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MATERIALS ENGINEERING APPLIED TO ARCHITECTURE: THERMAL ANALYSIS AND METALLURGICAL BEHAVIOR OF 18-8 STEEL AND CONVENTIONAL MATERIALS UNDER RADIATION AND NATURAL CONVECTION

ENGENHARIA DE MATERIAIS APLICADA À ARQUITETURA: ANÁLISE TÉRMICA E COMPORTAMENTO METALÚRGICO DO AÇO 18-8 E MATERIAIS CONVENCIONAIS SOB RADIAÇÃO E CONVECÇÃO NATURAL

INGENIERÍA DE MATERIALES APLICADA A LA ARQUITECTURA: ANÁLISIS TÉRMICO Y COMPORTAMIENTO METALÚRGICO DEL ACERO 18-8 Y MATERIALES CONVENCIONALES BAJO RADIACIÓN Y CONVECCIÓN NATURAL

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Alessandro Cruz Gonçalves[1], **Emanuel Lincol Duarte de Oliveira**[2], **Amanda Pisão Pinhal Noronha de Oliveira**[3], **Yan Oliveira Vasconcellos**[4], **Rachel Cristina Santos Pires**[5], **Marilyn Tamara Seguel Silva**[6], **Antonio Renato Bigansolli**[7], **Everton Rangel Bispo**[8]

ABSTRACT

Within the sustainable theme in civil construction, this article aims to analyze the heat transmission patterns through radiation and natural convection in the five most commonly used materials in civil construction, thereby demonstrating and justifying their behavior when heated. Thus, it seeks to present more effective energy solutions for civil construction in the future. As an observation tool, a three-dimensional box of a certain size, internally filled with air, will be used, where the main edge will be composed separately of 18-8 steel, aluminum, concrete, wood, and clear glass, in order to observe their characteristic behaviors. The remaining adjacent walls will be composed of insulating material. For each material, their respective values of emissivity, density, thermal conductivity, and specific heat were considered. The numerical and graphical results were obtained through the Ansys® software.

[1] BIM Specialist. UNISUAM. E-mail: gonclaves.alessandro@gmail.com

[2] Specialist in engineering and occupational safety. UNISUAM. E-mail: emanuelincon@gmail.com

[3] Postgraduate degree in legal and diagnostic engineering. Professor at the Augusto Motta University Center. E-mail: amandappisaoeng@gmail.com

[4] M.Sc. in Mechanical Engineering, COPPE-UFRJ. Professor at the Augusto Motta University Center. E-mail: yan.oliveira@souunisuam.com.br

[5] M.Sc. in Local Development with emphasis on Environmental Sciences, UNISUAM. Professor at the Augusto Motta University Center. E-mail: rachelpireseng@gmail.com

[6] M.Sc. in Civil Engineering, COPPE-UFRJ. Professor at the Augusto Motta University Center. E-mail: marilyntamara@souunisuam.com.br

[7] Ph.D. in Materials Engineering, UFRRJ. PPGCEMat Graduate Program in Materials Science and Engineering, Professor, Department of Chemical Engineering, Seropédica, RJ – Brazil. E-mail: bigansolli@ufrrj.br

[8] Ph.D. in Materials Engineering, PUC-Rio. Professor at the Augusto Motta University Center. E-mail: prof.evertonrangel@gmail.com

Keywords: Radiation and Natural Convection. Three-dimensional Box. Civil Construction.

RESUMO
Com a temática sustentável na construção civil o presente artigo tem como objetivo analisar os padrões de transmissão de calor através da radiação e convecção natural em cinco materiais mais utilizados na construção civil e dessa forma, demonstrar e justificar o seu comportamento ao ser aquecido. Assim sendo, busca-se futuramente apresentar soluções energéticas mais eficazes para a construção civil. Como instrumento de observação será utilizado uma caixa tridimensional de determinado tamanho e internamente preenchida com ar, onde a aresta principal será composta separadamente por aço 18-8, alumínio, concreto, madeira e vidro incolor, a fim de observar os seus comportamentos característicos, as demais paredes vizinhas serão compostas de material isolante. Para cada material foram consideradas os seus respectivos valores de emissividade, densidade, condutividade térmica e calor específico. Os resultados numéricos e gráficos foram obtidos por intermédio do programa Ansys®.

Palavras-chave: Radiação e Convecção Natural. Caixa Tridimensional. Construção Civil.

RESUMEN
Con la temática sustentable en la construcción civil, el presente artículo tiene como objetivo analizar los patrones de transmisión de calor a través de la radiación y convección natural en los cinco materiales más utilizados en la construcción civil y, de esta forma, demostrar y justificar su comportamiento al ser calentados. Así, se busca presentar futuras soluciones energéticas más eficaces para la construcción civil. Como instrumento de observación se utilizará una caja tridimensional de determinado tamaño, rellena internamente con aire, donde la arista principal estará compuesta separadamente por acero 18-8, aluminio, hormigón, madera y vidrio incoloro, con el fin de observar sus comportamientos característicos. Las demás paredes adyacentes estarán compuestas de material isolante. Para cada material se consideraron sus respectivos valores de emisividad, densidad, conductividad térmica y calor específico. Los resultados numéricos y gráficos fueron obtenidos mediante el programa Ansys®.

