Numerical Simulation of Heat Transfer through Uniform Multilayer Walls using ANSYS

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Abstract: - The paper presents a study on modelling the main heat transfer parameters through opaque building elements. The need for models to assess the thermal behavior of a building has increased greatly in recent years, primarily to allow a more accurate determination of the energy consumption of buildings to evaluate the performance of heating systems. In recent times, mathematical models and software have been implemented to obtain simulations that are very close to the real functioning of the main components of buildings. The present article consists in modeling a multi-layer homogeneous wall, which separates the interior space of an enclosure (rooms) from the outside environment. The article aims to carry out a series of simulations on the structure of a non-homogeneous multilayer wall using the ANSYS program. The simulations have been performed highlight how the values vary (both numerically and graphically) for a series of characteristic parameters such as heat fluxes, temperatures, convection coefficients. The values of the parameters obtained with the ANSYS program were also compared with those obtained by classical numerical calculations.

Key-Words: - thermal transfer, buildings, multilayer wall, modeling, mathematical model, thermal simulation.

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1 Introduction

The buildings sector has the highest energy consumption in the world, due to the increasing demand to construct buildings.

Several attempts have been made to improve energy consumption and increase energy efficiency in the building sector. To reduce carbon emissions, energy-efficient buildings are one way to save energy and reduce energy demand. Energy consumption in buildings is becoming increasingly important as it accounts for a large amount of overall energy consumption. Energy is a basic element and requirement for human existence and development.

To improve the energy efficiency of buildings the thermal properties of building materials are of great importance, [1].

A comfortable environment for people's activities, especially in terms of temperature, is very important. For this reason, thermal comfort becomes a key factor in the design and construction of a building as a place to carry out activities, especially a house as a place for everyday life. In general, the process of creating building comfort cannot be separated from efforts to limit the influence of outdoor temperature on the building. The warm outdoor temperature is the most difficult to deal with in tropical countries so as not to affect the indoor temperature. For a four-season country, the challenge becomes a little more complex, as the performance of the building in winter must also be able to withstand the heat (warm temperatures) inside the building without losing it easily. Heat loss from buildings occurs mainly through the exterior walls, ceiling, windows and basement of the building and through infiltration, [2]. In response, a well-designed building insulation system is needed to help achieve thermal comfort in buildings.

Buildings consume a third of the world's total annual energy, a ratio that continues to rise as population and urbanization increase, [3]. Most of the energy is consumed in buildings located in urban areas in developing countries and, due to the modernization of buildings in the construction sector, local climatic conditions and materials are neglected, [4]. Buildings play a vital role in creating a safe and comfortable living environment. To create thermal comfort in buildings, heating, ventilation and air conditioning (HVAC) systems use about 50% of the building's energy, [5]. Providing thermal comfort in buildings has always been one of the main concerns of architects around the world, and among these, residential buildings have always been of particular importance, [6].

The temperature in steady-state heat transfer remains constant throughout time, whereas the temperature in transient heat transfer fluctuates. Mathematical formulas can be used to describe these processes. Even today, a variety of software is available to assist the calculation process by providing more displays that make reading and providing information easier to generate.

The internal thermal climatic condition of a house is directly affected by how the building envelope (walls, windows and roof) is designed to suit the environment it is exposed. How the building envelope is constructed has a great effect on the energy required for heating and cooling to maintain human thermal comfort. Understanding how the internal climatic conditions react to the building envelope construction is therefore of great value, [7].

This study aims to provide an overview of how much influence the configuration system has on the installation of an insulating wall layer by using ANSYS software and the steady-state analysis approach, [8]. It is possible to assess how quickly and how much energy is transferred down the insulating wall by using the value of heat flow or heat transfer rate, [9].

2 Problem Formulation

2.1 Numerical Modeling of Heat Transfer in Multilayer Walls

Numerical modeling and energy simulation of buildings is a mature but growing field, benefiting from new computer and automation techniques that are increasingly expanding into even the most mundane sectors of activity.

The problem is that the contribution of computerized technology means that the majority of beneficiaries run the risk of forgetting the meaning of the phenomena that are at the basis of ensuring a pleasant climate in buildings; for the systems designer, on the other hand, it is a field that brings new challenges and new ways of optimizing problem solving.

