27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0501
NUMERICAL OPTIMIZATION OF THE THERMAL INSULATION OF AN ELBOW PIPE TYPE CONNECTION OF AN ELECTRIC BUS COOLING SYSTEM USING COMPUTATIONAL OPEN SOURCE CODE

Danilo Albuquerque Ribeiro[1]
André Yudi Lima Okamoto[2]
Leandro Oliveira Salviano[3]
Aluísio Viais Pantaleão[4]
São Paulo State University, School of Engineering. Department of Mechanical Engineering, 15385-000, Ilha Solteira, SP, Brazil
[1]danilo.albuquerque@unesp.br
[2]andre.yudi@unesp.br
[3]leandro.salviano@unesp.br
[4]aluisio.pantaleao@unesp.br

Abstract. *When considering heat exchange inside an internal fluid flow, factors such as the geometry of the pipe and the material and thickness of insulation layers becomes of great importance. As the pipe changes direction, the flow inside alters its dynamics, causing the heat exchange with the ambient to vary as well as the internal gradient of temperature of the fluid. These type of pipe circuit can be found in the connections between cooling systems and battery packs of electric urban transport vehicles (BEV – Battery Electric Vehicle), in which the rise of cooling the fluid's temperature is an undesirable phenomena. Therefore, the present work proposes to study and minimize the temperature difference between the inlet and outlet of an elbow pipe used for this purpose, subject to a constant heat flux from external environment, allowing to maintain a maximum difference threshold. The study were conducted by changing parameters of the pipe such as insulation layer thickness and material, maintaining the external wall temperature and the inlet fluid temperature as constants. To perform such study was used the free, open source computational Fluid Dynamics (CFD) software OpenFOAM to construct and parametrize the computational mesh as well as to obtain the flow profile and temperature distribution inside the fluid in steady-state. Coupled with the CFD software, was used the free, open source software Dakota to manage the simulations realized by the CFD software and vary the design parameters, with the minimization of the objective function as the goal. The principal method of optimization used was the Genetic Algorithm (GA) approach in which each combination of parameters represent a solution and by evaluating and comparing those the algorithm is capable to find a global optima in parameter space without the need to compute gradients, allowing for discrete variables optimization, although in a lengthy process. Utilizing the optimization method described, was possible to obtain an optimal set of parameters that minimizes the temperature difference from the inlet to the outlet in the elbow shaped pipe, therefore the study suggest that the set of design parameters chosen exert great influence in the final temperature obtained at the outlet.*

Keywords: *Optimization, Cooling System, Electric Vehicle, OpenFOAM, Dakota*

1. INTRODUCTION

Between 2011 and 2021 the electric vehicles (EV) market share in USA rose from 0,2% to 4,6%, this growth was provided by increasing global environmental concerns, higher competitiveness and significant rise in EVs autonomy due to technological improvements of equipped batteries (Colato; Ice, 2023). With governmental incentives, the adoption of this kind of transport will tend to grow even further in next decades and with that, the appeal of this technology to a wide variety of occupations (Colato; Ice, 2023). With rise in their applications, researches and technical developments related to EVs rose drastically, providing innovations to the whole industry. It is possible to visualize the sales percentage and circulating EVs rise from 2011 to 2021 in Figure 1.

The battery packs found in these type of vehicle are responsible for a significant share of the overall manufacturing costs associated (Yuksel et al., 2017) and principal aspect affecting their autonomy and longevity, thus, it becomes clear the importance of these components as well as the development of researches and improvements related to them. Because of that, achieving both higher charge capacity and lifespan are fundamentally important to viability of an EV project, those factors have become a big challenge in a sense that, as a consequence of the heat generate from the high charging and discharging associated with influence of adverse environmental impact, the operating temperature related to the battery pack is displaced out of the optimal work interval. According to Fan et al. (2021), the optimal operating temperature of the battery pack generally lies between 20 ºC and 40 ºC and therefore, as consequence of operational and environmental aspects mentioned, a system of thermal management must be employed to maintain the temperature inside the prescribed range, avoiding safety issues and additional electrical power consumption due to the battery pack operating outside the optimal range.

Due to environmental impact in operation of the battery packs present in EVs, in Brazil, the diffusion of this type of vehicle has been facing a barrier, keeping in mind that these vehicles are designed and developed in research centers located at European, Asiatic and North American countries, and therefore, are developed considering climate conditions encountered in these countries, which differs considerably from those found here. To address this issue, it is necessary the nationalization of these projects either by the accomplishing the full development or adapting existing projects to local conditions, demanding a capable engineering able to face and solve eventual operation problems, such as the thermal management of the battery pack. Thus, optimization of the cooling system is crucial for the viability of the project to deal with adverse temperatures and environmental conditions found in Brazil and other Latin American countries, being necessary for this, a precise numerical modeling of the system to reduce project costs obtaining greater efficiency.

