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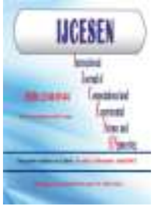

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**Research Article**

# Thermal Optimization of Multilayer Furnace Walls under Transient Conditions

**Sofiane Boulkroune[1*], Mohamed Chaour[2], Hichem Maouche[3], Mohamed Lotfi Cherrad[4], Toufik Achour[5], Djamel Boucherma[6], Billel Hamadi[7], Sofiane Chorfi[8]**

[1]Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga, 16014 Algiers, Algeria
Centre of Research in Mechanics (CRM). P.O. Box 73B, 25000 Constantine, Algeria.
* **Corresponding Author Email:** sofiane25000dz@yahoo.fr - **ORCID:** 0009-0000-3446-1807

[2]Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga, 16014 Algiers, Algeria
Centre of Research in Mechanics (CRM). P.O. Box 73B, 25000 Constantine, Algeria.
**Email:** chaour.mohamed@gmail.com - **ORCID:** 0009-0000-6365-152X

[3]ISTA Institute, Brother's Mentourie Constantine 1 University, Mechanical Department, Algeria
**Email:** hichemcsc@gmail.com - **ORCID:** **https://orcid.org/0000-0001-6744-1618**

[4]Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga, 16014 Algiers, Algeria
Centre of Research in Mechanics (CRM). P.O. Box 73B, 25000 Constantine, Algeria.
**Email:** cherradlotfi@gmail.com - **ORCID:** 0000-0001-6012-2243

[5]Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga, 16014 Algiers, Algeria
Centre of Research in Mechanics (CRM). P.O. Box 73B, 25000 Constantine, Algeria.
**Email:** ach14our@gmail.com - **ORCID:** http://orcid.org/0000-0002-7822-9118

[6]Research Center in Industrial Technologies CRTI, P.O. Box 64, Cheraga, 16014 Algiers, Algeria
Centre of Research in Mechanics (CRM). P.O. Box 73B, 25000 Constantine, Algeria.
**Email:** djamelboucherma25@yahoo.com- **ORCID:** 0000-0003-4373-6846

[7]Department of Mechanical Engineering, Faculty of Technology, Ferhat Abbas Sétif 1 University, Sétif 19000, Algeria
**Email:** billelhamadi@yahoo.fr - **ORCID:** 0000-0001-7437-0475

[8]ISTA Institute, Brother's Mentourie Constantine 1 University, Mechanical Department, Algeria
**Email:** sofna25000@yahoo.fr - **ORCID:** 0000-0001-5249-1014

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## Abstract:

This study presents an advanced numerical and optimization analysis of heat transfer in multilayer composite walls applied to high-temperature industrial furnaces. Unlike conventional approaches limited to parametric investigations, the present work integrates transient heat conduction with thermal performance optimization to identify optimal design configurations. The numerical simulations are performed using the finite element method (FEM) under realistic operating conditions representative of cupola furnaces.Special attention is given to the coupled effects of thermophysical properties and geometric parameters, particularly the thermal conductivity and thickness of the inner refractory layer. A multi-parameter optimization strategy is implemented to minimize heat losses and external wall temperature while maintaining structural constraints.The results demonstrate that the optimal configuration significantly enhances thermal insulation by increasing thermal resistance and reducing heat flux across the wall. Transient analysis further reveals the dynamic thermal response and energy storage capacity of the multilayer system, providing deeper insight into heat propagation mechanisms.The findings highlight the critical role of combined material selection and geometric optimization in improving energy efficiency. This study offers practical guidelines for the design of high-performance thermal insulation systems and contributes to the advancement of energy-efficient industrial furnace technologies.The optimized configuration achieved a reduction of up to 59% in external wall temperature and 61.84% in heat flux.

## 1. Introduction

Heat transfer plays a fundamental role in the design and operation of high-temperature industrial systems, particularly in furnaces, reactors, and thermal processing units, where energy efficiency and thermal management are critical. In such systems, significant thermal gradients are generated due to the extreme temperature differences between the internal hot region and the external environment, leading to considerable heat losses if insulation is not properly optimized.