A second risk that the development of technology can pose for people is the enclave of science for certain private research centers and the promotion of specific products, which, under patent or copyright protection (which nowadays are more likely to block the development of science than to promote it), only esoterically keep certain research results within themselves for commercial exploitation. In this sense, the present paper aims to deal with the fundamentals of numerical modeling of energy transfer phenomena in buildings, explicitly exposing both mathematical and descriptive models.

Energy optimization in buildings is done for people, so it starts from their needs for an acceptable microclimate, and the research results must converge to these needs, [10].

It is known that in the use of the finite difference method most expositions tend to present this method considering the uniform grid, being the most mathematically simple situation. However, it should be pointed out that complex geometrical models already require a more complex mathematical apparatus, and consequently a more elaborate grid, more flexible on the geometry of the modeled body.

Conditions that must be fulfilled by a numerical analysis to be considered valid:

- Consistency - the discretization of partial differential equations must be done in the sense of zero-tending of the mesh (so the truncation error must be reduced as much as possible);
- Stability - the errors generated in solving the discretized equations should not amplify;
- Convergence - the numerical solution must be close to the exact solution of the differential equation and must converge towards zero as the mesh tends to zero;
- Conservation - The underlying conservation laws must be respected at the discrete domain level (artificial sources of values or pits must be avoided - e.g. in rigid solid analysis artificial stress concentrators must be avoided);
- Marginalization - quantities such as mass, density, and temperature must appear strictly positive in any results;
- Repeatability - the model built and analyzed in one place should give the same results as a model built with the same initial conditions in another place.

There are several ways of numerically calculating heat transfer, but the most important are:

- The finite difference method - starting from the equations governing the phenomenon and arriving at a system of trivial equations after discretization and setting boundary conditions;
- Finite element method - starting from the equations governing the phenomenon at the scale of the whole, then after discretization the form of the equation is still recognized at the level of the resulting finite elements, each finite element is represented by a matrix, and the global matrix of the whole studied is the sum of all the matrices. of the finite elements.
- Finite volume method;

- Spectral method.

Figure 1 presents a composite wall, a wall made of several layers of different materials. The composite wall consists of three layers of thicknesses δ_1, δ_2, and δ_3, [11].

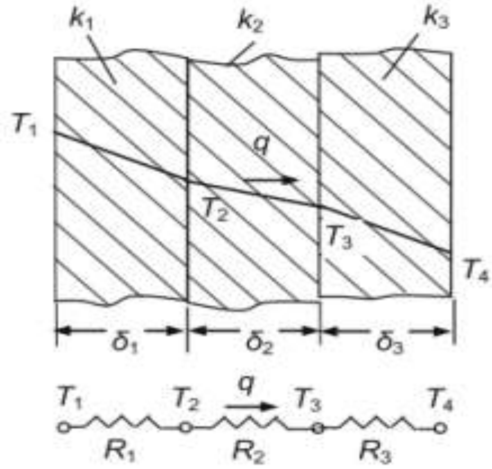

Fig. 1: Composite wall, [11]

The thermal resistance for each layer of the composite wall is determined with the relation (1).

$$R_1 = \frac{\delta_1}{k_1}\cdot A, R_2 = \frac{\delta_2}{k_2}\cdot A,\ R_3 = \frac{\delta_3}{k_3}\cdot A\ [\mathrm{m^2K/W}] \quad (1)$$

In a plane wall, the rate of heat transfer is as follows, relation (2), [11]

$$q = -k\cdot A\frac{\partial t}{\partial x} = k\cdot A\frac{t_1-t_2}{x_2-x_1} = k\cdot A\frac{t_1-t_2}{\delta} = \frac{t_1-t_2}{\frac{\delta}{k\cdot A}} = \frac{\Delta t}{R_k}\ [\mathrm{W/m^2}] \quad (2)$$

Where: R_1, R_2, … R_n are the thermal resistance for each material of the composite wall, [m^{2}K/W]; q is the unit thermal flux through the wall, [W/m^2]; k is the overall heat transfer coefficient, [W/m^{2}K]; Δt is the temperature difference between the indoor and outdoor environment, [K]; δ is the thickness for each component layer, [m], A the surface, [m^2].