Through the use of numerical simulation techniques with computational Fluid Dynamics (CFD) softwares it is possible do perform detailed studies related to complex engineering systems involving fluid mechanics and heat transfer phenomena without the need to accomplish complex costly experiments. Therewith, arose the possibility of utilizing specialized optimization softwares in problems related to fluid mechanics, allowing geometry optimizations to attend a wide variety of engineering problems. Cavazutti et al. (2019) were capable of coupling the optimization open-source software Dakota to a simulation seeking a more efficient thermal management of an electric motor employed in Formula E competitions. Quan et al. (2020) propose a method to couple the open-source softwares Dakota and OpenFOAM®, responsible for problem optimization and CFD numerical simulation respectively, in which a script was used to manage the interfacing between the two softwares, allowing the optimization of the airfoil geometry used in wind turbines. Benchikh Le Hocine et al. (2021) propose the use of a Dakota-OpenFOAM® coupling to optimize the rotor of a squirrel cage type fan, in which was presented a complete automatic optimization loop using the mentioned softwares as well as Salome for mesh generation used by OpenFOAM® and Python scripts for post-processing, mesh quality check and workflow control.

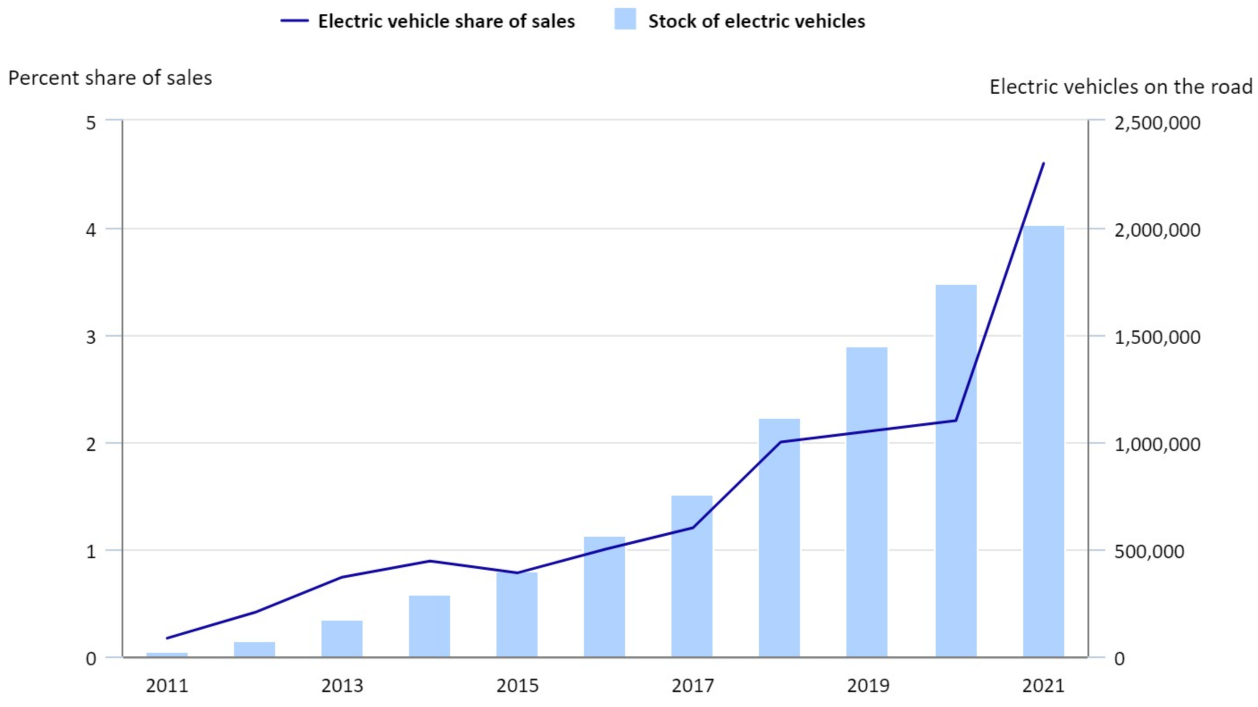

Figure 1. Sales share and stock of electric vehicles,2011-21 (Colato; Ice, 2023)

As previously discussed, the rise of the battery pack cooling fluid used in a EV thermal management system due to environmental factors imply in greater electrical power costs to maintain the battery pack in operational temperature interval, and thus reducing the vehicle range. Therefore, the present work aims to utilize computational numerical softwares to optimize the interconnection ducts of the thermal management system used in an electric bus, seeking to reduce the cooling fluid's temperature in operations with high temperatures and solar incidence by developing a proper coupling between the optimization software Dakota and the CFD software OpenFOAM® and considering aspects such as tubes material and thickness, thermal insulators and working fluid.