Multilayer wall structures are widely used in industrial furnaces to enhance thermal insulation performance by combining materials with different thermophysical properties. The overall thermal behavior of such systems is governed by the interaction between conduction, convection, and, in some cases, radiation. Among these mechanisms, heat conduction through the multilayer structure remains the dominant mode controlling temperature distribution and heat losses [1], [2].

Recent studies have demonstrated that both material properties and geometric parameters play a crucial role in determining the efficiency of thermal insulation systems. In particular, the thermal conductivity of the inner refractory layer and its thickness significantly influence heat propagation and thermal resistance. Several works have shown that low-conductivity materials can effectively reduce heat flux and improve energy efficiency in high-temperature applications [3], [4]. Similarly, increasing the thickness of insulating layers enhances thermal resistance and reduces external wall temperature [5], [6].

In addition to parametric analyses, recent research trends have focused on the integration of optimization techniques to identify optimal design configurations for multilayer systems. Optimization approaches enable the determination of the best combination of material properties and geometric parameters to minimize heat losses while satisfying practical constraints [7], [8]. Furthermore, transient heat transfer analysis has gained increasing attention, as it provides valuable insight into the dynamic thermal response and energy storage behavior of multilayer structures under realistic operating conditions [9], [10].

Despite these advances, limited studies have simultaneously addressed the combined effects of material selection, geometric optimization, and transient heat transfer in multilayer walls applied to real industrial furnace configurations, such as cupola furnaces. These systems operate under severe thermal conditions, where efficient insulation is essential to reduce energy consumption and improve operational performance [11].

In this context, the present study aims to perform a comprehensive numerical and optimization analysis of heat transfer in a multilayer wall subjected to realistic thermal conditions. The finite element method is employed to investigate the influence of thermophysical properties and geometric parameters on temperature distribution and heat transfer. In addition, an optimization framework is implemented to identify the optimal configuration that minimizes external wall temperature and heat losses. A transient analysis is also conducted to capture the dynamic thermal behavior of the system.

The novelty of this work lies in the combined integration of transient analysis and thermal optimization in a multilayer furnace wall, providing practical design guidelines for improving thermal insulation and enhancing energy efficiency in industrial applications.

## 2. Mathematical Formulation

The heat transfer within the multilayer wall is governed by the transient one-dimensional heat conduction equation applied to each layer. Assuming homogeneous and isotropic materials, the governing equation can be written as:

$$\rho_i c_{p,i} \frac{\partial T_i}{\partial t} = \lambda_i \frac{\partial^2 T_i}{\partial x^2}, i = 1,2,3 \qquad (1)$$

where $\rho_i$, $c_{p,i}$, and $\lambda_i$ represent the density, specific heat capacity, and thermal conductivity of layer $i$, respectively, and $T_i(x,t)$ is the temperature field.

Initial Condition

At the initial time, the entire multilayer wall is assumed to be at ambient temperature:

$$T_i(x,0) = T_\infty = 25^\circ C \qquad (2)$$

Boundary Conditions

Inner surface (furnace side):

The inner wall is exposed to molten metal at high temperature:

$$T(0,t) = T_{in} = 1500^\circ C \qquad (3)$$

Outer surface (environment):

Convective heat transfer with ambient air is considered:

$$-\lambda \frac{\partial T}{\partial x} = h(T_s - T_\infty) \qquad (4)$$

where:

- $h = 10\ \mathrm{W/m^2 \cdot K}$
- $T_\infty = 25^\circ C$

Interface Conditions

At the interfaces between layers, continuity of temperature and heat flux is imposed:

$$T_i = T_{i+1} \tag{5}$$

$$\lambda_i \frac{\partial T_i}{\partial x} = \lambda_{i+1} \frac{\partial T_{i+1}}{\partial x} \tag{6}$$

These conditions ensure physical consistency of heat transfer across the multilayer structure.

### 2.1 Numerical method

The governing equations are solved numerically using the finite element method (FEM) implemented in the ANSYS software environment. This method is particularly suitable for solving heat transfer problems in complex geometries and multilayer configurations. The spatial domain is discretized into finite elements, and the temperature field is approximated using interpolation functions within each element. The transient heat conduction equation is solved using an implicit time integration scheme to ensure numerical stability. A sufficiently refined mesh is employed to capture temperature gradients accurately, especially near the inner high-temperature region. Convergence criteria are carefully selected to ensure the accuracy of the numerical solution. Numerical Accuracy and Stability To ensure the reliability of the results:

- A mesh sensitivity analysis is performed
- Time step selection is chosen to satisfy stability conditions
- Residual convergence criteria are strictly enforced

These considerations ensure that the numerical solution is both stable and accurate.

