

Computational Fluid Dynamic Analysis in Tunnel Kiln, a Holistic Approach

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Abstract: - In this research, we analyze the effect of the geometric characteristics of the ceramics as well as the effect of their placement at different distances on the temperature distribution of the furnace. The computational analysis and simulation aimed at producing results were carried out with the ANSYS-CFX computer package. The analysis was based on how these factors affect the backflow and specifically to what extent the temperature rises in the preheating zone and how well we can maintain better thermal uniformity. Specifically, reducing the height of the stacks as well as increasing their width gives a greater increase in the backflow. The thermal distribution shows great non-uniformity by modifying these parameters. However, these smaller stacking widths help in thermal homogeneity. In relation to flow velocity and turbulence, it was observed that we have higher values in the center of the oven than on the sides. There is also great sensitivity to the Reynolds number.

Key-Words: - Tunnel kiln, thermal analysis, energy efficiency, Computational Fluid Dynamics (CFD), Turbulent flow, ceramics, combustion.

Received: February 13, 2026. Revised: April 15, 2026. Accepted: June 26, 2026. Published: October 21, 2026.

1 Introduction

The energy consumption of ceramic processes has been a topic of interest recently, resulting in many cost-benefit analyses. There are many recommendations for improvements [1], [2]. There are several mechanisms that recommend improvements in processes as well as in air circulation with the aim of saving energy and reducing the carbon footprint. All studies are based on the way heat transfer occurs and are based on mathematical and numerical analyses as well as statistical energy approaches. Therefore, measures must be taken to improve these conditions, and policies must also be directed in this direction [3], [4], [5], [6], [7].

Numerical analyses to examine the furnace performance and make suggestions for improvements were carried out [8], [9], [10]. These analyses particularly focused on the combustion zone and how it affects the overall furnace. The studies were also based on existing data, and the result was to suggest a way to recover heat for better energy efficiency [11]. [12] used a mathematical model to create the temperature curve according to which we would better understand what was happening inside the oven. It is a combination of

mathematical and experimental approaches to study the energy consumption in the tunnel kiln.

[13] created a model to study the temperature distribution inside the oven. The results were also compared with experimental measurements, resulting in the proposal of a way to reduce consumption and recover energy inside the oven [14], [15]. [16] used CFD to analyze the factors in a ceramic kiln and improve energy consumption. The factors that affect the heating analysis are many and have been analyzed [17], [18], [19]. [20] conducted their research in the firing zone. The mathematical model focused on the import and export of air, parameterizing it, and on the study of different fuels [21]. How to improve product quality and minimize the energy costs according to new data was analyzed [22], [23], [24], [25], [26].

[27] developed a model using CFD to study the heat transfer inside the kiln. He used validated values from experimental results to evaluate the tunnel kiln operation and to suggest improvements. The results concerned the environmental impact and physical impacts inside the kiln based on the temperature and air velocity as well. He also focused on the geometric positioning of the ceramics. [28] used a mathematical model focused

mainly on the two zones of the ceramic furnace, namely the preheating and combustion zone, where the effect of these zones on fuel consumption was studied [29], [30]; thus, a connection between temperature and energy consumption was made. A study focusing on the angle of incidence at which the temperature will be transmitted in an oven in combination with the heat transfer between the products was made. In addition, the stacking of the products was studied in combination with the Reynolds number [31]. [32] studied with a numerical model the different stacking of bricks in comparison with the surface roughness of the ceramics and how it affects the thermal behavior of the kiln. [33] tried to improve the final product by performing numerical analyses on the oven while at the same time studying the oven's performance from an energy perspective [34]. There is also a numerical study focusing on the addition of materials for better oven performance [35].

In the following research using CFD, the ceramic kiln was studied. The kiln is a typical square kiln consisting of three zones: preheating, combustion, and cooling. These zones have a specific length, and the air inlet for combustion and ventilation is made of circular cross-sections. For the solution, the ANSYS-CFX software was used, which, with the help of finite volumes and fluid dynamics, solves similar problems, while tetrahedral elements were chosen for the computing setup. The numerical solutions were estimated with the existing literature results and the industrial values so as to have a better understanding of the results and the chosen solution proposal.

2 Simulation Method

2.1 Tunnel Kiln Geometry

The assessment of the resolution of such simulations is based on the results of modeling flow in a tunnel kiln calculated with Computational Fluid Dynamics (CFD) methods. The tunnel kiln is designed as a rectangular shape with gas and air inlets and outlets. The tunnel kiln is 100 m long with a height of 1,50 m and a width of 3,24 m. The preheating zone is 38,40 m, the firing zone with burners is 14,52 m, and the cooling zone is 47,08 m, as shown in Figure 1. In the preheating zone, there are no burners. In the firing zone, the burners are at the top of the kiln, and there aren't any side burners.

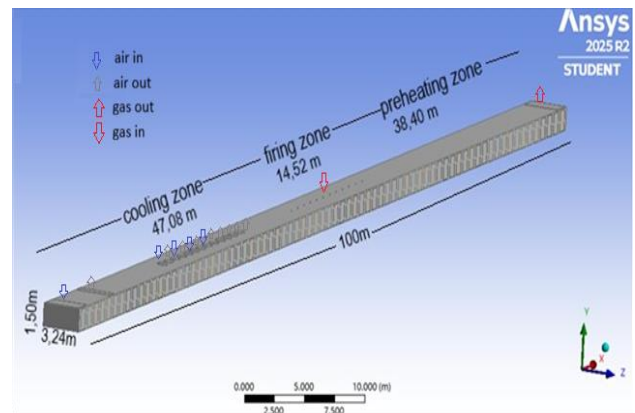


Fig. 1: A three-dimensional visualization of the tunnel kiln

Source: created by the authors

The first air in is located right at the beginning of the oven and has dimensions of 3.04 m * 1.69 m. Then follows the first air out with dimensions of 0.80 m * 3.04 m, and it is located at a distance of 6.50 m from the beginning. Then, at a distance of 20.68 m from the beginning, the second air-in system begins, consisting of 13 circular air-in and air-out with a diameter of 0.87 m each, and the distance between them is 1.32 m, as shown in Figure 1. The alignment of the circular air in is exactly centrally positioned at the top. Operating conditions of the air in are $T=300$ K and $p = 1$ atm, while those of the air conditioners are $p=1$ atm. The first gas inlet starts at a distance of 47.08 m from the beginning, and the last one is at a distance of 60.28 m from the beginning. The distance between them is 1.32 m, their diameter is 0.10 m, and their alignment is in the center from the top side of the furnace. The inlet temperature is 1200 K (where this is the operating temperature), and the gas velocity $v = 0.25$ m / s, with which Reynolds numbers between 31000 and 35000 are achieved, as shown in Figure 9. Similar simulations have been done [4], [36], [37], [38] and same method has been applied in other studies [39], [40], [41]. The gas outlet is located at the end of the oven with dimensions 3.04 m * 1.59 m and $p=1$ atm.