2. METHODOLOGY

In order to accomplish the coupling between the two softwares was developed a controller script named *simulator_script* in Bash scripting language, the first step was defining an objective function which depends on the problem being tackled, this function must attend project requirements. Next, the optimization proceeds according to Figure 2, no response surface methodology (RSM) was used. The communication between the script and Dakota is done with data file trading where input parameters given to the script by Dakota lies inside the file named *params.in* and the output values obtained after post processing by the script that will be provided back to Dakota lies inside the file named *results.out*. The flowchart in Figure 3 illustrate the working of this communication.

2.1 Parameters Extraction

So that the parameters contained in file *params.in* may be interpreted by the external software in order to occur the simulation (as proposed in Figure 3) it is necessary a script or program specialized for this function. In this work was proposed three different methodologies to accomplish this proceeding, listed as follow.

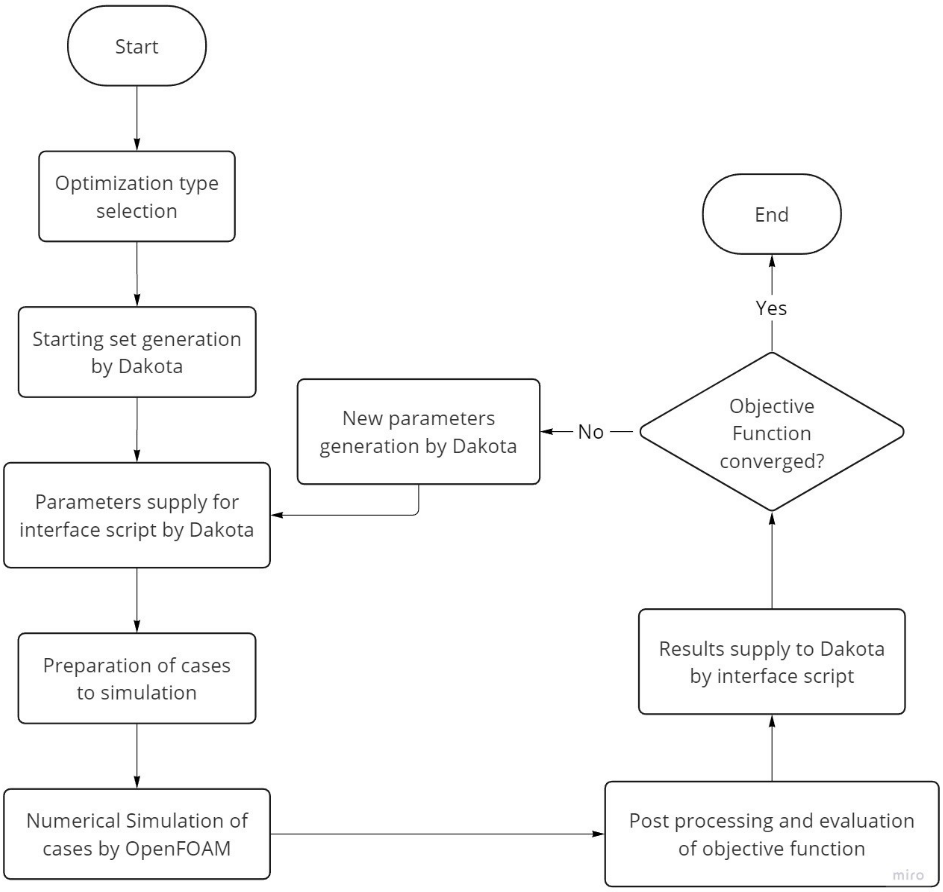

Figure 2. Direct Optimization Flowchart

- *dprepro*: Dakota native preprocessor, its working is based in search and replace keywords (parameters name defined in Dakota encased by {}) of a template file by the respective values described inside *params.in*, generating a new file;
- *dakota_params_extract*: preprocessor developed in Bash scripting language native to Linux operating system, its working is based in exporting keywords (parameters name defined in Dakota preceded by $) as system variables, with value as described in the file *params.in*, which will be read and interpreted by the software (OpenFOAM®), without file changing;

- dakota_prepro: preprocessor developed in C programming language, its working is based in search and replace keywords (parameters name defined in Dakota preceded by $) of a template file by the respective values described inside params.in, changing the existent template file.

