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Numerical Study of the Thermal Behavior of a Traditional Bread Oven Used in Togo

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Abstract This study focuses on the numerical investigation of the thermal behavior of a traditional bread oven commonly used in Togo. Constructed from clay using local artisanal techniques, this type of oven is predominantly operated by women as part of income-generating activities. Due to the lack of accurate data on its thermal efficiency, a substantial amount of firewood—estimated at approximately 215 kg—is typically used to sustain adequate baking temperatures over extended periods. However, significant heat losses through the oven walls considerably reduce the duration of effective heat availability. Among the various influencing parameters, the thickness of the dome has received particular attention. A heat transfer model was developed and coupled with numerical simulations conducted using COMSOL Multiphysics, under the assumption of a constant heat flux corresponding to the energy released by the combustion of 215 kg of dry wood. Under these conditions, the average internal temperature of the oven reaches approximately 375 °C, regardless of dome thickness, for values ranging from 5 cm to 30 cm. Following the cessation of the heat source, the oven enters a thermal relaxation phase, during which the internal temperature (in the absence of any load) gradually decreases. It is during this phase that baking typically occurs. A parametric analysis indicates that a dome thickness of 15 cm enables the highest average internal temperature to be maintained during this period. With this configuration, approximately 5 hours of heating are required to reach an average temperature of 375 °C, which then decreases to about 65 °C after 13 hours of thermal relaxation. These findings can inform the optimization of traditional ovens by enhancing their energy efficiency and reducing firewood consumption.

Keywords: *traditional clay oven, firewood consumption, energy efficiency, spherical dome geometry, heat transfer*

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1. Introduction

Various types of modern ovens have been developed and continuously refined to enhance thermal performance and improve baking conditions. These innovations typically involve advanced insulating materials, temperature regulation systems, and increased energy efficiency [1,2]. For example, Dwomoh et al. [1] reported a 16.7% reduction in heat loss using fiberglass, while Saint-Gobain Technical Insulation [2] recommends glass wool to boost oven efficiency. Despite these advancements, traditional bread ovens remain widely used in certain regions, particularly in rural areas. Similar cases have been documented in Armenia and the Middle Eastern [3], the Riff region of Morocco [4], and several Sahel countries. Tura et al. [5] observed that clay ovens are still prevalent in parts of sub-Saharan Africa, mainly due to their ability to preserve specific organoleptic and nutritional qualities of baked products.

In Togo, a West African country, artisanal bread production represents a key economic activity, primarily carried out by women. In the town of Niamtougou, for instance, all local bread production still relies on traditional ovens (see Figure 1(b)). This persistence is largely due to the local availability of construction materials, low installation costs, and the intergenerational transmission of know-how. These ovens, typically vaulted in shape, are built from clay, a local material that is abundant, inexpensive, and environmentally friendly. Traditionally used in rural construction, clay is particularly valued for its thermal properties. Its high thermal inertia allows it to retain heat for extended periods, enabling prolonged and uniform baking [6].

However, the intensive use of these ovens raises growing environmental and health concerns. As in many parts of Africa, baking relies predominantly on open fires fueled by wood or charcoal—energy sources that are both inefficient and highly polluting. In Benue State, Nigeria, 70% of household energy supply comes from wood or charcoal [7]. In southeastern Ethiopia, average household consumption is estimated at 0.2 tonnes per week during the rainy season and 0.09 tonnes during the dry season [8]. At the continental scale, pressure on forest resources is substantial. Between 1990 and 2020, the average annual forest area loss is estimated at 1.6×10^3 thousand hectares, corresponding to approximately 0.786 petagrams of carbon released into the atmosphere [9]. Although wood and charcoal production contributes significantly to the economies of these countries (approximately 1.3% of GDP in Cameroon [10]), the effects of deforestation are becoming increasingly concerning: irregular rainfall, droughts, and extreme precipitation events. In Togo, Komlagan et al. [11] observed a significant increase in both minimum and maximum temperatures in the northern regions between 1981 and 2019—areas particularly affected by deforestation.