Palabras clave: Radiación y Convección Natural. Caja Tridimensional. Construcción Civil.

1 INTRODUCTION

Modeling natural radiation and convection in civil construction projects has become of paramount importance in terms of heat propagation in environments and the dimensioning of structures, bringing more effective results for energy efficiency planning in large and small constructions, cost reduction, thermal comfort, and greater precision in structural calculations.

Convection can occur naturally or through forced processes, where heat transfer happens through fluid flow along with conduction or diffusion. The fluid's behavior is determined by its tendency to contract or expand when exposed to a specific pressure and temperature.

When fluid flow occurs “naturally,” without any external influence, whether due to a difference in density resulting from a difference in temperature or specific mass between two points of a given body within a gravitational field, this process is characterized as natural convection. Fluid movement, when it occurs through external agents, such as wind or the heating of the object itself generating pressure and causing fluid movement, is called forced convection. (BEJAN and KRAUS, 2003, pages 525 and 526).

Thermal radiation transfer occurs through the exchange of energy in the form of electromagnetic waves. Due to its ability to propagate in a vacuum, it does not require a gravitational medium for heat dissemination, making it dominant in heat transfer at low or near-zero pressures. It is important to note that for its emission, the application surface must be above 0 Kelvin, equivalent to -273.15 °C (Celsius). While the flux occurring through conduction and natural convection is more linearly dependent on temperature differences, the flux of thermal radiation tends to be proportional to differences up to the fourth temperature force. (BEJAN and KRAUS, 2003, page 574).

2 LITERATURE REVIEW

2.1 COMPUTER SIMULATIONS

As a research tool and to obtain more effective results in the analysis of the proposed model, the Ansys® – Fluent software was used, which performs the study of Computational Fluid Dynamics. Fluent's scope is physical modeling, where flow patterns, turbulence, heat transfer, and radiation are determined as inputs for the study. The modeling used in this article will be directed towards heat transfer by radiation and convection.

Fluent works with all types of radioactive heat exchange, in a single fluid or between a different set of fluids and solids, from total or semi-transparent to radiation, or opaque.

2.2 THE MODEL

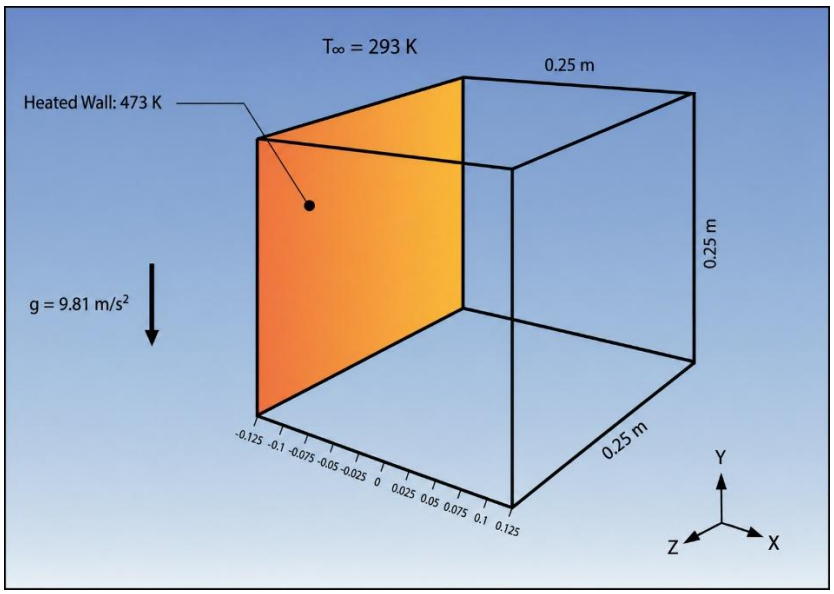
The Fluent software uses the surface-to-surface (S2S) model as its default and will be used to calculate radiation exchange.

According to the gray-body model, if a certain amount of radiation falls on a surface, a fraction will be reflected, another absorbed, and some transmitted. The surface-to-surface (S2S) model assumes that all surfaces included in the system under study are gray and diffuse, where its main premise is that any absorption, emission, or scattering of radiation can be ignored. In this analysis, only radiation between surfaces will be considered.

The research was conducted using a three-dimensional model with the following specifications:

Figure 1

Studied Three-Dimensional Model



Source: author's own work.

The main wall, located on the X-axis at point -0.125, will be considered a non-participating boundary zone in the S2S model and will have the characteristics of a given building material listed in section 2.4. This will allow for the analysis of the heat radiation emission capacity of this material to the adjacent walls.