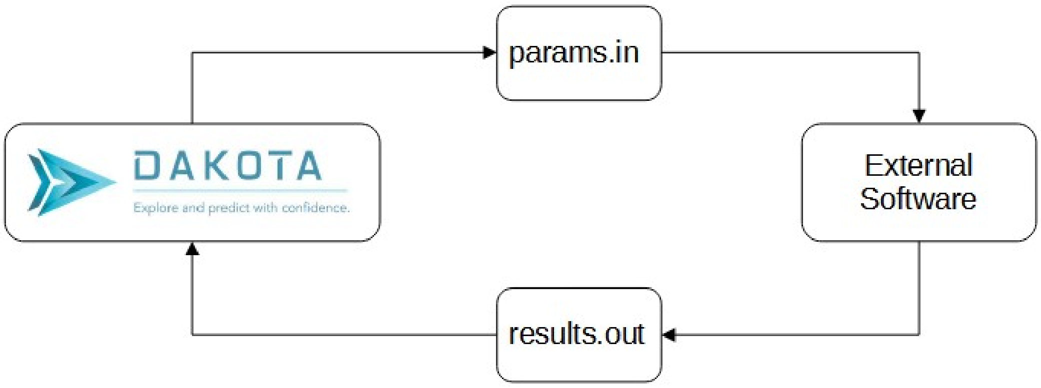

Figure 3. Dakota and external softwares communication flowchart

The choice of which preprocessor may use in a problem is based in two principal aspects, capability of the software in interpreting system variables and availability of the native preprocessor (*dprepro*) in the system. In softwares capable of interpreting system variables (such as OpenFOAM®) the use of *dakota_params_extract* is more appropriate since this preprocessor make the assembly of the optimization workflow and coupling easier. In softwares that don't have this capability it must be used *dprepro* or *dakota_prepro*, being *dprepro* the preferred one since its native to Dakota, however, if its no available, *dakota_prepro* must be used.

2.2 External wall temperature fitting

To approximate the real heat transfer phenomena between ambient air and interconnection ducts, the numerical simulation software was configured to provide a constant temperature to the external tube wall (or external insulation wall, in case of insulated tubes). An example of this phenomenon can be seen in Figure 4.

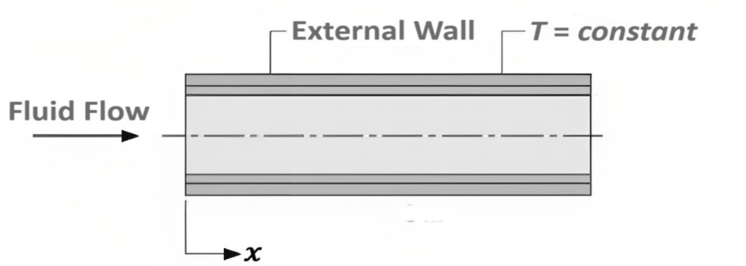

Figure 4. Constant wall temperature duct. Adapted from Incropera and Witt (2014)

This external temperature, subject to thermal resistances from wall and or insulation, provide a fluid flow temperature rise (when the temperature is greater then inlet temperature) or drop (when the temperature is lower then inlet temperature) relative to the duct inlet. Since knowing the real heat transfer process is to much complex, the objective of this approximation is to facilitate the analysis of the flow temperature difference due to ambient and how adding or removing of insulation on the duct wall influence in flow final temperature at duct outlet, however, to make this possible the external wall temperature must be first estimated.

With this goal in mind, it was done an optimization as the flowchart in Figure 2 illustrate, in which the objective function (f_{obj}) was defined as the squared difference between numerical simulation via OpenFOAM® temperature ($T_{cfd,o}$) and the experimental temperature measured with sensors at the duct outlet in a certain day ($T_{exp,o}$), using as design parameter that will be modified by the optimization the desired wall temperature value (T_{wall}), as can be seen in Equation (1).

$$f_{obj}(T_{wall}) = [T_{cfd,o}(T_{wall}) - T_{\exp,o}]^2 \quad (1)$$

The coupling utilized to this procedure was developed from the ideas previously proposed, using a *simulator_script* to manage the whole optimization loop, data file flow and the *dakota_params_extract* as preprocessor, the entire coupling flowchart can be seen in Figure 5.