In the kiln, different distances between the stacks have been selected, such as 0.20 m, 0.40 m, 0.60 m, and 0.80 m (Figure 7), which gives a number of stacks of 89, 75, 64, and 57, respectively. The dimensions of the stacks are the same, and only the distance between them changes in these cases. The dimensions of the stacks and their placement are shown in Figure 2 for the case where we have 75 stacks. Scenarios of reducing the stacking height (Figure 4) without reducing the number of stacks

were studied, as well as cases of height reduction and width increase (Figure 5). Finally, keeping a constant height and increasing the width (Figure 6) was also studied.

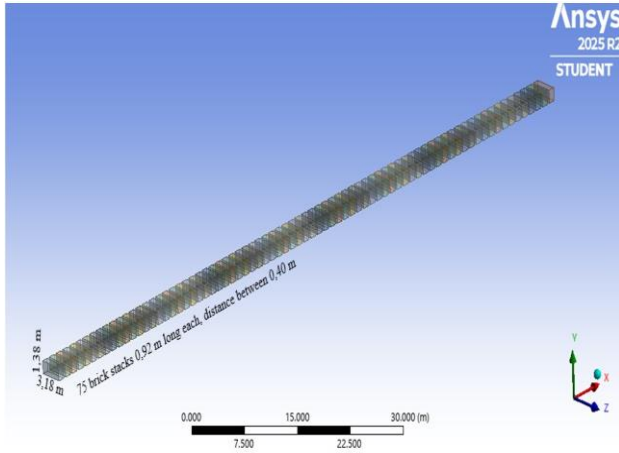


Fig. 2: A three-dimensional visualization of the brick stacks

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2.2 Mathematical Model

This study investigates turbulent flow by employing the Reynolds-Averaged Navier-Stokes (RANS) equations alongside the k-ε turbulence model. The approach involves decomposing flow variables, including velocity, into their mean (time-averaged) and fluctuating parts. This decomposition allows for a more accurate representation of turbulence effects within the flow field. By using this combined method, the research aims to better predict complex turbulent behaviors, facilitating improved design and analysis in engineering applications involving fluid dynamics. Symbolizing $\vec{U}$ the velocity vector at a point in the flow field as the sum of the time-averaged velocity and a time-dependent velocity fluctuation $\vec{u}$, i.e., so arises:

$$\vec{U} = \vec{\bar{U}} + \vec{u} \quad (1)$$

The time-averaged velocity vector is defined as:

$$\vec{\bar{U}} = \frac{1}{\Delta t} \int_t^{t+T} \vec{U} dt \quad (2)$$

where T is a time interval much longer than the characteristic periods of the turbulence fluctuations. The use of mean values (in time) in the conservation equations leads to the Reynolds-Averaged Navier-Stokes (RANS) equations:

$$\partial \rho / \partial t + \nabla \cdot (\rho \vec{U}) = 0 \quad (3)$$

$$\frac{\partial \rho \vec{U}}{\partial t} + \nabla \cdot (\rho \vec{U} \otimes \vec{U}) = \nabla \cdot (\tau - \overline{\rho \vec{u} \otimes \vec{u}}) + \vec{S}_M \quad (4)$$

In Eq. (4), $\overline{\rho \vec{u} \otimes \vec{u}}$ are the Reynolds stresses and τ denotes the stress tensor due to molecular viscosity.

After introducing the concept of an effective viscosity, μ_{eff} , the conservation of mass equation is unchanged, and the conservation of momentum equation is written as:

$$\frac{\partial (\rho \vec{U})}{\partial t} + \nabla \cdot (\rho \vec{U} \otimes \vec{U}) - \nabla \cdot (\mu_{\text{eff}} \nabla \vec{U}) = -\nabla p' + \nabla \cdot (\mu_{\text{eff}} \nabla \vec{U})^T + \vec{B} \quad (5)$$

where $\vec{B}$ the total body force per unit mass, μ_{eff} is the effective viscosity, and p' is the modified pressure defined as:

$$p' = p + \frac{2}{3} \rho k + \nabla \cdot \vec{U} \left(\frac{2}{3} \mu_{\text{eff}} - \zeta \right) \quad (6)$$

In Eq. (6), ζ is the fluid bulk viscosity, ρ is the fluid density, and k denotes the turbulent kinetic energy.

In this study, the k-ε turbulence model is employed to determine the spatial distribution of turbulent viscosity. This two-equation approach defines the effective viscosity (μ_{eff}) as the cumulative result of both the fluid's inherent molecular viscosity (μ) and the sum of turbulent viscosity (μ_t), i.e.,

$$\mu_{\text{eff}} = \mu + \mu_t \quad (7)$$

The spatial distribution of turbulent viscosity is determined by coupling the local values of turbulent kinetic energy k with the dissipation rate ε . This allows the model to calculate the eddy viscosity at every coordinate within the flow domain using the following relation:

$$\mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon} \quad (8)$$

The required values of k and ε are computed at each point of the turbulent flow field by concurrently solving the following two partial differential equations:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \vec{U} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k - \rho \varepsilon \quad (9)$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \vec{U} \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_{\varepsilon}} \right) \nabla \varepsilon \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P_k - C_{\varepsilon 2} \rho \varepsilon) \quad (10)$$

where $C_{\varepsilon 1} = 1.45$, $C_{\varepsilon 2} = 1.90$, $\sigma_k = 1.00$, $\sigma_{\varepsilon} = 1.30$ and P_k in Equation 11 is the rate of production of turbulence kinetic energy calculated by:

$$P_k = \mu_t \nabla \vec{U} \cdot (\nabla \vec{U} + \nabla \vec{U}^T) - \frac{2}{3} \nabla \cdot \vec{U} (3 \mu_t \nabla \cdot \vec{U} + \rho k) \quad (11)$$

This work utilizes the ANSYS CFX software package to solve the flow field under the assumption of constant physical properties ($\rho = \text{constant}$, $\mu = \text{constant}$) and bulk viscosity $\zeta = 0$. Specifically, the fluid is assumed to be incompressible, maintaining a uniform density and viscosity throughout the domain.