The thermal conductivities of these layers are k_1, k_2, and k_3, respectively. The temperature of the outer layers of the wall is T_1 and T_4 as shown in the Figure 2, with interface temperatures as T_2 and T_3. It is being assumed that different layers are having perfect contact between them and hence the adjacent surfaces are at the same temperature. In the steady-state condition, the heat flow q is the same for all the layers and is constant, [10], [11].

The equations of unit thermal flux through these layers are:

$$q = k_1\cdot A\frac{T_1-T_2}{\delta_1},\ [\mathrm{W/m^2}] \text{ – for the first layer}$$
$$q = k_2\cdot A\frac{T_2-T_3}{\delta_2},\ [\mathrm{W/m^2}] \text{ – for the second layer} \quad (3)$$
$$q = k_3\cdot A\frac{T_3-T_4}{\delta_3},\ [\mathrm{W/m^2}] \text{ – for the third layer}$$

The temperature differences across the layers, resulting from the above equations are presented in the formula (4):

$$T_1 - T_2 = q\left(\frac{\delta_1}{k_1\cdot A}\right)[^\circ\mathrm{C}]$$
$$T_2 - T_3 = q\left(\frac{\delta_2}{k_2\cdot A}\right)[^\circ\mathrm{C}] \quad (4)$$
$$T_3 - T_4 = q\left(\frac{\delta_3}{k_3\cdot A}\right)[^\circ\mathrm{C}]$$

In a composite wall the rate of heat transfer is presented in formula (5):

$$q = \frac{T_1 - T_{n+1}}{\sum_{i=1}^{n} R_i} = \frac{T_1 - T_{n+1}}{\frac{1}{A}\sum_{i=1}^{n}\frac{\delta_i}{k_i}},\ [\mathrm{W/m^2}] \quad (5)$$

3 Case Study for Modeling Thermal Transfer Parameters for a Multilayer Composite Wall

Figure 2 presents a multilayer composite wall that will be analized. It is a multilayer wall composed of 4 layers with different materials structures and thicknesses. The materials and their thermal characteristics are presented in Table 1. The interior temperature is considered 20 °C and the outside temperature is -15 °C.

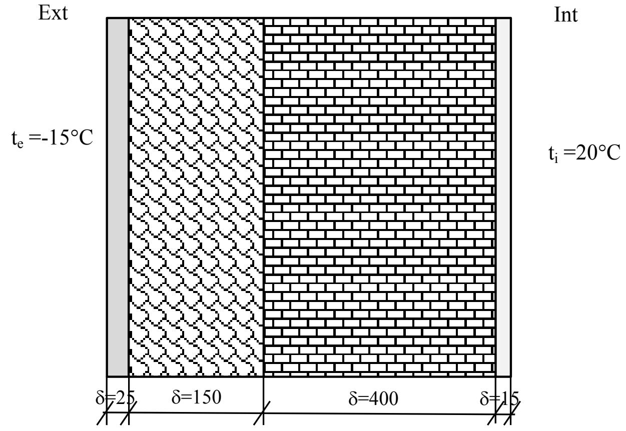

Fig. 2: The analized multilayer composite wall

Table 1. The type of material used and the dimensions of the wall

Layer	Thickness, δ [mm]	Thermal conductivity, λ [W/mK]
Exterior plaster	25	0.93
Thermal insulation - polystyrene	150	0.04
BCA	400	0.27
Interior plaster	15	0.87

The validation of the numerical solution will be made by comparison with the overall analytical solution.

The computational relationship characterizing the heat transfer through a multi-layer plane wall is presented in equation (6):

$$q = k \cdot \Delta T \text{ [W/m}^2\text{]} \quad (6)$$

The calculation relation for the overall heat transfer coefficient, k, it is described in equation (7):

$$k = \frac{1}{\frac{1}{\alpha_{ext}} + \sum \frac{\delta_i}{\lambda_i} + \frac{1}{\alpha_{int}}} \text{ [W/m}^2\text{K]} \quad (7)$$

Were: α_{ext} is the convection coefficient between the wall and the outside air, [W/m^{2}K]; α_{int} is the convection coefficient between the wall and the indoor air, [W/m^{2}K]; δ_i is the thickness of each wall layer, [m], $_i$ is the thermal conductivity of each wall layer, [W/mK];

The value of the convection coefficient between the wall and the outside air was taken as 24 W/m^{2}K. The value of the convection coefficient between the wall and the indoor air was assumed to be 8 W/m^{2}K.