The fluid considered in the study is laminar, has a Prandtl number of 0.71, a Rayleigh number relative to the 0.25 m length of the wall equal to $1x10^8$, and a Planck number of 0.06.

2.3 NUMERICAL SOLUTION

2.3.1 Equations of natural convection

The principle governing the movement of a fluid in natural convection is thermodynamics.

Considering the analyzed system in isolation, with a fluid of varying mass Δm flowing clockwise. The main wall is heated, and the neighboring walls are heated by thermal diffusion. At points where the static pressure is lower, the mass Δm tends to expand. Through conservation of mass, the fluid flowing to the upper part of the system must be complemented by a flow to the region of colder fluid. This process forms a cycle. When analyzing the flow system as a whole, it can be considered as the sum of the fluids of type Δm, where this clockwise movement is driven by the temperature difference Tw - T∞.

Performing the analysis through the laminar boundary layer on a flat vertical wall, the conservation equations for mass, momentum, and energy in steady state are expressed in vector form, by:

$$\rho\nabla \cdot V = 0 \tag{1}$$

$$F - \nabla P + \mu\nabla^2 V = 0 \tag{2}$$

$$\nabla \cdot (k\nabla T) + q + \mu\Phi = 0 \tag{3}$$

Where ρ is the fluid density, V is the velocity vector, F is the force vector, P is the pressure field, μ is the fluid's dynamic viscosity, k is the fluid's thermal conductivity, T is the temperature field, and Φ is the viscous dissipation.

For the sake of simplifying the analysis, this system can be considered to be in steady state, given that these are partial differential equations:

a) Flow in the laminar boundary layer;

b) Newtonian Fluid;

c) Force of gravity acting in the x direction and in the negative sense;

d) Cooling fluid: air, considered to be incompressible;

e) Absence of the source term in the Energy Equation;

f) Boussinesq approximation [(ρ – ρ∞) ≈ (Ts – T∞)];

g) Negligible viscous dissipation.

Thus, the governing equations for natural convection in the boundary layer, for Cartesian coordinates, can be expressed as:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{4}$$

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\beta(T - T_\infty) + \nu\left(\frac{\partial^2 u}{\partial y^2}\right) \tag{5}$$

$$\mathrm{u}\frac{\partial \mathrm{T}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{T}}{\partial \mathrm{y}} = \alpha\left(\frac{\partial^2 T}{\partial y^2}\right) \tag{6}$$

Where u is the velocity component in the x direction, v is the velocity component in the y direction, g is the acceleration due to gravity, v is the coefficient of thermal volumetric expansion of the fluid, T∞ is the temperature of the quiescent medium, v is the kinematic viscosity of the fluid, and α is the thermal diffusivity of the fluid. (MACHADO and ALVES, 2014, pages 4 and 5).

2.3.2 Energy equations

Heat transfer by thermal radiation consists of the transport of energy through electromagnetic waves (or photons), originating from changes in the electronic configurations of the atoms or molecules of a material (ÇENGEL; GHAJAR, 2021). Due to its ability to propagate in a vacuum, this mechanism does not require a material medium or a gravitational field for the transfer of thermal energy to occur (KREITH; MANGLIK; BOHN, 2018).

Assuming the concept of a hypothetically black body, an ideal radiator is defined that emits and absorbs the maximum amount of energy possible. That is, it absorbs all incident electromagnetic radiation, regardless of wavelength and direction, and emits the maximum possible thermal radiation for a given temperature (INCROPERA *et al.*, 2019).

Radiation emission occurs isotropically in a black body; regardless of direction, the radiation will propagate in the same way, depending only on the absolute temperature of the body (OLIVEIRA, 2014).

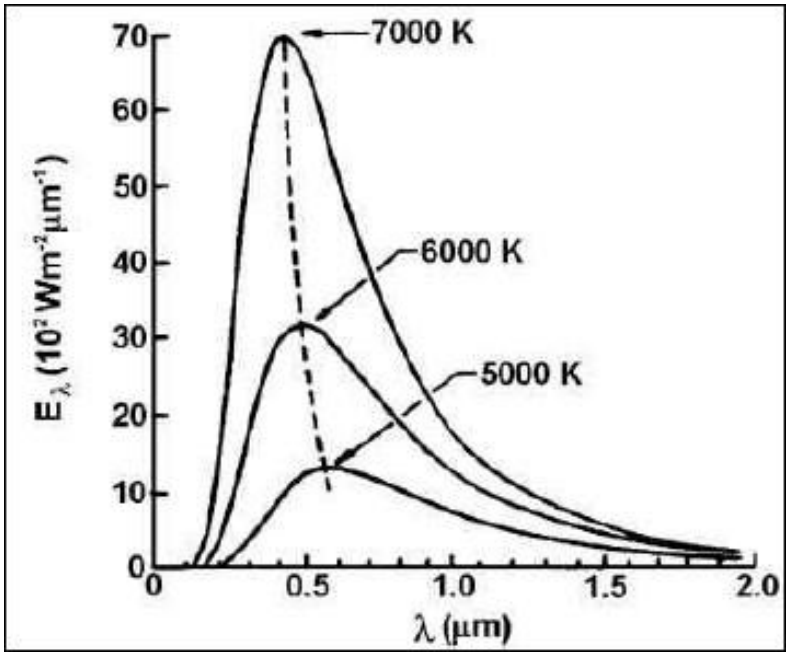
As described by Planck's Law of Distribution, the radiation emitted by a black body (spectral emissive power) is determined by its absolute temperature and the wavelength considered (MODEST; MAZUMDER, 2021). The mathematical equation that describes this phenomenon is:

$$E_{\lambda,b}(\lambda,T) = \frac{C_1}{\lambda^5\left(e^{\frac{C_2}{\lambda T}}-1\right)} \tag{7}$$

Where $E_{\lambda,b}$ is expressed in $\mathrm{W}/(\mathrm{m}^2 \cdot \mu\mathrm{m})$, T in Kelvin (K), λ is the wavelenght, C_1 e C_2 are the radiation constants and e is the base of natural logarithms ($e \approx 2{,}718$). Graphs of spectral emissive power as a function of wavelength for some temperatures are shown in the image below.

Figure 2

Monochromatic irradiance for a black body at various temperatures



Source: gRIMM,1999. TOPIC 2.5.

For very large wavelengths, equation (7) can be simplified using the Rayleigh-Jeans approximation (HOWELL *et al.*, 2020), resulting in another equation:

$$E_{\lambda,b}(\lambda,T) \approx \frac{C_1 T}{C_2 \lambda^4} \quad (8)$$

Using Planck's Law, it is possible to show, through differentiation, that the wavelength of the emission peak for a black body with temperature T is given by:

$$\lambda_{max} T = 2897.8\ \mu m \cdot K \quad (9)$$

Where λ_{max} is expressed in micrometers (μm) and T in Kelvin.

Equation (9) represents Wien's Displacement Law. Through it, it is possible to estimate the temperature of a source material from its emission spectrum. According to Wien's law, solar radiation is concentrated in visible waves and near-infrared, contrasting with that of the Earth, where the emitted radiation is confined to the atmosphere at longer wavelengths (thermal infrared). The higher the temperature of the body, the shorter the wavelength corresponding to the maximum radiation (GRIMM, 1999).

The total irradiance of the black body (total emissive power), obtained by integrating equation (7) over all wavelengths, is given by:

$$E_b = \sigma T^4 \quad (10)$$

where σ is the Stefan-Boltzmann constant, whose value is

$$\sigma \approx 5.67 \times 10^{-8}\ \frac{W}{m^2 \cdot K^4} \quad (11)$$

This is the equation for Stefan-Boltzmann's Law (ÇENGEL; GHAJAR, 2021). From it, one can conclude that a body with a higher temperature emits significantly more energy per unit area than one with a lower temperature.

As previously mentioned, blackbody radiation represents the maximum radiation limit that a real body can emit at a given wavelength, for a given temperature. For real bodies, a property called spectral emissivity is defined (ϵ_λ):

$$\epsilon_\lambda = \frac{E_\lambda(\lambda,T)}{E_{\lambda,b}(\lambda,T)} \quad (12)$$

and the total emissivity (ϵ) of a gray body (where emissivity is independent of wavelength) is given by (INCROPERA *et al.*, 2019):

$$\epsilon = \frac{E(T)}{E_b(T)} \tag{13}$$

For a black body, ϵ_λ and ϵ are equal to 1, and for real bodies they are between 0 and 1. Corresponding quantities can be defined for absorption, called spectral absorptivities (α_λ):

$$\alpha_\lambda = \frac{G_{\lambda,abs}(\lambda)}{G_{\lambda,inc}(\lambda)} \tag{14}$$

and the total absorptivity (α):

$$\alpha = \frac{G_{abs}}{G_{inc}} \tag{15}$$

Kirchhoff's radiation law states that, for a body in thermal equilibrium with its surroundings, its spectral emissivity is equal to its spectral absorptivity (HOWELL *et al.*, 2020):

$$\begin{aligned} \alpha_\lambda &= \epsilon_\lambda \\ \alpha &= \epsilon \end{aligned} \tag{16}$$

We can conclude that if a given material is a strong absorber at a certain wavelength, it becomes a strong emitter at that same wavelength. Similarly, if we consider a body with low absorption capacity, it will be a weak emitter (GRIMM, 1999).

3 DEVELOPMENT

3.1 MATERIALS

The most common materials used in civil construction were considered for the research, including 18-8 steel, aluminum, concrete, wood, and glass.

For each material, the static temperature, wall temperature, heat radiation flux, and velocity magnitude will be calculated.

The table below lists the values of the variables required to perform the computational calculations.