The quadratic difference was chosen as objective function since the goal is that the simulation temperature match the experimentally measured temperature, because of this, the function have a minimum when the two temperatures are equal or very close to each other, by using the quadratic difference this criteria are met, reaching values close to zero when the two are very close to each other and rising when they differ.

In this procedure, the optimization method chosen to carry out the task was Quasi-Newton method of indirect search, in which an approximation of the function Hessian (the objective function second derivative in this case with only one design variable) is estimated by using the function gradient (objective function first derivative) to reach a function extreme (maximum or minimum point).

Since the value of the function depends on a CFD result determined via OpenFOAM® the evaluation of the function derivative analytically is impracticable, thus a numerical approach for the derivative estimation must be used. For this work, it was used a numerical derivative carry out by Dakota using central derivative, making the estimation process more costly in computational terms but with second-order accuracy $O(h^2)$.

This optimization method was chosen due to the capability of Newton based methods of reaching local extreme points fast, which in the case of this problem correspond to the global minimum, as well as the benefit of avoiding computation of second order derivatives, which in the case of lengthy CFD problems, would result in greater computation time as more cases would have to be simulated.

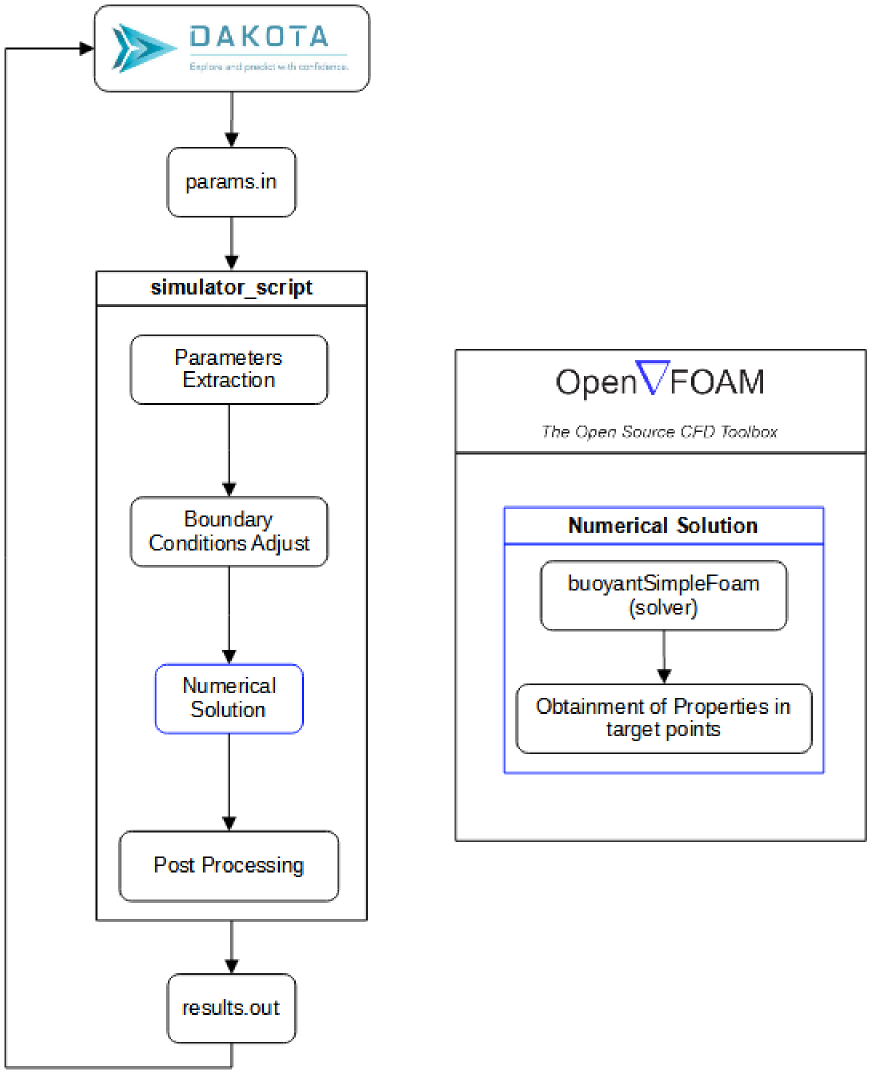

Figure 5. Wall temperature coupling optimization flowchart

2.3 Insulation layer optimization

The insulation layer was proposed to be composed of a multi-layer arrangement of two types of insulation commercially available denominated as *thin insulation* and *thick insulation*, their material names, physical properties and cost per meter can be visualized in Table 1. To determine the best arrangement two aspects were considered, those being the capability of the arrangement in reduce temperature difference between inlet and outlet as well as total cost of the arrangement. In order to model these goals it was proposed an objective function (g_{obj}) composed of the weighted sum of the difference between the inlet temperature obtained experimentally ($T_{exp,i}$) and outlet temperature obtained with simulation via OpenFOAM® ($T_{cfd,o}$), as well as the total cost of the arrangement, both normalized by the temperature difference without insulation (the two temperatures being experimentally obtained) and the maximum cost respectively, where the parameters are the *thin insulation* layers number (n_{thn}) and *thick insulation* layers number (n_{thk}), as can be seen in Equation (2). In this work the maximum number of layers for each material as set to 5 and the weights where chosen to be equal for both temperature difference and cost, this could be easily adapted for other goals if needed.