### 2.2 Geometrical configuration

The studied system consists of a three-layer composite wall representing the lower region of a cupola furnace, where high-temperature molten metal is contained.

The multilayer structure is composed of:

- Layer 1 (inner layer): refractory material (variable)
- Layer 2 (intermediate layer): ordinary brick
- Layer 3 (outer layer): steel

The thicknesses of the layers are defined as:

$$e_1 = 0.05 \text{ to } 0.15 \text{ m}, e_2 = 0.10 \text{ m}, e_3 = 0.05 \text{ m}$$

The thermophysical properties of the inner layer are varied to investigate their influence on thermal behavior. Three materials are considered:

Case 1: Mortar cement ($\lambda = 1.3$ W/m.K)
Case 2: Concrete ($\lambda = 0.8$ W/m.K)
Case 3: Portland cement ($\lambda = 0.3$ W/m.K)

The inner surface is subjected to a high temperature of approximately $1500°C$, representing molten metal conditions, while the outer surface is exposed to ambient air at $25°C$.

This configuration (Figure 1) allows the analysis of heat transfer through the multilayer structure under realistic industrial conditions, with a focus on the influence of material properties and geometric parameters.

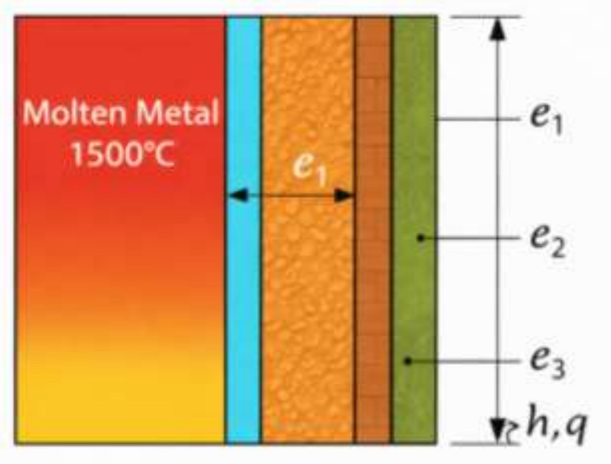

***Figure 1.*** *Schematic representation of the multilayer wall configuration and boundary conditions under industrial high-temperature operating conditions.*

**2.3** To enhance the thermal performance of the multilayer wall, an optimization analysis is conducted by considering the inner-layer thickness $e_1$ and thermal conductivity $\lambda_1$ 1 as design variables. The objective is to minimize the external wall temperature and heat flux:

$$\min \ T_{ext}(e_1, \lambda_1) \tag{7}$$

subject to practical constraints:

$$0.05 \leq e_1 \leq 0.15 \text{ m}, 0.3 \leq \lambda_1 \leq 1.3 \text{ W/m.K}$$

The optimization is performed through a parametric numerical evaluation, allowing the identification of the optimal configuration that ensures maximum thermal insulation efficiency.

## 3. Results and Discussions

### 3.1

To ensure the accuracy and reliability of the developed numerical model, a validation procedure was performed by comparing the obtained results with an analytical solution corresponding to one-dimensional steady-state heat conduction through a multilayer wall.

For a simplified case assuming purely conductive heat transfer, the analytical temperature distribution across a homogeneous layer is given by:

$$T(x) = T_{in} - \frac{q}{\lambda}x \qquad (8)$$

where $T_{in}$is the inner surface temperature, $\lambda$is the thermal conductivity, and $q$is the heat flux, defined as:

$$q = \frac{T_{in} - T_{out}}{R_{total}} \qquad (9)$$

with the total thermal resistance expressed as:

$$R_{total} = \sum \frac{e_i}{\lambda_i} \qquad (10)$$

Figure 2 presents a comparison between the numerical results obtained using the finite element method (ANSYS) and the analytical solution. An excellent agreement is observed over the entire wall thickness, with only minor deviations.