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Table 1

Specification of Materials

Materials	Specific Heat (c_p) J/Kg. K	Density Kg/m³	Thermal Conductivity W/m. K	Emissivity ε
18-8 steel	500	7900	16	0,14
Aluminum	871	2719	202,4	0,95
Normal Concrete	1000	2400	1,75	0,95
Wood (Oak)	1340	700	0,23	0,90
Common Glass (Colorless)	840	2500	1	0,84

Source: (Brazilian Association of Technical Standards, 2003). Stainless Steel Technical Data Sheets (Irestal Group).

The interior of the box is filled with air and has the following characteristics:

- Specific Heat (cp) = 1021 J/Kg. K
- Thermal Conductivity = 0,0371 W/m. K
- Viscosity = 2.485 x 10-5 Kg/m.s
- Molecular weight = 28.966 Kg/Kmol.
- The medium does not emit, absorb, or scatter radiation.

3.2 ANALYSIS

The numerical results for static temperature, wall temperature, heat radiation flux, and velocity magnitude for each material studied will be presented below.

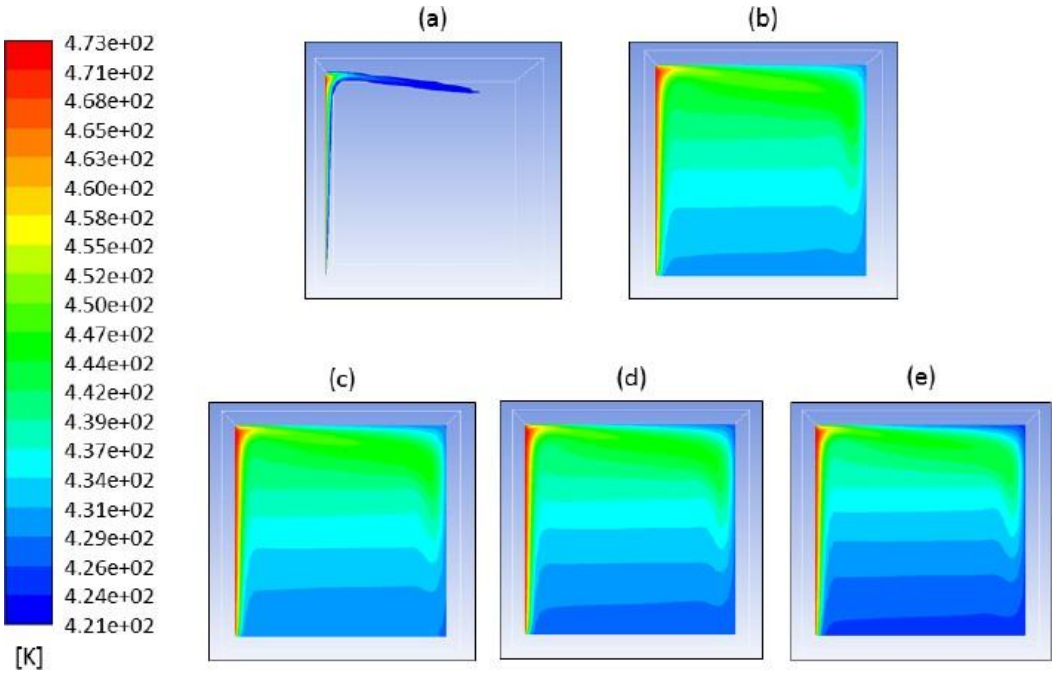
The program uses the natural convection and energy equations as the basis for its mathematical analyses, as explained in section 2.2.

3.2.1 Static temperature

The graphs shown below, as in Figure 3, present the static temperature inside the box. For this example, the temperature cutoff is shown in the middle, given its greater stability, thus providing more certainty to the results. The software uses the natural convection equations as the principle for the solution. The results are presented in Kelvin.

Figure 3

(a) 18-8 Steel (b) Aluminum (c) Concrete (d) Wood (e) Glass



Source: author's own work.