2.3 Boundary Conditions with Mesh Details

In order to solve the problem, the parameters were set as follows. The external wall of the tunnel kiln is considered adiabatic with no-slip wall and smooth wall conditions, so that there is no temperature transfer outside the kiln, and the internal brick stacks are also considered as walls but with the ability to transfer heat. For gas inlets, the flow regime is set as subsonic and the turbulence intensity as 5%. Figure 3 displays a three-dimensional perspective of the mesh created with the ANSYS-CFX preprocessor.

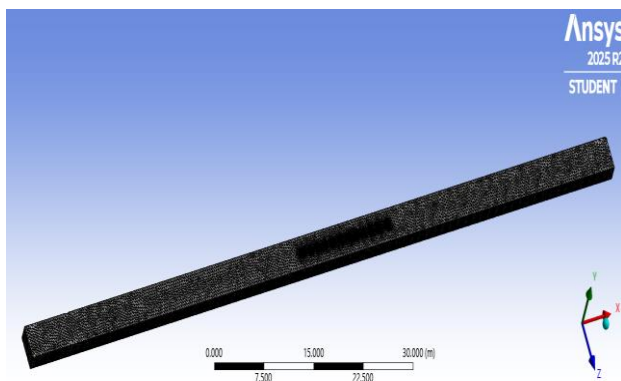


Fig. 3: A 3-D view of the mesh

Source: created by the authors

A series of mesh designs was employed in order to accomplish grid independence. A maximum edge length of 0,25 m and a minimum edge length of $5 \cdot 10^{-2}$ were generated to effectively resolve solid boundary layers in fluid simulation. The 10^{-7} setting for the RMS was selected. Although formally the convergence took place much earlier than 2500 iterations, the solution ran for 10000 iterations. Tetrahedra were initially applied to discretize the computing domain. Table 1 displays the layout that was used for each instance. Assessing the approximate convergence of the solutions was made easier by sensitivity to global factors, such as mass conservation. A well-structured grid is required for the results, which should not vary by more than 5% throughout the research.

Table 1. Mesh parameters and mean velocity for each case

	Number of nodes	Number of tetrahedra	Mean velocity m/s	%difference
Case 1	62364	199202	0,066119	0,15
Case 2	64978	214074	0,065122	2,27
Case 3	68006	230812	0,063643	3,74

Source: created by the authors

The stabilization of the mean velocity was monitored in parallel with the mass conservation, ensuring that the flow field was adequate. Also, extending the solution to 10.000 iterations contributed a boundary against local fluctuations, thus ensuring that, as shown in Table 1, the 5% grid-independence criterion was satisfied.

3 Results

To analyze the results, we focused on the geometric characteristics of the stacks as well as the method of placement inside the oven. The stack moves from the preheating zone to the aeration zone; the preheating zone starts at position $x=100$ m and the aeration zone at position $x=0$ m. In Figure 4, we observe the change in temperature if we reduce the stacking height while keeping the other parameters unchanged. We observe that decreasing the height increases the temperature in the preheating zone (for $x = 80$ m, $h = 1.28$ m, $T=950$ K and $h = 1.38$ m, $T= 600$ K), while conversely, there is a decrease in the cooling zone. This happens because the stack volume decreases, resulting in initially having less heat absorption, while in the cooling zone we have a faster temperature drop for the lower stacking heights. Also, the temperature curve has less penetration into the cooling zone (for $X=20$ m, $h=1,28$ m, $T=400$ K and $h=1,18$ m, $T= 300$ K), as a result, at lower stack heights, we have a greater backflow and the temperature remains high in the preheating zone.

In Figure 5, we notice that by reducing the height and increasing the width, we have greater backflow (for $X=80$ m, $h=1,18$ m, $w= 1,12$ m, $T=700$ K) and less penetration in the cooling zone (for $X=20$ m, $h=1,18$ m, $w= 1,12$ m, $T=300$ K). In the intermediate-width stacking, we have the smallest backflow (for $X=80$ m, $h=1,18$ m, $w= 1,02$ m, $T=400$ K) and greater penetration into the aeration zone (for $X=20$ m, $h=1,18$ m, $w= 1,02$ m, $T=400$ K) compared to the case with the largest width. This happens because in this case we have a

smaller number of stacking volumes than in the case with 1,12 m width.

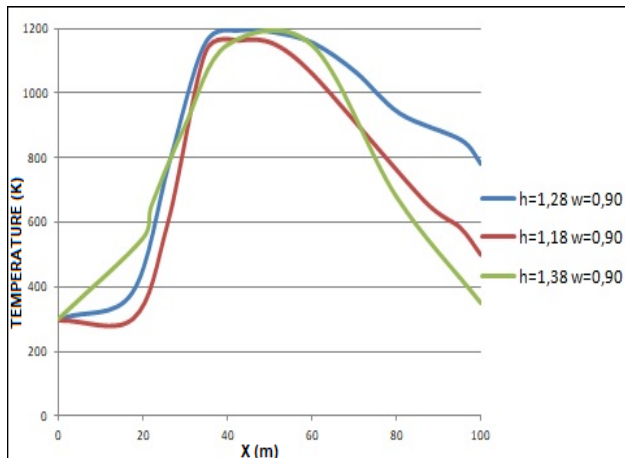


Fig. 4: Brick stack height distribution to temperature for constant stack width for height: ($h=1,18$ m, $h=1,28$ m, $h=1,38$ m and width 0,90 m)

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For a width 1,02 m, the brick stacks are 69, while for 1,12 m width the brick stacks are 65. The number for the other case is known from previous cases.

