fluid and still the mixture of the two, where they all interact within the same computational domain in use. Thus, it is possible to understand that there may be three (03) types of volume elements, which result in six (06) possible interactions between the elements, and yet another three interactions that portray the EV. with the border.

Furthermore, another important aspect is the possibility that the method offers to treat the content that makes up the EV as a single homogeneous mixture of substances, and thus calculate, through a weighted average proportional to the mass, the general properties of the EV in a uniform way. Or still, treat this same EV as containing a set of distinct entities, creating subsystems for each entity, separating and applying the equations for each subsystem, since that, for this situation, the same volume element may contain more than one ODE, and the quantity will be limited by the number of subsystems created within the EV with each subsystem being a type of element.

Finally, prudence must be exercised in relation to the mesh to be generated for the system, since this factor directly influences the accuracy of the results and the number of equations in the mathematical model.

When elaborating the mathematical model for systems such as telecommunications offices, using systems engineering, elements of the three types were defined, solid, fluid and mixed, in the last one, a mixture of homogeneous substances in a single phase, and the properties considered uniform. The thermal management challenges in this case are to calculate the temperature and relative humidity fields inside the case. To satisfy the conservation of mass the flow is determined by the flow of the fans, and to calculate the initial vapor pressure in the EV, the following expression is used:

$$p_{V,i} = \varphi_{i0} \cdot p_{VS}(T_{i0}) \tag{1}$$

$p_{VS}(T_{i0})$ represents the saturation pressure of water at temperature (T_{i0}). For the absolute humidity in each volume element, assume that it remains approximately constant. So the relative humidity in the EV can be described, but $p_{VS}(T_i)$ indicates the water pressure in the EV at the temperature T_i. Para EVs sólidos, fluidos ou uma mistura de ambos, a umidade relativa é definida como zero, ou seja, $\varphi_i = 0$.

In the heat transfer rate modeling, empirical correlations are used to find the rates on the faces of the volume element, however, first it must be observed if the EV under analysis is in contact with another volume element or is in contact with the outside, for each situation there are different particularities. For the EVs that have any face in contact with the outside, the transfer by conduction and convection is analyzed, the modeler must verify how the heat transfer occurs at that point. The total heat transfer rate (radiation (if any), conduction and convection) at each element face is calculated next in the equation (2):

$$\dot{Q}_{i,j} = \dot{Q}_{rad\ i,j} + U_{i,j}A_{i,j}(T_{ext} - T)_i, \quad \mathrm{j} = \mathrm{e,w,n,s,t,b} \tag{2}$$

The overall heat transfer coefficient T is elaborated in equation (3) below:

$$U_{i,j} = \frac{1}{R_{i,j}} \tag{3}$$

$$R_{i,j} = \frac{1_{i,j}/2}{k_i} + \frac{t_w}{k_w} + \frac{1}{h_{ext}} \quad (para\ elemento\ sólido) \tag{4}$$

$$R_{1,i} = \frac{1}{h_{int}} + \frac{t_w}{k_w} + \frac{1}{h_{ext}} \quad (para\ elemento\ fluído) \tag{5}$$

The heat transfer coefficient h is shown in equation (6):

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

The term k_f represents the thermal conductivity of the fluid, Pr is the Prandtl number of the fluid, $Ra_H = (g\beta/\alpha_T \nu)H^3|T_{neigh,i} - T_i|$, and g indicates the acceleration of gravity, β the volumetric expansion coefficient of the fluid, α_T represents the thermal diffusivity of the fluid, whereas ν is the kinematic viscosity of the fluid, since ν is the kinematic viscosity of the fluid; $T_{neigh,i}$ is the temperature of the neighboring EV or the temperature at the boundary with the outside of the system, H is the total height of the analyzed solid EV.