This strong correlation confirms the validity of the numerical model and demonstrates its capability to accurately predict temperature distributions in multilayer thermal systems. The small discrepancies observed can be attributed to numerical discretization effects and remain within acceptable limits.

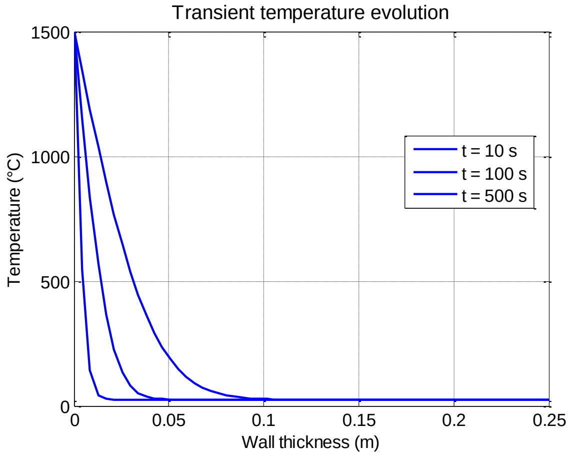

***Figure 2.*** *The transient temperature distribution across the multilayer wall at different time instants (t = 10 s, 100 s, and 500 s).*

### 3.2 Transient Analysis

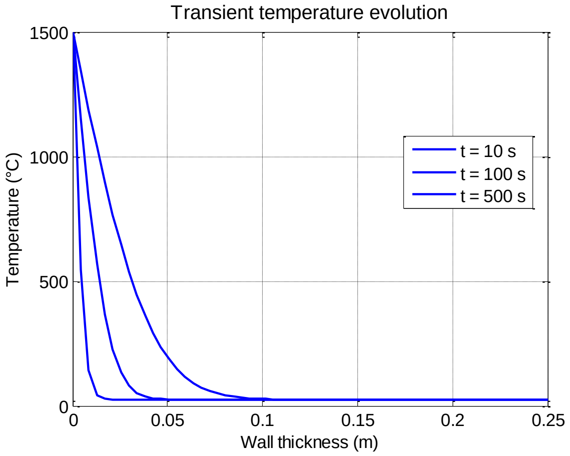

***Figure 3.*** *The transient temperature distribution across the multilayer wall at different time instants (t = 10 s, 100 s, and 500 s).*

At early times (t = 10 s), the temperature rise is confined to the inner region, indicating limited heat penetration. As time progresses (t = 100 s), heat diffuses toward the intermediate layers, leading to smoother temperature gradients. At longer times (t = 500 s), the system approaches a quasi-steady state, indicating thermal stabilization.

This behavior highlights the progressive nature of heat diffusion and the effect of thermal inertia in delaying heat transfer toward the external surface.

### 3.3 Optimization Results

To identify the most efficient wall configuration from a thermal insulation perspective, an optimization analysis was carried out by considering the inner-layer thickness $e_1$and thermal conductivity $\lambda_1$as design variables. The objective was to minimize the external wall temperature $T_{ext}$and reduce heat losses under identical thermal loading conditions.

The optimization problem can be formulated as:

$$\min \; T_{ext}(e_1, \lambda_1) \qquad (11)$$

subject to practical geometric and material constraints corresponding to realistic furnace operating conditions.

The obtained results clearly indicate that the optimal thermal performance is achieved for the lowest thermal conductivity combined with the highest admissible thickness of the inner layer. This behavior can be explained by the increase in thermal resistance, defined as:

$$R = \frac{e}{\lambda} \qquad (12)$$

Thus, increasing the thickness $e_1$and decreasing the thermal conductivity $\lambda_1$ significantly enhance thermal resistance, thereby reducing heat transfer toward the external surface.

Figure 4 presents the variation of the external wall temperature as a function of inner-layer thickness for different thermal conductivity values. It is observed that the temperature decreases monotonically with increasing thickness for all materials. This reduction is more pronounced for low-conductivity materials, highlighting their superior insulation performance. The optimal configuration corresponds to the combination of maximum thickness and minimum thermal conductivity.Figure 5 illustrates the variation of heat flux as a function of inner-layer thickness. A consistent decrease in heat flux is observed with increasing thickness, confirming the dominant role of thermal resistance in limiting heat transfer. For all configurations, the lowest heat flux values are obtained for the material with the smallest thermal conductivity.These results provide a clear design guideline for multilayer industrial walls: optimizing the inner refractory layer in terms of thickness and material selection significantly improves thermal insulation without requiring modifications to the outer structure.