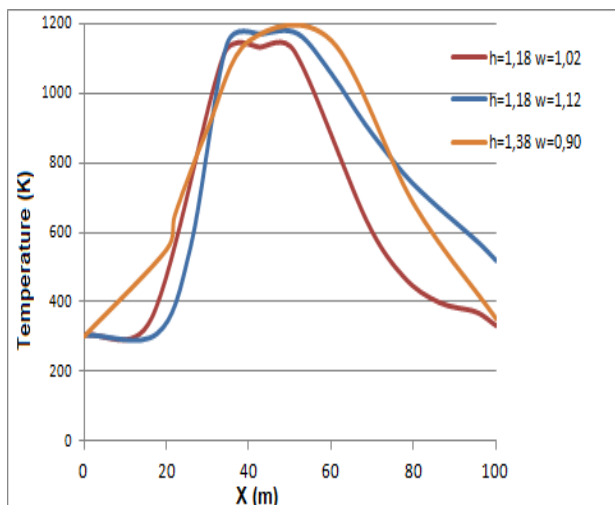


Fig. 5: Brick stack width and height changes distribution to temperature cases: ($h=1,18$ m, $w=1,02$ m, $h=1,18$ m, $w=1,12$ m, $h=1,38$ m, $w=0,90$ m)

Source: created by the authors

In Figure 6, the height was kept constant, and the width was increased. The effect of increasing the width is to give greater backflow ($w=1,02$ m, $T=1000$ K, $X=80$ m) and ($w=1,12$ m, $T=800$ K, $X=80$ m). In this case, we notice that by keeping the height the same, the backflow increases for the case

with more brick stacks. The number of brick stacks was analyzed previously.

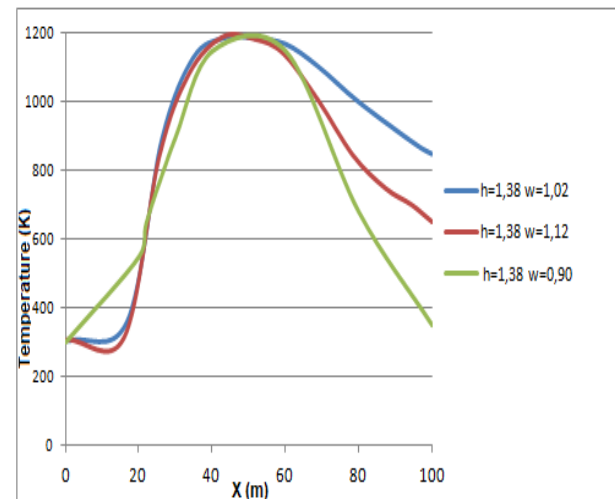


Fig. 6: Brick stack width distribution to temperature by keeping height constant, cases: ($h=1,38$ m, $w=1,02$ m, $h=1,38$ m, $w=1,12$ m, $h=1,38$ m, $w=0,90$ m)

Source: created by the authors

In Figure 7, the height and width were kept constant, and the distance between the stacks changed. The effect of increasing the distance between the stacks is to give greater backflow and less penetration into the cooling zone. By reducing the distance to 0,20 m, we notice that we have more penetration into the cooling zone ($X=20$ m, $T=600$ K) and the backflow also increases in the zone ($X=80$ m, $T=860$ K) but in a smoother way, which is acceptable for experimental results till 80 m, then the backflow continues to be maintained at high levels ($X=100$ m, $T=550$ K). Analytically, we observe that for widths of 0.60 m and 0.80 m, as the distance increases, there is greater air circulation inside the oven, resulting in greater backflow ($X=80$ m, $d=0,80$ m, $T=900$ K) on the contrary, at shorter distances between stacks ($d=0,20$ m and $d=0,40$ m) due to less air circulation, we have greater penetration into the cooling zone ($X=20$ m, $d=0,40$ m, $T=600$ K) and less backflow backflow ($X=80$ m, $d=0,40$ m, $T=650$ K). These last two scenarios are the most acceptable for ideal conditions in the kiln (Figure 8).

In Figure 8, by analyzing all the previous results and considering all the aspects- height, width, and stacking distance we compared the most acceptable scenarios with the ideal curve for a tunnel kiln according to [5].

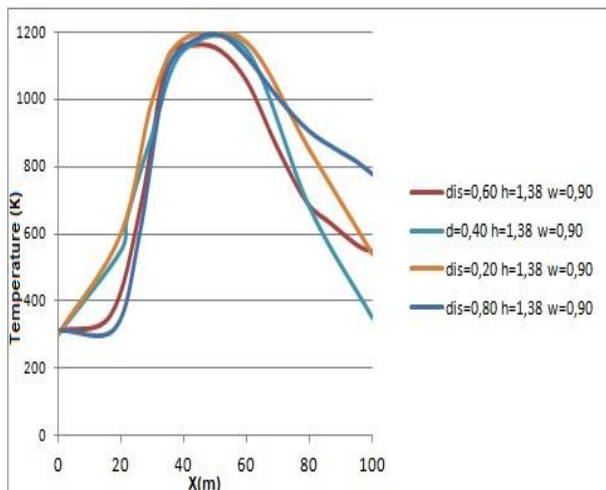


Fig. 7: Brick stack distance distribution to temperature by keeping constant height and width cases: ($d=0,60$ m, $h=1,38$ m, $w=0,90$ m, $d=0,40$ m, $h=1,38$ m, $w=0,90$ m, $d=0,20$ m, $h=1,38$ m, $w=0,90$ m, $d=0,80$ m, $h=1,38$ m, $w=0,90$ m)

Source: created by the authors

The results show which geometric design and ceramic placement are more acceptable. At a distance between 20 and 80 meters, there are no significant deviations, while larger deviations appear both at the beginning of the preheating part of the kiln and towards the end of the aeration zone. In these two cases, the temperatures in the combustion zone are close to the ideal curve, while in the cooling zone there is no significant penetration, as has been mentioned (Figure 7). Finally, in the preheating zone, the ideal curve is between these two curves. Specifically, for $d=0.40$ m the curve is below, while for $d=0.20$ m the curve is above, with the prevailing scenario being $d=0.40$ m, while in the other case ($d=0.20$ m) the backflow continues, as previously mentioned (Figure 7).

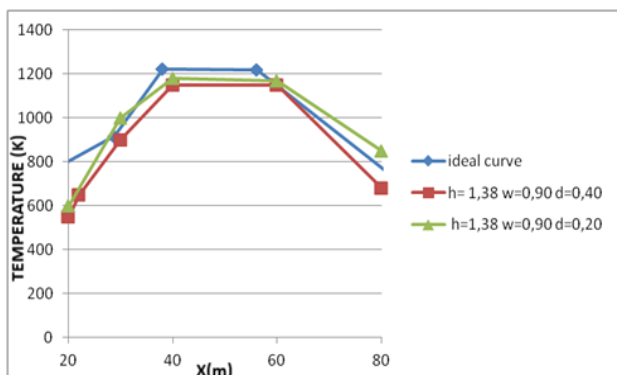


Fig. 8: Scenarios compared with ideal curve

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In Figure 9, we tried to create the ideal temperature curve based on all the data. We focused on the desired Reynolds number that would include the airflow within the oven and found an approximate area to focus on. [4] conducted research on heat transfer for different kinds of configurations in a tunnel ceramic kiln. We observed that there is a significant degree of sensitivity to the Reynolds number we choose, and it is also affected by the internal geometric characteristics. The ideal Reynolds numbers that approximate the ideal curve in combination with the positioning and geometric characteristics of the stacking are 31000-35000. The most likely scenario is this for 33700, and numerically, between 33000-34000 there is the ideal solution for this combination (Figure 9).