In the fluid/fluid interaction condition, also without flow in the horizontal direction, the heat transfer rate is determined with the following equation (7):

$$\dot{Q}_{1,i} = U_{1,i}A_{1,i}(T_i - T_a), \quad 1 = \mathrm{e,w,n,s} \tag{7}$$

The $U_{1,i}$ term is given below in equation (8):

$$U_{1,i} = \frac{k_f}{(1_{m,i}+1_{m,a})/2} \tag{8}$$

When the upper/lower face of the EV is in contact with another EV, it is important to evaluate some considerations that are described throughout the text. As already mentioned before, there can be three types of interaction between the EVs, which must be taken into account: (i) fluid/fluid; (ii) fluid/solid; and (iii) solid/solid. For the first situation (i) fluid/fluid, so the two EVs are formed by fluid and the heat flux is given by equation (9):

$$\dot{Q}_{1,i} = \dot{m}_{1,i} c_{p,f} (T_a - T_i), \quad l = \text{t}, \text{b} \tag{9}$$

By having $\dot{m}_{1,i} = \rho_f V_i (A_{1,i}/2)$. By natural convection, the estimation of the velocity of the fluid crossing the surface of the EV can be represented by $V_i = \alpha_T \left[\left[\left(\frac{g\beta}{\alpha_T v} \right) |T_a T_i| H \right] \right]^2$, being a representative scale for natural convection. By assumption it is understood that half of the upper or lower face of an element is crossed by a flow in the vertical direction upwards, and the other half in the opposite direction, one representing the entrance to the EV and the other the exit.

And for the adjustment of the model, it will be done by solving the inverse problem of parameter estimation (IPPE) (MINKOWYCZ et al., 2006), using the mathematical model

4. RESULTS AND DISCUSSIONS

The results are divided into experimental measurements, computer simulation and correlation between them. A summary of the experimental data follows in the Figure below.

Point	Test 1	Test 2	Test 3
T_0	54,71	55,27	50,94
T_1	55,83	50,79	46,30
T_2	55,60	55,83	52,44
T_3	58,30	57,24	52,41
T_4	57,36	58,58	54,61
T_5	62,26	60,74	55,70
T_6	45,98	42,05	42,99
T_7	62,04	61,25	55,70
T_8	58,11	57,40	50,79
T_9	42,83	42,01	48,51
T_{10}	47,00	48,12	49,55
T_{11}	48,40	44,46	42,57
T_{12}	56,56	54,27	44,97
T_{13}	55,40	51,22	46,87

Point	Test 1	Test 2	Test 3
T_{14}	47,02	48,88	47,25
T_{15}	55,73	50,79	44,86
T_{16}	45,93	45,13	42,16
T_{24}	43,19	43,18	39,95
T_{25}	44,68	50,46	46,56
T_{26}	48,87	46,34	43,33
T_{27}	46,31	42,11	40,32
T_{28}	39,34	36,49	51,19
T_{29}	47,47	40,66	39,67
T_{30}	44,15	52,99	52,19
Average chamber temperature	44,86	44,61	44,74
Average internal temperature of the front compartment	56,69	55,46	51,32

Figure 5. Summary of average temperatures obtained during the tests: UFPR (2016).

The following is an example of a simulation with only one source of heat generation allocated in the center of the y and x axis and height z shifted to the base (height z variable in the tests). Test power of 3000 W - Figure 6