The outside air temperature is -15°C. The temperature considered for indoor air is 20°C.

Applying the above calculation equation (7) for the overall heat transfer coefficient, k, result:

$$\mathrm{k} = \frac{1}{\frac{1}{\alpha_{\mathrm{ext}}} + \sum \frac{\delta_{\mathrm{i}}}{\lambda_{\mathrm{i}}} + \frac{1}{\alpha_{\mathrm{int}}}} = \frac{1}{\frac{1}{24} + \frac{0.025}{0.93} + \frac{0.150}{0.04} + \frac{0.400}{0.27} + \frac{0.0015}{0.87} + \frac{1}{8}} = \frac{1}{0.041+0.026+3.75+1.481+0.0017+0.125} = 0.1843$$

W/m^{2}K

k = 0.1843 W/m^{2}K

Substituting k into the relation for unit thermal flux through the wall will result:

$$q = k \cdot \Delta_t = 0.1843 \cdot (20 + 15) = 5.4247 \cdot 35 = 6.45 \text{ W/m}^2$$

q = 6.45 W/m^2

Recall that the value of the unit thermal flux through the wall obtained by numerical simulation is: 6.58 W/m^2.

In the next presented figures will be described the composite wall structure and the numerical simulations regarding the temperature variations, the influence of the convective coefficient and the thermal flux variation.

In the Figure 3 is represented the wall structure from outside to inside- the model was implemented in ANSYS workbanch.

The temperature T$_2$ it can be determine, using equation (4):

$$T_1 - T_2 = q\left(\frac{\delta_1}{k_1 \cdot A}\right)$$

$$-T_2 = q\left(\frac{\delta_1}{k_1 \cdot A}\right) - T_1 \rightarrow T_2 = T_1 - q\left(\frac{\delta_1}{k_1 \cdot A}\right)$$