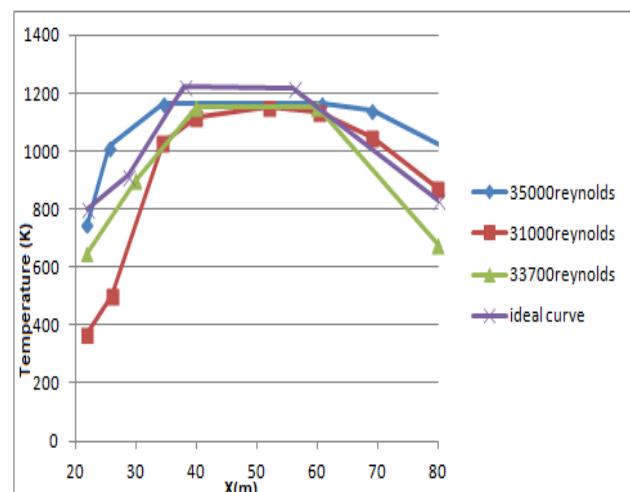


Fig. 9: Averaged Reynolds compared with ideal curve, stacking distance 0,40 m, height 1,38 m and width 0,90 m.

Source: created by the authors

In Figure 10, we observe the temperature distribution in the furnace along the preheating, combustion, and cooling zones. We see that at the beginning of the combustion zone, we have lower temperatures than in the rest of the zone, while in the cooling zone, the temperature decreases rapidly. Temperature variations across the different regions of the oven can be visually identified, as illustrated in the Legend. In Figure 11, we observe that in the lower layers ($y=0,10$ m and $y=0,40$ m), we have greater temperature homogeneity, while in the higher layers ($y=1,00$ m and $y=1,30$ m), we have higher temperatures and greater homogeneity.

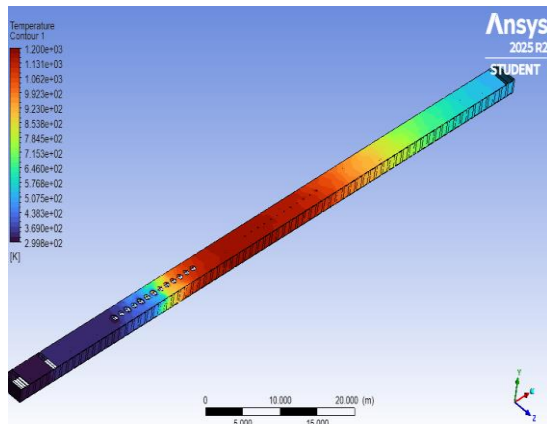


Fig. 10: Temperature distribution throughout the kiln (stacking dis=0,40 m, h=1,38 m and w=0,90 m).

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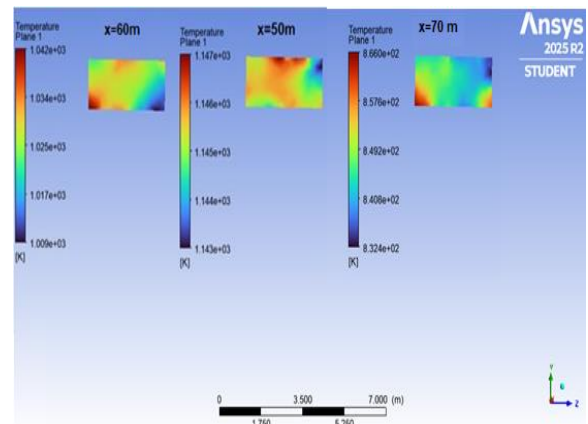


Fig. 13: Local temperature cross-sections in areas of interest (X=50 m, X=60 m, X=70 m)

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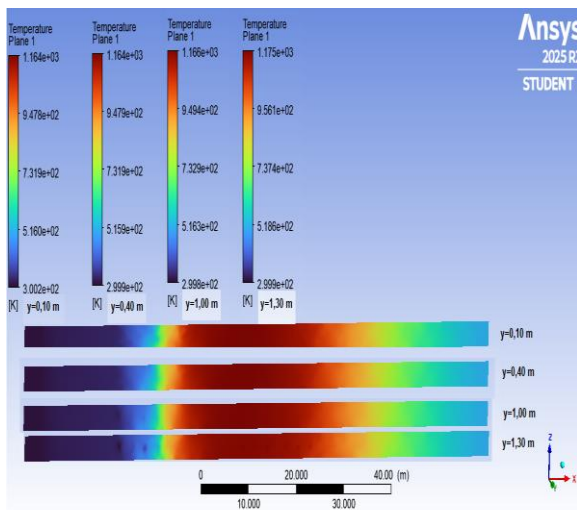


Fig. 11: Temperature distribution at different heights within the kiln

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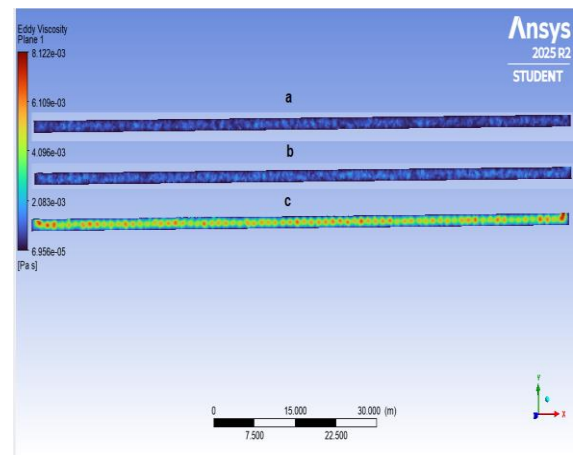


Fig. 14: Eddy Viscosity contours on plane a) z=0,10m (left side), b) z=3,10m (right side), c) z=1,62 m (center)