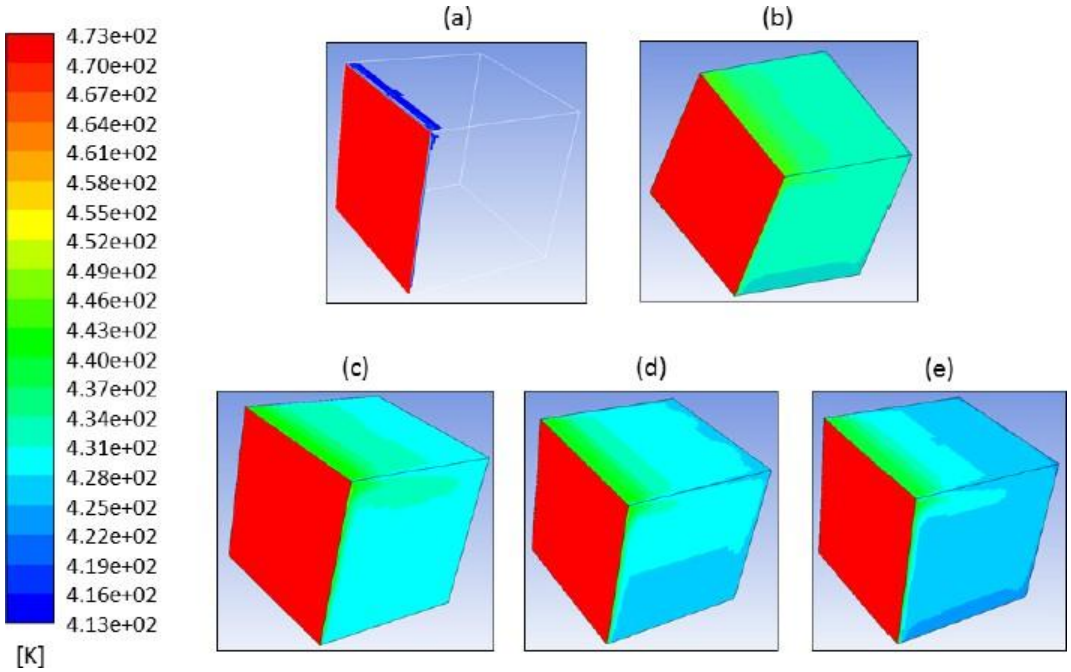
18-8 steel (a) showed very low values in relation to heat absorption and retention inside the cube; when heat was applied to it, within the imposed temperature limits, it was no longer able to visually demonstrate this. The other materials showed similar values for heat dispersion within the studied limits and their retention capacity.

3.2.2 Wall temperature

The graph shown below, Figure 4, aims to present the heat radiation values between the main wall and the neighboring walls, using the energy equations as a basis; the values are obtained in Kelvin.

Figure 4

(a) 18-8 Steel (b) Aluminum (c) Concrete (d) Wood (e) Glass



Source: author's own work.

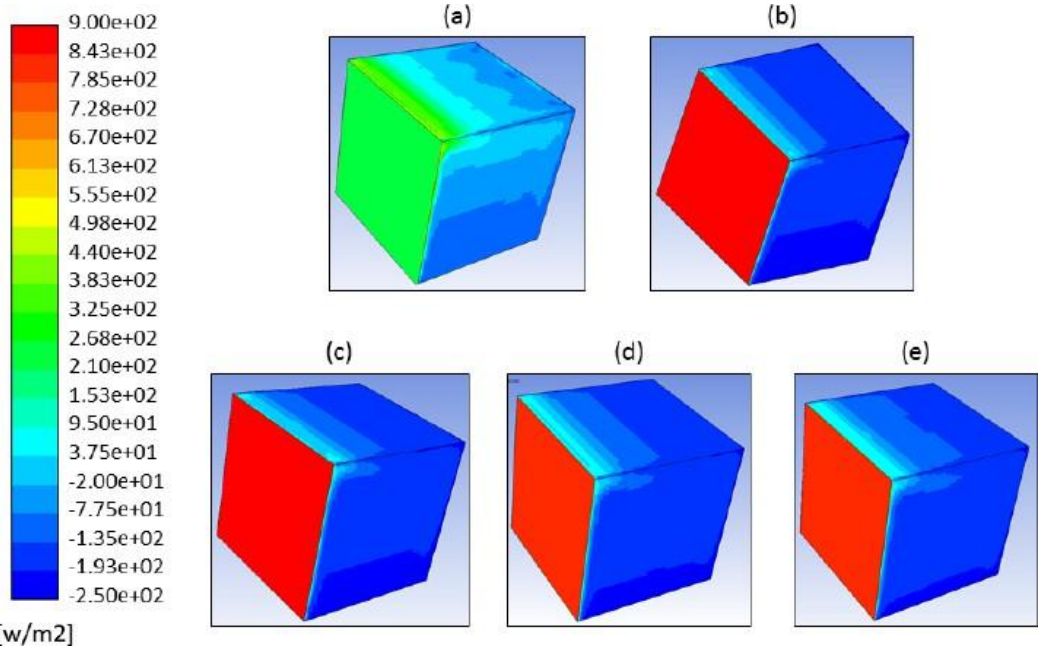
18-8 steel (a) showed surprising values compared to the other materials studied. Within the arbitrary limits, near the heated wall, the material radiated its lowest temperature limit and then, at values far below, was unable to demonstrate such results. Aluminum (b) showed high temperatures, as did concrete (c). Glass (e) demonstrated that its heat transfer capacity is much lower compared to the other materials, being very similar to that of wood (d).

3.2.3 Heat radiation flux

Figure 5, shown below, will present the heat flux to the adjacent walls when a main wall is heated. The flux is given in watts per square meter, and the energy equations are used as the basis for calculation.

Figure 5

(a) 18-8 Steel (b) Aluminum (c) Concrete (d) Wood (e) Glass



Source: author's own work.