Table 1. Insulation Properties

Properties	Thin Insulation	Thick Insulation
Material	Armaflex (elastomeric) Tape	Polipex (expanded polyethylene) Foam
Thickness [mm]	3	10
Thermal Conductivity [W/m·K]	0.037	0.036
Cost per meter	R$ 9.26	R$ 4.00

$$g_{obj}(n_{thn}, n_{thk}) = \left[0.5 \cdot \frac{T_{cfd,o}(n_{thn}, n_{thk}) - T_{\exp,i}}{T_{\exp,o} - T_{\exp,i}} + 0.5 \cdot \frac{9.26 \cdot n_{thn} + 4 \cdot n_{thk}}{9.26 \cdot 5 + 4 \cdot 5}\right] \quad (2)$$

Due to the discrete nature of the variables (those being the quantity of layers from each material), an optimization method capable of tackling these type of variables as well as finding a global optima (in these case with minimization goal) must be chosen, in this work, for this purpose the *Genetic Algorithm* technique was selected where each combination of parameters compose a solution and by comparing the result of the objective function, the best solutions can be combined to form new solutions in an evolutionary process, being able to explore the parameter space and reach a global optima but with significant computational cost due to a great number of solutions needed to be evaluated. Similarly to the wall temperature fitting case, the optimization procedure follows as described in Figure 5.

3. RESULTS

3.1 External wall temperature fitting

Starting from the methodology described and utilizing experimental data as can be seen in Table 2, it was possible to perform the procedure of optimizing the external wall temperature boundary condition to equal measured temperature with numerically obtained temperature from OpenFOAM® in a case where no thermal insulation was added beyond the own duct wall, using the starting point for the optimization 310 K. A graphic illustrating the optimization evolution each iteration can be seen in Figure 6.

Table 2. Experimental parameters

Ambient Temperature [K]	306.71
Inlet Temperature [K]	309.7564
Outlet Temperature [K]	309.8103
Flow Rate [m³/s]	$3.2727 \cdot 10^{-4}$
Tube Wall Thickness [mm]	1.5
Tube Wall Conductivity [W/m·K]	16.2

Observing the graphics from Figure 6 it can be seen that the optimization rapidly converged to a minimum value of the objective function (value close to zero at $9 \cdot 10^{-8}$ K^2) after 10 iterations, the temperature in the external duct walls evaluated with this approach is valued at 309.8101 K reaching value very close to outlet fluid temperature, this is due to almost negligible thermal resistance imposed by the duct walls as consequence of their small thickness and considerable thermal conductivity (as can be seen in Table 2), causing the outlet temperature to be almost the same as the external wall temperature.