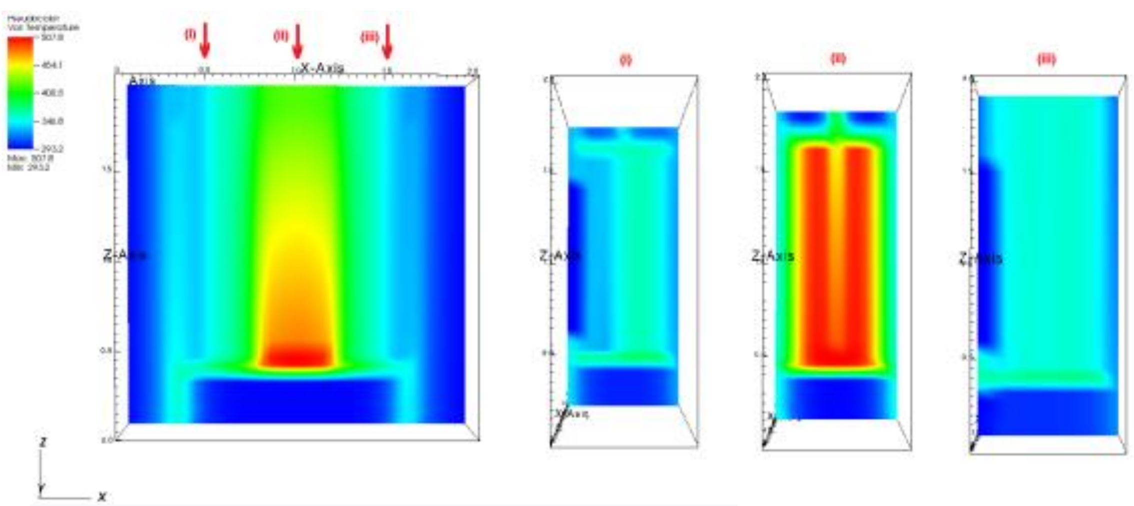


Figure 6. Demonstration of computer simulation - Cabinet analyzed (sliced): RIGATTI (2018).

It was noticed in the experimental tests the higher temperature at the top of the cabinet due to natural convection related to the lower density of hot air. Thus, the mathematical model must be adjusted to consider such a fault. Due to the heat exchange being carried out by conduction in solid elements, it usually occurs more quickly, however such (solid) elements generally have greater thermal inertia. Thus, analyzes of the average air temperature only, can hide critical temperatures in components, so this information must be taken into account (DILAY et al., 2014).

Finally, it can be verified that the Volume Elements Method used in the elaboration of the mathematical model, allowing a simple formulation that depends on of little computational time, but that allows to obtain answers of temperature and relative humidity and still simulate the system with different different parameters and settings, regardless of the diversity of system components, as this methodology allows the interaction of solid and fluid elements and the mixture of both in the same system, all dependent on the physical properties of the materials selected by the modeler (RIGATTI, 2018).

By using the computer simulation tool briefly demonstrated here, it is possible to perform simulations of the variation of the height z of the source of heat generation inside the telecommunications cabinet, in order to observe the results and understand the future application of the tool in phases. of product design and optimization. So to conclude, in the simulations performed by changing the height parameter z, it is possible to find the ideal position of the generation source in relation to height (only) for greater heat dissipation inside the cabinet.

The tool proved to be effective in solving problems where maximum heat transfer between the system and the environment must be found. In this case, the height, physical point, was changed, but other simulations can also be performed, which this tool proposes, such as the optimization for the maximum heat transfer as a function of optimal adjustment between airflow capacity in in relation to the heat generated by the electrical resistance with the fixed volume (RIGATTI, 2018).

5. REFERENCES

CAMPOS, Marcos Carvalho. Modelagem, simulação e otimização numérica e experimental de sistemas de resfriamento de equipamentos eletrônicos e motores stirling. 2004. 114 f. Tese de Doutorado- Universidade Federal do Paraná, Curitiba, 2004.

DIAS, F. G. et al. Notional all-electric ship thermal simulation and visualization. Electric ship technologies symposium, 2009. ESTS 2009. IEEE, p. 539-546.

DILAY, E. et al. The experimental validation of a transient power electronic building block (PEBB) mathematical model. Applied thermal engineering, v. 60, n. 1, p. 411-422, 2013

DILAY, Emerson. Modelagem e simulação para engenharia de sistemas: acondicionamento de eletrônicos, navios elétricos e fotobiorreatores.2013.198 f. Tese de Doutorado - Universidade Federal do Paraná,Curitiba, 2013.

ETSI EN 300 019-2-4 V2.2.1 (2003-03) European Standard (Telecommunications series) Environmental Engineering (EE); Environmental conditions and environmental tests for telecommunications equipment; Part 2-4: Specification of environmental tests; Stationary use at non-weatherprotected locations. Disponível em: . Acesso em: 21 jan. 2018.