$$T_2 = -15 - 6.45\left(\frac{0.025}{0.1843 \cdot 1}\right) = -14{,}12\,℃$$

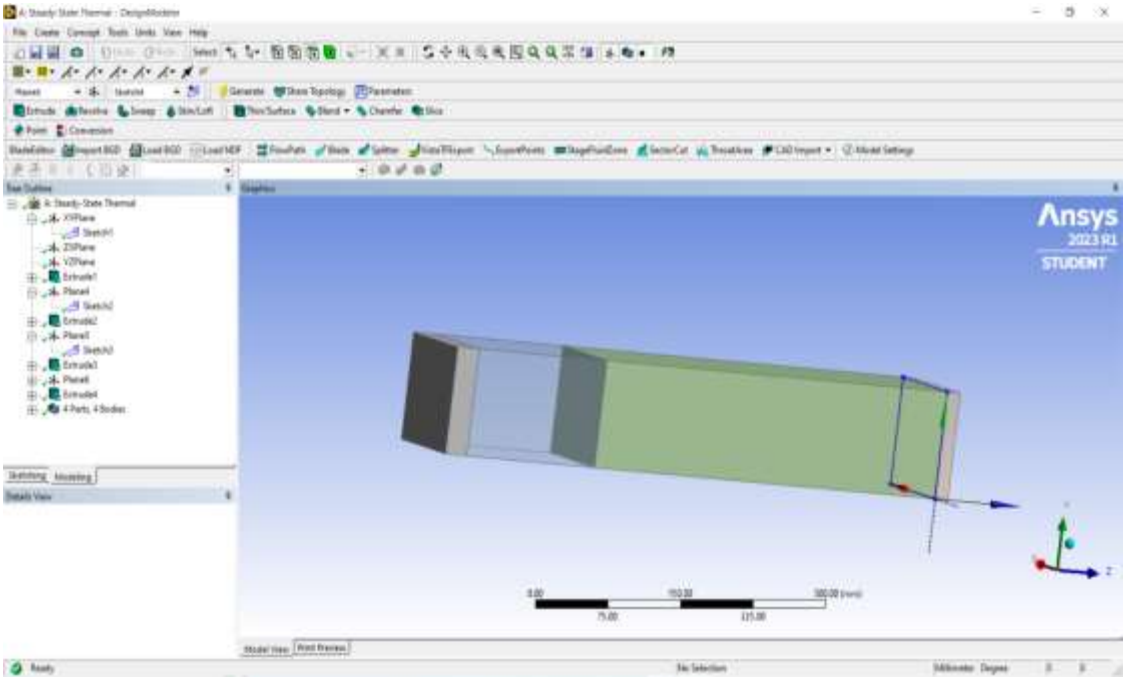

Fig. 3: Wall structure from outside to inside-model in ANSYS

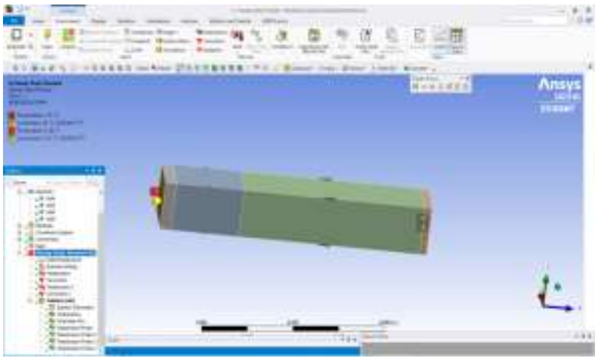

Fig. 4: Wall structure - with values for temperatures and convection coefficient on the outer/inner faces

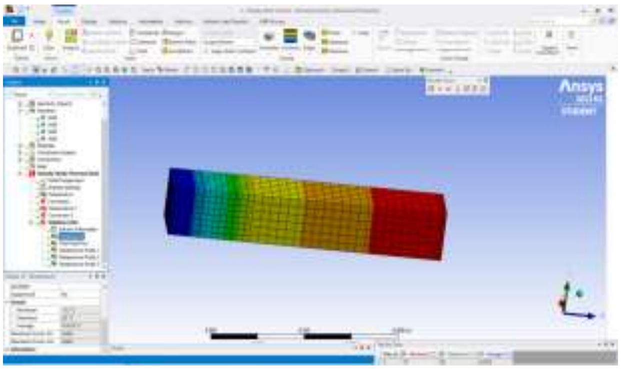

Fig. 5: Simulation of temperatures variations in the multilayer wall, from outside to inside

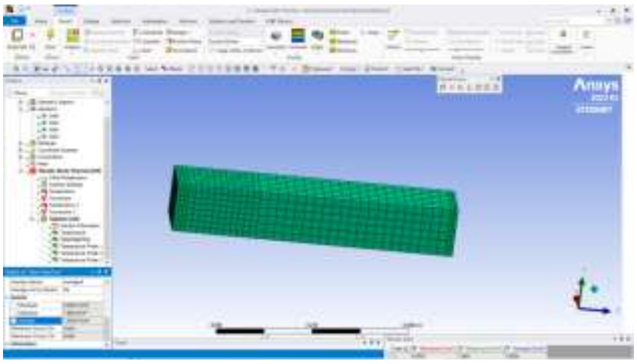

Fig. 6: Heat flow simulation for the multilayer wall, q = 6.585 W/m^2

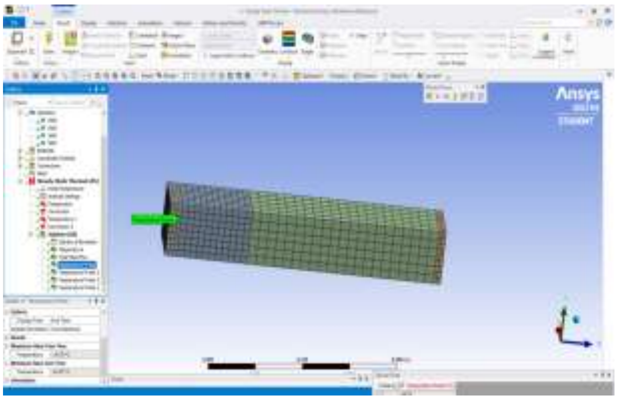

Fig. 7: The temperature after the external plaster layer, between the plaster and the thermal insulation, t_1=-14.79°C