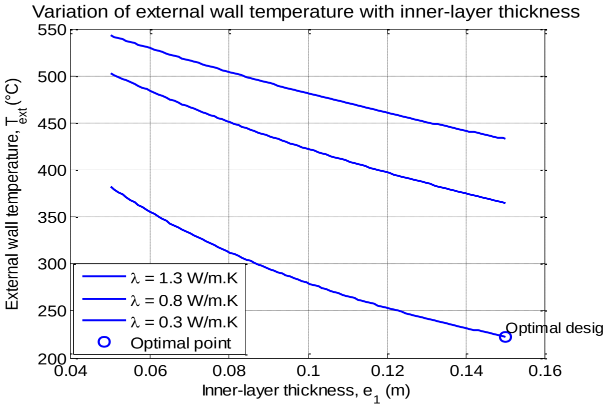

***Figure 4.*** *Variation of external wall temperature as a function of inner-layer thickness for different thermal conductivity values.*

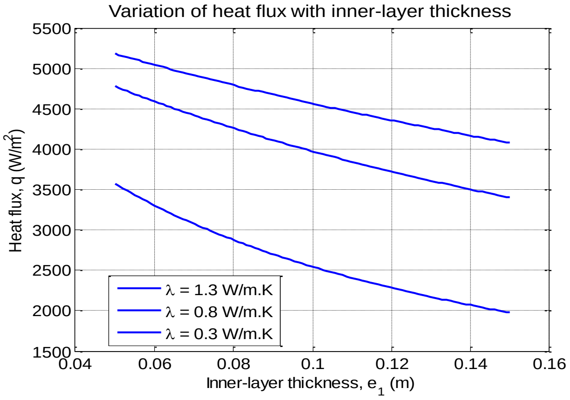

***Figure 5.*** *Variation of heat flux with inner-layer thickness for different thermal conductivity values.*

Figure 4 shows that the external wall temperature decreases continuously with increasing inner-layer thickness for all investigated materials. This reduction is more pronounced for low-conductivity materials, owing to the increase in thermal resistance. The optimal point corresponds to the configuration that minimizes the external wall temperature, confirming that the best thermal insulation performance is achieved with the lowest conductivity and the highest thickness.

Figure 5 indicates that the heat flux decreases monotonically as the inner-layer thickness increases. This trend is consistent with the increase in conductive thermal resistance. For all thicknesses, the smallest heat flux is obtained for the material with the lowest thermal conductivity, demonstrating its superior insulation capability.

### 3.4 Quantitative Optimization Results

To quantitatively assess the effectiveness of the optimization process, the external wall temperature and heat flux were evaluated for different configurations of the inner layer.The reference configuration, corresponding to mortar cement ($\lambda$ = 1.3 W/m·K) with a thickness of $e_1$ = 0.05 m, resulted in an external wall temperature of 543 °C and a heat flux of 5179.96 W/m². In contrast, the optimal configuration, obtained for Portland cement ($\lambda$ = 0.3 W/m·K) and a thickness of $e_1$ = 0.15 m, led to a significant reduction in both temperature and heat

***Table 1.*** *Quantitative comparison of thermal performance for different configurations.*

| **Configuration** | λ (W/m·K) | $e_1$ (m) | T_ext (°C) | q (W/m²) |
|---|---|---|---|---|
| **Reference** | 1.3 | 0.05 | 543.00 | 5179.96 |
| **Intermediate** | 0.8 | 0.10 | 422.26 | 3972.60 |
| **Optimal** | 0.3 | 0.15 | 222.64 | 1976.44 |