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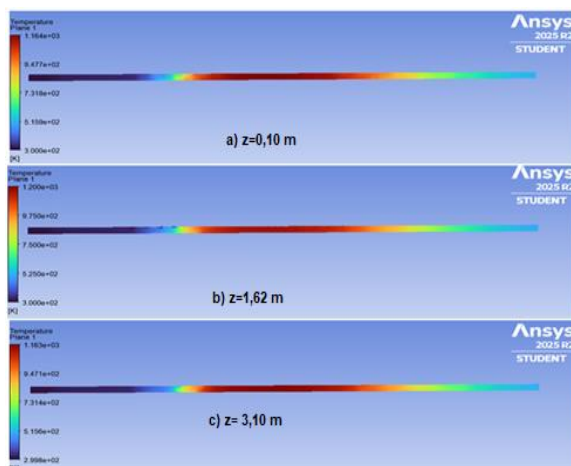


Fig. 12: Temperature distribution in the center and the sides of the kiln

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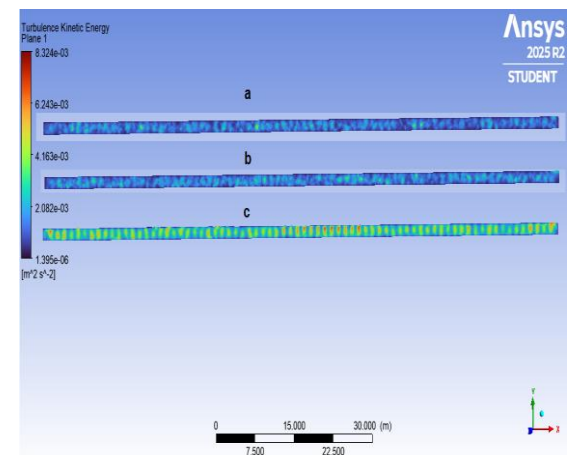


Fig. 15: Turbulence Kinetic Energy contours on plane a) z=0,10m (left side), b) z=3,10m (right side), c) z=1,62 m (center)

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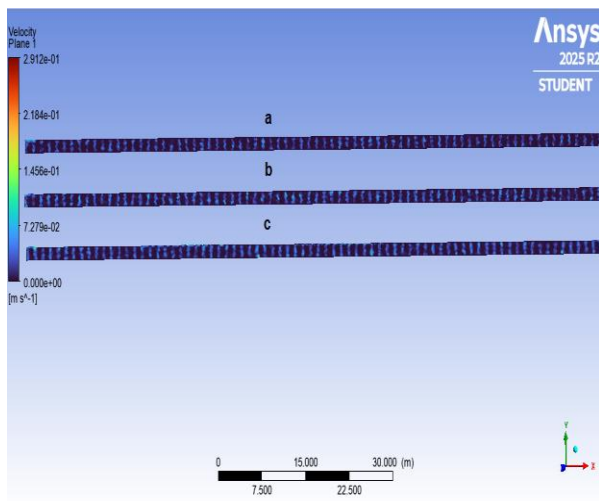


Fig. 16: Velocity contours on plane a) $z=0,10\text{m}$ (left side), b) $z=3,10\text{m}$ (right side), c) $z=1,62\text{ m}$ (center)
Source: created by the authors

It can also be concluded that the temperature increases in the upper regions of the oven. In Figure 12, we observe that the temperatures are higher in the center of the oven ($z=1,62\text{ m}$, $T=1200\text{ K}$) than at the sides ($z=0,10\text{ m}$, $T=1164\text{ K}$ and $z=3,10\text{ m}$, $T=1163\text{ K}$). This means that we do not have the same heat transfer to the sides of the oven as we do in the center. It is also observed that the temperatures at both edges of the oven are similar. Similar studies focusing on the presentation of temperature and velocity effects using CFD for other applications have been conducted [42], [43], [44].

In Figure 13, in the characteristic sections, we observe that in the center and slightly to the left of the combustion zone ($X=60\text{ m}$), we have a better temperature distribution than in the rightmost part of the combustion zone and also near the preheating zone where greater temperature deviations are observed ($X=70\text{ m}$), while in the center we have better thermal performance ($X=50\text{ m}$, temperature between $1143\text{--}1147\text{ K}$). Finally, in Figure 14, Figure 15, and Figure 16, the Eddy Viscosity, Turbulence kinetic energy, and velocity have higher values in the center of the furnace than at its sides. Also, their values are significantly higher among the stacks.

4 Conclusions

In conclusion, we developed a model to study the heat transfer within a tunnel ceramic kiln, taking into account the factors that influence it. Decreasing the stack height or increasing the width increases backflow and decreases temperature penetration into the cooling zone. This higher backflow effectively

maintains a higher temperature in the preheating zone. The effect of width is complex. An intermediate width produced the smallest backflow and greatest penetration compared to the largest width, suggesting a non-linear relationship where optimal flow depends on the combination of height and width. It is important to understand the importance of stack placement and specifically the distances between them. It was observed that increasing the distance between them increases the backflow and reduces the temperature in the cooling zone. This creates, as a consequence, heterogeneity in the smoothness of the temperature curve. Also, the temperature presents higher values at the top than at the bottom, as well as differences between the central and the side regions of the kiln. This differentiation in the temperature curve affects the final product and shows fluctuations in the three zones of the oven, both due to the geometric characteristics and the placement inside the oven, thereby creating the need for additional design improvements. What also shows great sensitivity to the temperature curve and its smoothness is the Reynolds number, with the help of which we control the flow of air inside the oven. The distances between the stacks that provide better performance are between 0.20 m and 0.40 m , with a stack height of 1.34 m , which is 0.12 m lower than the oven ceiling. However, in the case of the 0.20 m distance between the stacks, we have greater flow, which should be studied in combination with the improvement of the cooling zone, as it significantly affects the backflow. All these parameters create a dynamic environment through which we can control the operation and optimization to create better products but also save energy within it.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work, the author(s) utilized artificial intelligence (AI) technologies solely for the purpose of linguistic refinement and grammatical correction. Following the application of these tools, the author(s) comprehensively reviewed, verified, and edited the resulting text. The author(s) maintain full accountability and responsibility for the accuracy, integrity, and final content of the publication.