ETSI EN 300 753 V1.2.1 (2009-03) European Standard (Telecommunications series) Equipment Engineering (EE); Acoustic noise emitted by telecommunications equipment. Disponível em: . Acesso em: 21 jan. 2018.

HONOUR, E. C. INCOSE: history of the International Council on Systems Engineering. Systems Engineering, v. 1, n. 1, p. 4-13, 1998.

IEC 60068-2-11:1981 BASIC ENVIRONMENTAL TESTING PROCEDURES - PART 2-11: TESTS - TEST KA: SALT MIST. Disponível em: . Acesso em: 21 jan. 2018.

IEC 61587-3:2013 Mechanical structures for electronic equipment - tests for iec 60917 and iec 60297 - part 3: electromagnetic shielding performance tests for cabinets and subracks. Disponível em: . Acesso em: 21 jan. 2018.

KAISER, Kenneth L.Electromagnetic compatibility handbook. 1ª Ed.New York: CRC Press, 2004.

KINCAID, D.; CHENEY, W. Numerical analysis. 1ª Ed. Belmont, CA: Cole Publishing Company, 1991.

MENG, X. Z. et al. Experimental and numerical investigation on thermal managemente of an outdoor battery cabinet. Applied thermal engineering, v. 91,p. 210-224, 2015.

MINKOWYCZ, W. J.; SPARROW, E.M.; SCHNEIDER, G.E.; PLETCHER, R.H.; **Handbook of Numerical Heat Transfer**, second edition, Chapter 17, Wiley, New York, 2006.

ORDONEZ, J. C.; VARGAS, J. V. C.; HOVSAPIAN, R. Modeling and simulation of the thermal and psychrometric transient response of all-electric ships, internal compartments and cabinets. Simulation, v. 84, n. 8-9, p. 427-439, 2008.

PASQUIER, P.; MARCOTTE, D. Short-term simulation of ground heat exchanger with an improved TRCM. Renewable energy, v. 46, p. 92-99, 2012.

RIGATTI, L. F.; VARGAS, J.V.C; BALMANT, W. Modeling and simulation of thermal management systems of electronic equipment. International Congress of Mechanical Engineering. COBEM, Curitiba, 2017.

RIGATTI, Luiz Fernando. Modelagem, simulação e validação de sistemas de gerenciamento térmico de equipamentos eletrônicos.2018.93 f. Dissertação de Mestrado - Universidade Federal do Paraná,Curitiba, 2018.

SAGE, ANDREW P.Systems Engineering. 1ª Ed. EUA: John Wiley & Sons, 1992.

SHAPIRO, B. Creating compact models of complex electronic systems: an overview and suggested use of existing model reduction and experimental system identification tools. IEEE transactions on components and packaging technologies, v. 26, n. 1, p. 165-172, 2003.

TRIVELATO, Gilberto da Cunha. Técnicas de modelagem e simulação de sistemas dinâmicos. São José dos Campos: INPE, 2003.

TSUZUKI, N.; KATO, Y.; ISHIDUKA, T.High performance printed circuit heat exchanger. Applied thermal engineering. v. 27, Ed. 10, p. 1702-1707, 2007.

VARGAS, J. V. C. et al. A numerical model to predict the thermal and psychrometric response of electronic packages. Journal of electronic packaging, v. 123, n. 3, p. 200-210, 2001.

VARGAS, J. V. C. et al. Notional all-electric ship systems integration thermal simulation and visualization. Simulation, v. 88, n. 9, p. 1116-1128, 2012.

VARGAS, José Viriato Coelho; ARAKI, L. K. Cálculo numérico aplicado. 1ª Ed. São Paulo: Manole, 2016.

WOODS, Robert L.; LAWRENCE, Kent L. Modeling and simulation of dynamic systems.1ª Ed. University of Michigan: Prentice Hall, 1997.

6. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.