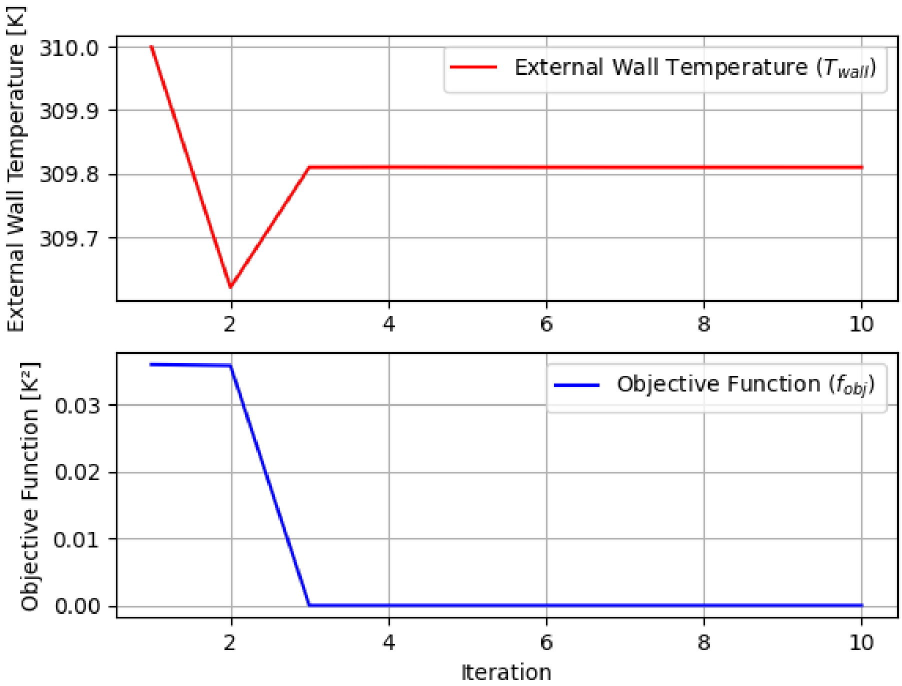

Figure 6. Temperature Fitting Evolution

3.2 Insulation layer optimization

With the methodology previously described and utilizing the external wall temperature found by the fitting procedure realized, it was possible to evaluate the performance of each insulation type proposed in Table 2 individually, as can be seen in Tables 3.

Table 3. Individual insulation performance

Properties	**Thin Insulation**	**Thick Insulation**
Material	Armaflex (elastomeric) Tape	Polipex (expanded polyethylene) Foam
Temperature Difference [K]	0.047	0.026
Percentage Reduction	12.8%	51.76%
Cost per meter	R$ 9.26	R$ 4.00

The results contained in Table 3 show that the *thick insulation* is more capable of reducing the temperature difference between inlet and outlet, this is due to its greater thickness compared to the *thin insulation*, even tough the thermal conductivity of the two are very similar in value, however, it must be noted that for more strict and compact spaces the *thin insulation* could be a better option, for the same reasoning discussed.

Next, with same methodology was possible to perform the Genetic Algorithm for reducing the objective function in order to obtain the best relation between cost and effectiveness for the insulation layer. A graphic containing the objective function evolution across the populations can be seen in Figure 7. A maximum of 20 populations was defined with 8 solutions per population. Observing the graphic from Figure 7 it can be seen that the objective function converge to the best solution in generation 16 even though the mean of each population continued to improve but never reaching the best solution found.

The specifications of the best solution insulation layer as well as total cost and temperature difference between inlet and outlet are listed in Table 4. It was identified that, to achieve the better relation between cost and effectiveness, the best insulation layer arrangement was composed of four layers of the *thick insulation* and no *thin insulation* layers, this is due to higher cost and less thermal resistance of the *thin insulation* compared to the *thick insulation*, making the second one more economically viable. Also, as with four layers of *thick insulation* it was already possible do reduce the temperature difference significantly (obtaining an 85.27% reduction in value), making the four layers arrangement found satisfactory without need to additional layers that would increase the total cost without major improvements in temperature difference reduction, keeping in mind that, by adjusting the weights in the objective function, a greater emphasis in temperature difference reduction could be achieved if necessary.

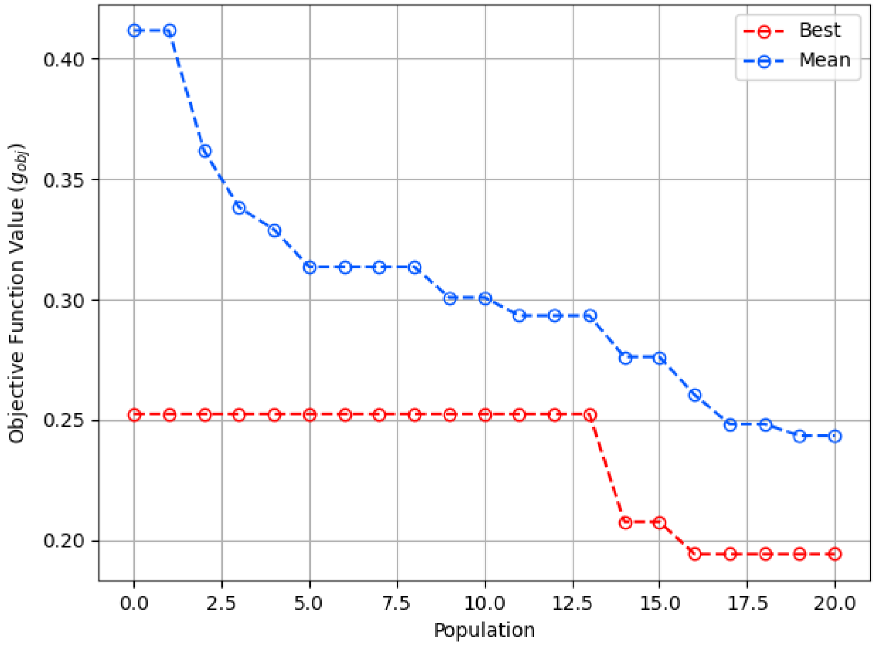

Figure 7. Layer Optimization Evolution

Table 4. Best insulation layer identified

Objective Function	0.1943
Temperature Difference [K]	0.008
Total Cost per Meter	R$ 16.00
Thin Insulation Layer Number	0
Thick Insulation Layer Number	4