References:

- [1] Hussnain, S. A., Farooq, M., Amjad, M., Riaz, F., Tahir, Z. U. R., Sultan, M., ... & Bokhari, A. (2021). Thermal analysis and energy efficiency improvements in tunnel kiln for sustainable environment. *Processes*, 9(9), 1629.
<https://doi.org/10.3390/pr9091629>.
- [2] Agrafiotis, C., Tsoutsos, T., 2001. Energy saving technologies in the European ceramic sector: a systematic review. *Appl. Therm. Eng.* 21, 1231–1249. [https://doi.org/10.1016/S1359-4311\(01\)00006-0](https://doi.org/10.1016/S1359-4311(01)00006-0).
- [3] Alonso-Romero, S., Alfaro-Ayala, J. A., Frias-Chimal, J. E., López-Núñez, O. A., Ramírez-Minguela, J. D. J., & Zitzumbo-Guzmán, R. (2025). A Transient Combustion Study in a Brick Kiln Using Natural Gas as Fuel by Means of CFD. *Processes*, 13(8), 2437. <https://doi.org/10.3390/pr13082437>.
- [4] Abou-Ziyan, H. Z. (2004). Convective heat transfer from different brick arrangements in tunnel kilns. *Applied Thermal Engineering*, 24(2-3), 171-191. <https://doi.org/10.1016/j.applthermaleng.2003.08.014>.
- [5] Alex, D. M., Redemann, T., & Specht, E. (2023). Effect of kiln car weight on the tunnel kiln process. *Thermal Science and Engineering Progress*, 41, 101861. <https://doi.org/10.1016/j.tsep.2023.101861>.
- [6] Unterluggauer, J., Schieder, M., Gutschka, S., Puskas, S., Vogt, S., & Streibl, B. (2024). Numerical Investigations on the Enhancement of Convective Heat Transfer in Fast-Firing Brick Kilns. *Energies*, 17(22), 5617. <https://doi.org/10.3390/en17225617>.
- [7] Kaya, S., Küçükada, K., Mançuhan, E., 2008. Model-based optimization of heat recovery in the cooling zone of a tunnel kiln. *Appl. Therm. Eng.* 28, 633–641. <https://doi.org/10.1016/j.applthermaleng.2007.04.002>.
- [8] Essenhigh, R. H. 2001. Studies in furnace analysis: Prediction of tunnel kiln performance by application of the integral energy equation. *Energy and Fuels*, 15 (3), 552-558. <https://doi.org/10.1021/ef000119t>.
- [9] Milani, M., Montorsi, L., Stefani, M., Saponelli, R., Lizzano, M., 2017. Numerical analysis of an entire ceramic kiln under actual operating conditions for the energy efficiency improvement. *J. Environ. Manag.* 203, 1026–1037. <https://doi.org/10.1590/S1678-58782009000400003>.
- [10] Oba, R., Possamai, T.S., Nicolau, V.P., 2014. Thermal analysis of a tunnel kiln used to produce roof tiles. *Appl. Therm. Eng.* 63, 59–65. <https://doi.org/10.1016/j.applthermaleng.2013.10.063>.
- [11] Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., & Tassou, S. A. (2018). Waste heat recovery technologies and applications. *Thermal science and engineering progress*, 6, 268-289. <https://doi.org/10.1016/j.tsep.2018.04.017>.
- [12] Durakovic, J., and Delalic, S., 2006. Temperature field analysis of tunnel kiln for brick production. *Materials and Geoenvironment*, 53 (3), 403-408.
- [13] Nicolau, V. D. P., & Dadam, A. P., 2009. Numerical and experimental thermal analysis of a tunnel kiln used in ceramic production. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, 31 (4), 297-304. <https://doi.org/10.1590/S1678-58782009000400003>.
- [14] Argyrou, M., Georgiou, G.S., Tassou, S.A., Jouhara, H., Kalogirou, S.A., Florides, G.A., et al., 2019. Waste Heat Recovery in the EU industry and proposed new technologies. *Energy Procedia*, 161, 489–496. <https://doi.org/10.1016/j.egypro.2019.02.064>.
- [15] Redemann, T., and Specht, E., 2017. Mathematical model to investigate the influence of circulation systems on the firing of ceramics. *Energy Procedia*, 120, 620-627. <https://doi.org/10.1016/j.egypro.2017.07.199>.
- [16] Meng, P., 2011. Solid-solid Recuperation to improve the energy of tunnel kiln. PhD thesis, Otto von Guericke University. <http://dx.doi.org/10.25673/5135>.
- [17] Refaey, H. A., Abdel-Aziz, A. A., Salem, M. R., Abdelrahman, H. E., and Al-Dosoky, M. W., 2018. Thermal performance augmentation in the cooling zone of brick tunnel kiln with two types of guide vanes. *International Journal of Thermal Sciences*, 130, 264-277. <https://doi.org/10.1016/j.ijthermalsci.2018.04.027>.
- [18] Refaey, H. A., Almohammadi, B. A., Abdel-Aziz, A. A., Abdelrahman, H. E., Abd El-Ghany, H. A., Karali, M. A., & Al-Dosoky, M. W., 2022. Transient thermal behavior in brick tunnel kiln with guide vanes: Experimental