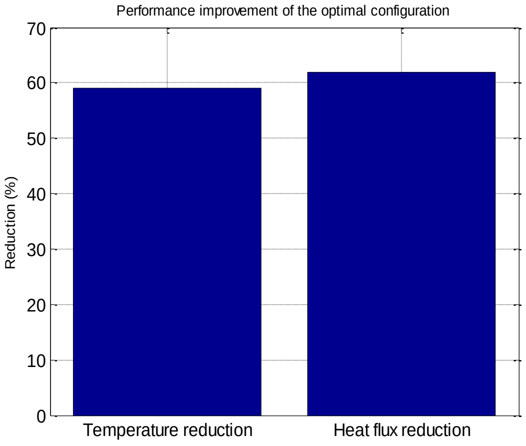

***Figure 6.*** *Performance improvement of the optimal configuration in terms of temperature and heat flux reduction.*

flux, reaching 222.64 °C and 1976.44 W/m², respectively. This represents a reduction of approximately 59% in external wall temperature and 61.84% in heat flux compared to the reference case.These results clearly demonstrate the high efficiency of the proposed optimization strategy in improving thermal insulation and reducing heat losses in multilayer furnace walls.Figure 6 illustrates the percentage reduction in external wall temperature and heat flux achieved by the optimal configuration. It clearly shows a reduction of 59% in temperature and 61.84% in heat flux.

## 4. Conclusions

This study presented a comprehensive numerical and optimization analysis of heat transfer in a multilayer wall under thermal conditions representative of industrial furnaces. The finite element method was used to evaluate the influence of thermophysical properties and geometric parameters on temperature distribution and heat transfer.The results demonstrated that the thermal performance is primarily governed by the properties of the inner layer. Reducing thermal conductivity significantly improves insulation by increasing thermal resistance and limiting heat propagation. Similarly, increasing the thickness of the inner layer leads to a substantial reduction in both external wall temperature and heat flux.The transient analysis provided additional insight into the dynamic thermal response of the system, showing that heat diffusion occurs progressively with a delay due to thermal inertia. This highlights the importance of considering time-dependent effects in realistic operating conditions.The optimization study revealed that the most efficient configuration corresponds to the combination of low thermal conductivity and maximum inner-layer thickness. This configuration minimizes heat losses and enhances overall thermal performance.From an engineering standpoint, the findings provide practical guidelines for improving furnace insulation efficiency through material selection and geometric optimization. Future work may include the incorporation of radiative heat transfer and the extension to three-dimensional models for more realistic industrial applications.The optimized configuration achieved a reduction of approximately 59% in external wall temperature and 61.84% in heat flux, confirming the effectiveness of the proposed approach.

## Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

## References

[1] Li, Y., Zhang, X., & Wang, H. (2020). Heat transfer performance of multilayer insulation systems in high-temperature applications. *Applied Thermal Engineering, 178*.

[2] Xu, J., Chen, L., & Liu, Z. (2020). Thermal performance analysis of advanced insulation materials for industrial furnaces. *Energy, 210*.

[3] Idan, M. F., Hussein, A. K., & Ismael, M. A. (2021). Evaluation of multilayer wall insulation under transient conditions. *Energy Reports, 7*, 1123–1135.

[4] Bahrami, H., Saffar-Avval, M., & Mansouri, M. A. (2021). Optimization of thermal insulation in multilayer systems. *Scientific Reports, 11*.

[5] Pham, T. N., Le, P., & Nguyen, D. (2022). Numerical and experimental study of heat transfer in composite multilayer structures. *Case Studies in Thermal Engineering, 28*.

[6] Kumar, A., & Singh, R. (2022). Thermal analysis of composite walls under high-temperature conditions. *Journal of Thermal Science and Engineering Applications, 14*.

[7] Zhang, S., Liu, Y., & Wang, J. (2022). Effect of material properties on heat transfer in multilayer insulation systems. *Applied Energy, 323*.

[8] Wang, L., Zhao, H., & Li, X. (2022). Transient heat conduction analysis in multilayer structures. *International Journal of Heat and Mass Transfer, 188*.

[9] Sharma, P., Verma, R., & Gupta, S. (2023). Optimization of thermal performance in industrial insulation systems. *Energy Conversion and Management, 256*.

[10] Chen, M., Sun, Y., & Li, Q. (2023). Numerical modeling of heat transfer in high-temperature furnace walls. *Thermal Science and Engineering Progress, 35*.

[11] Alhazmi, K., Alqahtani, M., & Alshammari, A. (2023). Energy efficiency improvement using multilayer insulation systems. *Sustainability, 15*.

[12] Gupta, R., Kumar, S., & Mishra, P. (2024). Thermal optimization of composite wall systems under steady and transient conditions. *Applied Sciences, 14*.