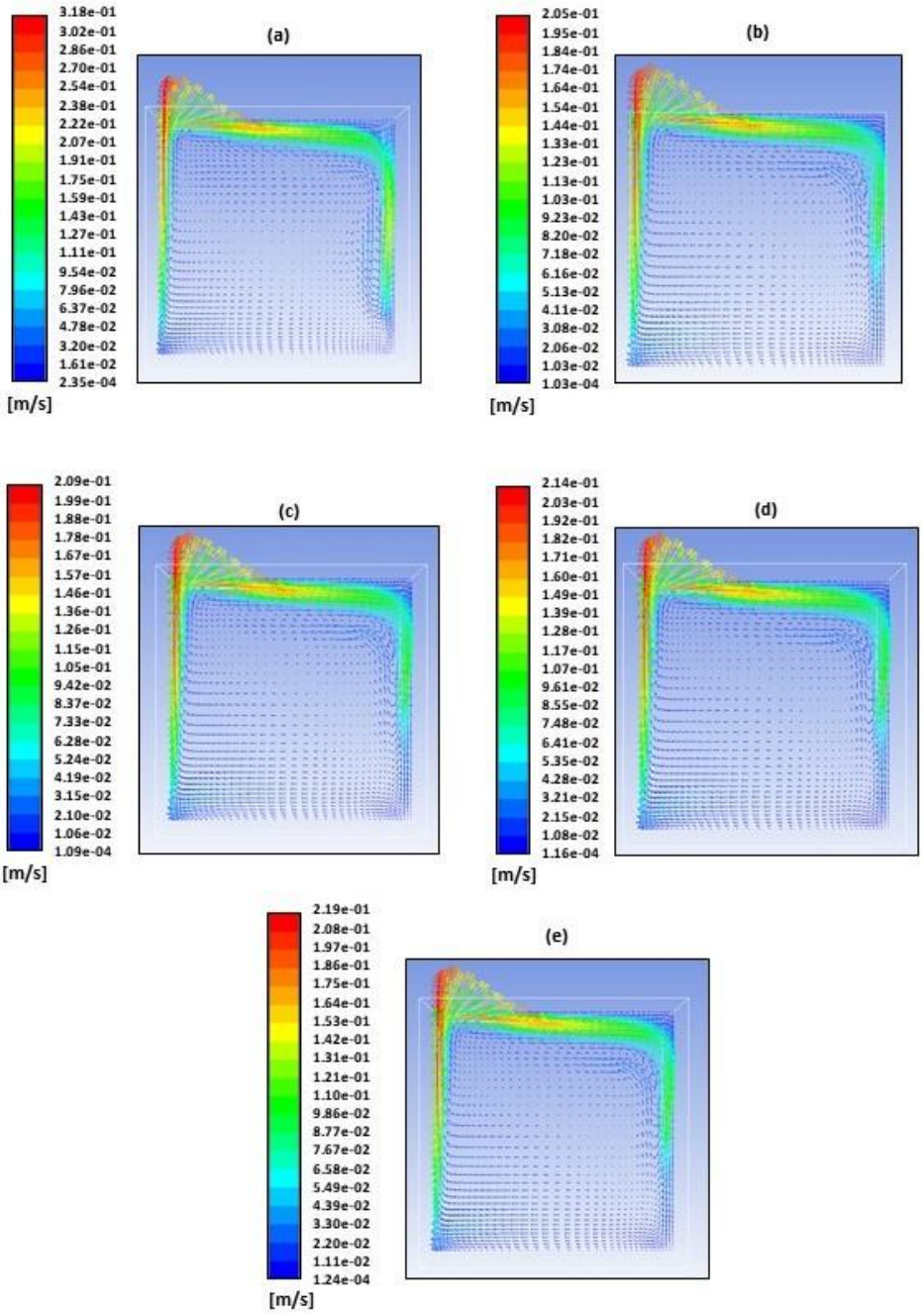
18-8 steel (a) at the instant heat is applied does not absorb and already exhibits lower values, but along its shape, it shows a more uniform distribution. Comparing materials (b) to (c), a very similar behavior was observed in terms of radiation flux; they initially absorb heat completely, but when radiating to the rest of the object, they radiate at their lowest value, thus demonstrating the low transmission capacity of these materials as well as their high capacity to retain heat.

3.2.4 Velocity magnitude

The graph shown below, Figure 6, will present the rate at which heat propagates naturally into the material, following the equations of natural convection. The result is presented in meters per second.

Figure 6

(a) 18-8 Steel (b) Aluminum (c) Concrete (d) Wood (e) Glass



Source: author's own work.