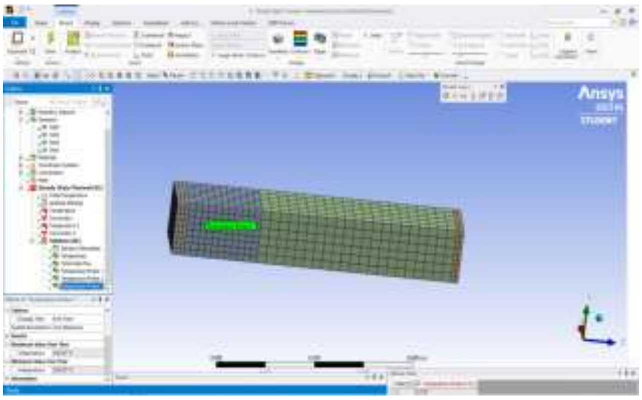

Fig. 8: Simulation of temperatures between the thermal insulation layer and the BCA layer, t_2=9.3727°C

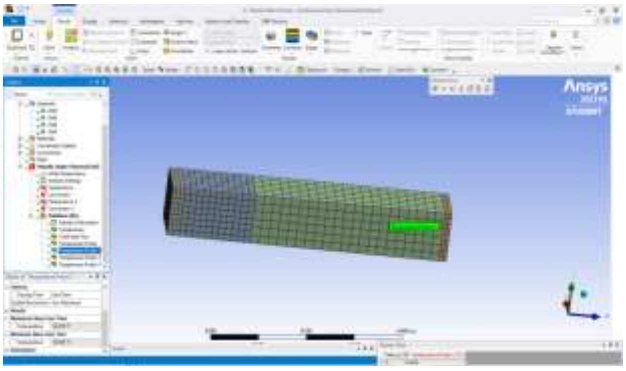

Fig. 9: Simulation of temperatures between the BCA layer and the interior plaster, t_3=19.878°C

4 Conclusion

The study presents a comparison of the determination and simulation of heat transfer, temperatures, convection coefficient for a multi-layer wall made of several component elements, different in structure and thickness.

The modeling of these types of structures with the Ansys simulation software allows a very good accuracy of the delineation of the component layers and the consideration of different heat transfer rates, coefficients, etc.

Of course, to simplify the calculations and the simulation model, both the influence of convective coefficients and indoor and outdoor temperatures have been taken into account.

As can be seen, the numerical calculations performed using the calculation relations (1) .. (7) and the values obtained from the simulations performed using Ansys are very close.

Figure 3 shows the analyzed model of the wall structure, modeled in ANSYS.

In the drawing you can see each component layer of the wall, external plaster, thermal insulation - polystyrene, BCA, and internal plaster.

Figure 4 shows the structure of the wall detailing the values of indoor/outdoor temperatures and convection coefficient for the interior and exterior surfaces.

After determining the temperatures between each component layer of the wall structure, Figure 5 shows the simulation of temperature variations in the multi-layer wall from outside to inside using the Ansys software.

The calculated value for the heat flow was q = 6.45 W/m^2, and according to Ansys simulation program the obtained value was q = 6.585 W/m^2 also very close comparing to the calculated one. Figure 6 presents the heat flow simulation at the multilayer wall.

Figure 7, Figure 8 and Figure 9 show the simulation of the temperatures at the level of each component layer of the multilayer wall, on the inner surface, t_3, between the inside component layers, t_2, and at the level of the layer in contact with the outer surface, t_1.

The temperature inside the wall varies from +20°C, to -15°C, as considered and the temperatures determined using the Ansys program simulation from outside to inner surface are: t_3=-14.79°C, t_2=9.3727°C and at the t_1= 19.878°C.

It can be seen that the largest temperature variation is, as expected after the thermal insulation layer, i.e. a difference of 10 degrees Celsius, from, t_2=9.3727°C to t_1= 19.878 °C (Figure 8 and Figure 9).

The heat flow transmitted from the inside of the room to the outside environment depends on both the overall heat transfer coefficient and the temperature difference between the two environments separated by the wall.

The simulation was made, of course, taking into account some simplifying assumptions such as, considering the values of indoor/outdoor temperatures constant throughout the simulation period, the simulations were performed in steady state regime.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

- Stan Ivan Felicia Elena carried out the simulation.
- Dinu Radu Cristian has implemented the section 2.1. Numerical modelling of heat transfer in multilayer walls
- Duinea Adelaida Mihaela has organized and executed the calculations for Section 3.

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Conflict of Interest

The authors have no conflicts of interest to declare.