- study. *Case Studies in Thermal Engineering*, **33**, 101959. <https://doi.org/10.1016/j.csite.2022.101959>.
- [19] Xin, Y., Robert, D., Mohajerani, A., Tran, P., & Pramanik, B. K. (2023). Energy efficiency of waste reformed fired clay bricks-from manufacturing to post application. *Energy*, **282**, 128755. <https://doi.org/10.1016/j.energy.2023.128755>.
- [20] Kaya, S., Mançuhan, E., & Küçükada, K., 2009. Modelling and optimization of the firing zone of a tunnel kiln to predict the optimal feed locations and mass fluxes of the fuel and secondary air. *Applied Energy*, **86** (3), 325-332. <https://doi.org/10.1016/j.apenergy.2008.04.018>
- [21] Mancuhan, E., & Kucukada, K. (2006). Optimization of fuel and air use in a tunnel kiln to produce coal admixed bricks. *Applied Thermal Engineering*, **26**(14-15), 1556-1563. <https://doi.org/10.1016/j.applthermaleng.2005.12.002>.
- [22] Del Rio, D. D. F., Sovacool, B. K., Foley, A. M., Griffiths, S., Bazilian, M., Kim, J., & Rooney, D. (2022). Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems. *Renewable and Sustainable Energy Reviews*, **157**, 112081. <https://doi.org/10.1016/j.rser.2022.112081>.
- [23] Alonso-Romero, S., Alfaro-Ayala, J. A., Frias-Chimal, J. E., Ramírez-Minguela, J. J., & López-Núñez, O. A. (2024). Transient thermal analysis of a kiln using different numerical approaches by means of CFD. *Case Studies in Thermal Engineering*, **64**, 105441. <https://doi.org/10.1016/j.csite.2024.105441>.
- [24] Makrygiannis, I., & Karalis, K. (2023). Optimizing building thermal insulation: the impact of brick geometry and thermal coefficient on energy efficiency and comfort. *Ceramics*, **6**(3), 1449-1466. <https://doi.org/10.3390/ceramics6030089>.
- [25] Al-Hasnawi, A. G. T., Refaey, H. A., Redemann, T., Attalla, M., & Specht, E. (2018). Computational fluid dynamics simulation of flow mixing in tunnel kilns by air side injection. *Journal of Thermal Science and Engineering Applications*, **10**(3), 031007. <https://doi.org/10.1115/1.4038840>.
- [26] Tahtalı, G., Olgun, H., Güneş, M., & Hepbaşlı, A. (2024). Theoretical Exergoenvironmental Analysis of a Tunnel Furnace and Drying System in a Brick Production. *Gazi University Journal of Science*, **37**(1), 249-262. <https://doi.org/10.35378/gujs.1052416>.
- [27] Tehzeeb, Bhuiyan, M., & Jayasuriya, N., 2012. Evaluation of brick kiln performances using computational fluid dynamics (CFD). *Energy and Environmental Engineering*, **1** (2), 86–93.
- [28] Refaey, H. A., Specht, E., and Salem, M. R., 2015. Influence of fuel distribution and heat transfer on energy consumption in tunnel Kilns. *International Journal of Advances in Engineering & Technology*, **8** (3), 281.
- [29] Lezcano, C., Echeverri-Urbe, C., López, Y., & Amell, A. (2025). Numerical simulation of a batch furnace for heating of ceramic bricks using flameless combustion burners. *Case Studies in Thermal Engineering*, 107266. <https://doi.org/10.1016/j.csite.2025.107266>.
- [30] Mancuhan, E., Kucukada, K., & Alpman, E. (2011). Mathematical modeling and simulation of the preheating zone of a tunnel kiln. *J. Therm. Sci. Technol*, **31**(2), 79-86.
- [31] Refaey, H. A., Abdel-Aziz, A. A., Ali, R. K., Abdelrahman, H. E., and Salem, M. R., 2017. Augmentation of convective heat transfer in the cooling zone of brick tunnel kiln using guide vanes: An experimental study. *International Journal of Thermal Sciences*, **122**, 172-185. <https://doi.org/10.1016/j.ijthermalsci.2017.08.018>.
- [32] Alrahmani, M., Almesri, I., Almutairi, J., & Abou-Ziyan, H., 2022. Combined Effect of Brick Surface Roughness and Lattice Setting Density on Brick Firing in Tunnel Kilns. *Energies*, **15** (15), 5670. <https://doi.org/10.3390/en15155670>.
- [33] Arvanitidis, A. L., Kostoglou, M., & Georgiadis, M. C. (2024). Optimizing industrial tunnel kiln operations for ceramic roof tile production: A bi-objective approach. *Chemical Engineering Science*, **295**, 120223. <https://doi.org/10.1016/j.ces.2024.120223>.
- [34] Baccarin, L. I. P., & Bragança, S. R. (2024). Thermodynamic simulations for optimizing the firing of traditional ceramic formulations using waste glass as a flux. *Materials Today Communications*, **38**, 107913. <https://doi.org/10.1016/j.mtcomm.2023.107913>
- [35] Gutschka, S. (2024). *Numerical investigations on heat transfer in a fast firing brick kiln* (Doctoral dissertation, Technische

Universität (Wien).
<https://doi.org/10.34726/hss.2024.118884>.

- [36] Refaey, H. A., Alharthi, M. A., Salem, M. R., Abdel-Aziz, A. A., Abdelrahman, H. E., & Karali, M. A. (2021). Numerical investigations of convective heat transfer for lattice settings in brick tunnel Kiln: CFD simulation with experimental validation. *Thermal Science and Engineering Progress*, 24, 100934. <https://doi.org/10.1016/j.tsep.2021.100934>.
- [37] Refaey, H. A., Alharthi, M. A., Abdel-Aziz, A. A., Elattar, H. F., Almohammadi, B. A., Abdelrahman, H. E., ... & Al-Dosoky, M. W. (2023). Fluid flow characteristics for four lattice settings in brick tunnel kiln: CFD simulations. *Buildings*, 13(3), 733. <https://doi.org/10.3390/buildings13030733>.
- [38] D. Kasiteropoulou (2009). Microscopic, mesoscopic and macroscopic simulations of flow in grooved channels, Ph.D. Thesis, University of Thessaly (in greek).
- [39] Keramaris, E., Kasiteropoulou, D., Liakopoulos, A., Michalolias, N., & Pechlivanidis, G. (2017). A study of flow in open channels with vegetation: Experiments and numerical models. *Special Topics & Reviews in Porous Media: An International Journal*, 8(2). <https://doi.org/10.1615/SpecialTopicsRevPorousMedia.2017019692>.
- [40] Keramaris, E., Pechlivanidis, G., Kasiteropoulou, D., Michalolias, N., & Liakopoulos, A. (2016). Experimental and numerical study of turbulent flow in open channels with impermeable and porous bed. *Procedia Engineering*, 162, 381-387. <https://doi.org/10.1016/j.proeng.2016.11.078>.
- [41] Spiliotis, X., Ntampegliotis, K., Kasiteropoulou, D., Lamprakopoulos, S., Lolos, K., Karayannis, V., & Papapolymerou, G. (2014). Valorization of mill scale waste by its incorporation in fired clay bricks. *Key Engineering Materials*, 608, 8-13. <https://doi.org/10.4028/www.scientific.net/kem.608.8>.
- [42] Larsson, I. S., Ljung, A. L., & Marjavaara, B. D. (2021). Simulation of Thermal Effects on the Flow Field in a Pilot-Scale Kiln. *Mining, Metallurgy & Exploration*, 38(3), 1487-1495. <https://doi.org/10.1007/s42461-021-00422-x>.
- [43] Tran, V. T., Nguyen, D. K., Dang, N. T., Le, K. N. M., Duong, Y. H. P., & Le, T. M. (2023, August). Numerical Simulation of Gas Flow in a Tunnel Drying Kiln System. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1226, No. 1, p. 012019). IOP Publishing. <https://doi.org/10.1088/1755-1315/1226/1/012019>.
- [44] Mujumdar, K. S., & Ranade, V. V. (2008). CFD modeling of rotary cement kilns. *Asia-Pacific Journal of Chemical Engineering*, 3(2), 106-118. <https://doi.org/10.1002/apj.123>.

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

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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