4. CONCLUSIONS

The fitting of the external wall temperature shows that the thermal resistance of the tube walls without any insulation is small enough in order that the wall temperature is very close to the outlet temperature, meaning the two achieve thermal equilibrium, showing that the environment plays a big role in increasing the fluid temperature from the interconnection tubes inlet to the outlet, possibly increasing energetic costs with cooling systems to maintain these temperatures in operating range.

Additionally, the two insulation types were evaluated individually and compared, stating that the *thick insulation* has more thermal resistance due to its greater thickness compared to *thin insulation*, even tough with similar thermal conductivites, with a reduction of fluid temperature difference between inlet and outlet of 12.8% and 51.76% for the *thin insulation* and *thick insulation* respectively.

Also, it was possible to identify that using only four layers of *thick insulation* (composed of expanded polyethylene foam) is enough to reduce the temperature between inlet and outlet in 85.27% with moderate-low cost, this arrangement proves to be both effective and economically viable, reducing the impact of the environment in vehicle autonomy due to cooling fluid heating.

The optimization procedure also shown that the coupling developed for this work is robust and adaptable for usage in similar methodologies, involving geometrical, physical property and boundary conditions parameters analysis, succeeding in developing a generic approach that will be useful for future works.

5. ACKNOWLEDGEMENTS

This work was made possible by the funding provided by Teaching, Research and Extension Foundation of Ilha Solteira (FEPISA), process 005/2022 (Scientific Initiation).

6. REFERENCES

BENCHIKH LE HOCINE, A. E.; PONCET, S.; FELLOUAH, H. CFD modeling and optimization by metamodels of a squirrel cage fan using OpenFoam and Dakota: Ventilation applications. **Building and Environment**, vol. 205, no. June, p. 108145, 2021. DOI 10.1016/j.buildenv.2021.108145. Available at: https://doi.org/10.1016/j.buildenv.2021.108145.

CAVAZZUTI, M.; GASPARI, G.; PASQUALE, S.; STALIO, E. Thermal management of a Formula E electric motor: Analysis and optimization. **Applied Thermal Engineering**, vol. 157, no. December 2018, p. 113733, 2019. DOI 10.1016/j.applthermaleng.2019.113733. Available at: https://doi.org/10.1016/j.applthermaleng.2019.113733.

COLATO, J.; ICE, L. Charging into the future: the transition to electric vehicles. 2023. Available at: https://www.bls.gov/opub/btn/volume-12/charging-into-the-future-the-transition-to-electric-vehicles.htm. Accessed on: 30 May 2023.

FAN, Y.; ZHAN, D.; TAN, X.; LYU, P.; RAO, J. Optimization of cooling strategies for an electric vehicle in high-temperature environment. **Applied Thermal Engineering**, vol. 195, no. January, p. 117088, 2021. DOI 10.1016/j.applthermaleng.2021.117088. Available at: https://doi.org/10.1016/j.applthermaleng.2021.117088.

HOANG QUAN, N. N.; LAM, P. Van; LONG, L. Van. Wind Turbine Blade Design Optimization using OpenFOAM and DAKOTA software. **IFAC-PapersOnLine**, vol. 56, no. C, p. 71–78, 2020. DOI 10.1016/j.trpro.2021.09.009. Available at: https://doi.org/10.1016/j.trpro.2021.09.009.

INCROPERA, F. P.; WITT, D. P. De. **Transferência de Calor e de Massa**. 7th ed. [*S. l.*]: gen LTC, 2014.

YUKSEL, T.; LITSTER, S.; VISWANATHAN, V.; MICHALEK, J. J. Plug-in hybrid electric vehicle LiFePO4 battery life implications of thermal management, driving conditions, and regional climate. **Journal of Power Sources**, vol. 338, p. 49–64, 2017. DOI 10.1016/j.jpowsour.2016.10.104. Available at: http://dx.doi.org/10.1016/j.jpowsour.2016.10.104.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.