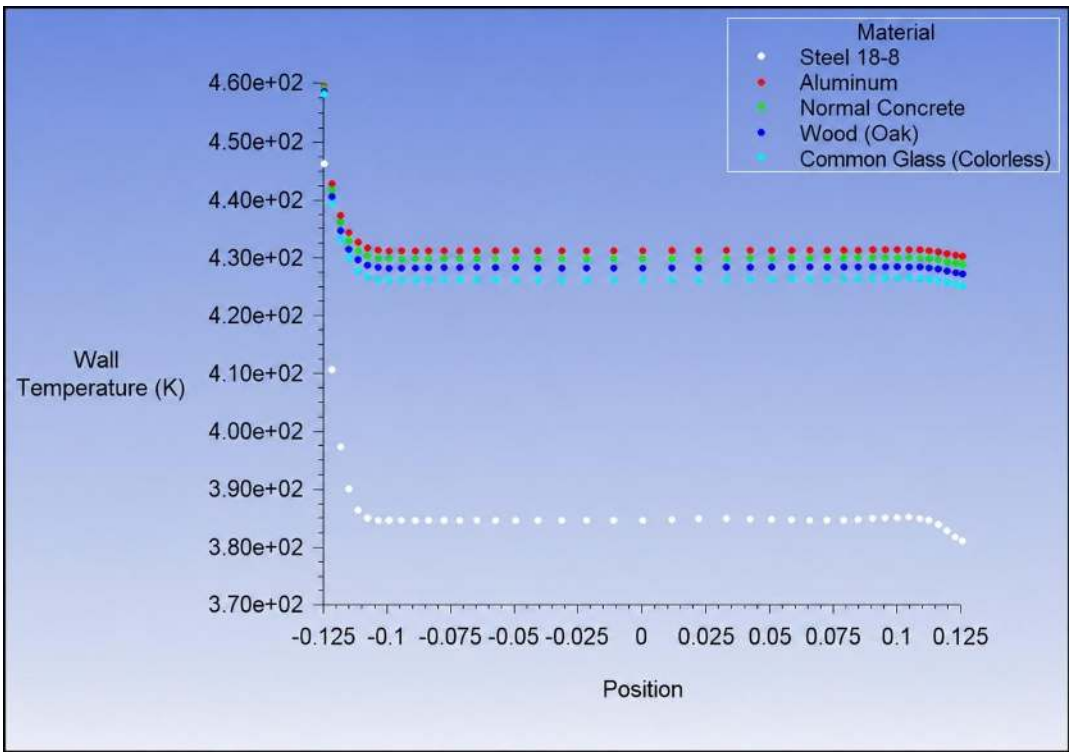
18-8 steel (a) exhibits a propagation speed approximately 0.5 times greater than that of the other materials compared here. This result demonstrates that, even when compared within the context of natural convection, in terms of radiation, its heat loss occurs at much higher rates compared to the other items between (b) and (e).

4 RESULTS

Figure 7 below shows a comparison graph of temperature flux along the geometry presented for study. This provides an overview of the entire study presented here, and its related discussions.

Figure 7

Comparison between materials



Source: author's own work.

Along the X-axis, the heat radiation between the trained materials is demonstrated, where the point -0.125 is located on the main wall and is directly heated. It is possible to observe that the 18-8 steel exhibits divergent behavior compared to other trained materials, which show similar values among themselves.

When heated, 18-8 steel tends not to absorb heat and dissipates it very quickly.

The greatest losses occur along the initial and final axes, while losses remain constant in the center.

Because it yielded the most significant values in this research, 18-8 steel receives greater attention due to its comparison with aluminum, also a metal, which differs considerably from generally metallic materials, which have a very high capacity for heat absorption and radiation.

The results obtained are justified when observing Table 1, where, in comparison with other materials, the specific heat (cp) of 18-8 steel is much lower than the others, and when compared to aluminum, another metallic material, it is half as low. Another coefficient that justifies this behavior is its emissivity (ε) and density values, which are directly correlated to the energy equations, characterizing the analysis of the material's radiation capacity.

We can conclude that if a material, such as 18-8 steel, is a poor absorber of heat at a given wavelength, it becomes a weak emitter at that same wavelength, just as a strong absorber will be a strong emitter, such as aluminum.

Analyzing the study from the perspective of the use of these materials in civil construction, the focus is not on the cost of the material, but rather on its structural performance.

When designing a structure, its performance is considered in terms of load capacity, durability, construction, and cost.

The materials studied here aim to demonstrate, not only in the area of construction, but also in the final result, which one performs best.

In Brazil, the use of steel and aluminum for cleaner and faster construction is becoming more common, contrasting with concrete. Similarly, glass, with its more architectural appeal, has gained ground due to its sustainability benefits, generating less energy consumption in the form of electricity.

From a structural standpoint, comparing the most commonly used materials, which are aluminum, steel, concrete, and wood, steel would offer significantly more benefits in terms of thermal comfort compared to the others under analysis, given its low emissivity and specific heat. However, at the level of structural calculations, it presents a high density.

From an architectural perspective, steel is highly sought after due to its workability and ease of construction. Glass, on the other hand, is widely used for internal lighting purposes, thus saving on electricity costs for lighting. However, for thermal comfort, it is not as advantageous due to its heat absorption, radiation, and temperature transfer to the environment, making the use of a more efficient cooling system necessary.

In summary, 18-8 steel is the material that offers the most benefits in terms of civil construction, both in terms of physical and mechanical properties, and is therefore the most suitable for such purposes.

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