From a health perspective, prolonged exposure to combustion by-products—such as smoke, ash, and carbon monoxide—poses a serious risk to users. These pollutants are associated with chronic respiratory conditions, particularly affecting women and children. Tadevosyan [3] reported elevated levels of carboxyhemoglobin (COHb) among female bakers exposed to carbon monoxide concentrations exceeding 35 ppm. In Ouagadougou, Sana et al. [12] found that the prevalence of dry cough, breathing difficulties, and throat irritation was significantly higher among biomass users compared to those using liquefied petroleum gas (LPG).

In terms of energy demand, baking bread in traditional ovens requires high temperatures, often exceeding 300 °C, to ensure rapid dough dehydration and crust formation. Akinoso [13] showed that dome-shaped ovens with surface areas ranging from 27.4 to 36 m² and wall thicknesses between 0.19 and 1.11 m required 244 to 270 kg of wood to reach an average temperature of 451 °C after 180 minutes of heating. In Niamtougou, bakers use an average of 215 kg of wood per heating session, with baking durations of up to 13 hours. With a frequency of three to four sessions per week, monthly wood consumption reaches approximately 3.44 tonnes.

However, thermal management remains largely empirical. Internal oven temperature is often assessed by simple contact with the external walls, due to the lack of appropriate measuring instruments. This artisanal method results in significant energy losses, both through the walls, whose thickness varies between ovens, and via the front aperture used to feed the fire. Although the ovens share a relatively uniform design and identical volume, variations in wall thickness significantly impact heat loss.

In this context, the present study aims to evaluate the impact of wall thickness on the thermal performance of traditional ovens. The objective is to identify the optimal thickness that balances two key requirements: maintaining sufficiently high internal temperature after heating stops, and significantly reducing heat losses. Achieving this compromise could reduce firewood consumption and mitigate the associated environmental and health impacts of this traditional practice.

2. Materials and Methods

2.1. System Description

The studied oven is illustrated in Figure 1(b). For the purpose of three-dimensional modeling, and neglecting thermal losses through the oven opening, the system is idealized as a closed spherical cap with a radius of 172 cm, containing air. Owing to the system's axisymmetric geometry and in order to reduce computational time, the analysis was limited to a representative portion of the domain, as depicted in Figure 1(a). The spherical cap rests on a 75 cm-thick base, which is thermally insulated on its lower surface to minimize downward heat losses and to prevent moisture migration. This base is defined as Domain 1. The heat source is represented by Domain 2, while the ambient air enclosed within the cap constitutes Domain 3. Finally, the spherical wall, with thickness *e*, is designated as Domain 4.

2.2. Assumption and Equations

The flow within the oven is assumed to be incompressible, and the governing equations are formulated under the Boussinesq approximation. These consist of the conservation equations for mass, momentum, and energy, respectively expressed as follows:

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

$$\rho\left(\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}.\vec{\nabla}\right)\vec{V}\right) = -\vec{\nabla}p+\mu\vec{\nabla}^2\vec{V}+\rho\beta\left(T-T_0\right)\vec{g} \tag{2}$$

$$\rho c_p\left(\frac{\partial T}{\partial t}+\left(\vec{V}.\vec{\nabla}\right)T\right) = -\lambda\vec{\nabla}.\vec{\nabla}T \tag{3}$$

Where ρ, μ, β, c_p and λ are the density, dynamic viscosity, thermal expansion coefficient, specific heat capacity at constant pressure, and thermal conductivity of the air, respectively.

In the oven walls, where pure conduction occurs from one face to the other, the temperature field is governed by the following equation:

$$\rho_w c_{pw}\frac{\partial T}{\partial t} = -\lambda_w\vec{\nabla}.\vec{\nabla}T \tag{4}$$

Where ρ_w, c_{pw} and λ_w denote the density, specific heat capacity at constant pressure and thermal conductivity of the clay, respectively.

The above equations are complemented by the following initial and boundary conditions, expressed as follows:

- At $t = 0s$, the system is in thermodynamic equilibrium and at every point M, the following conditions hold: $\vec{V}(0,\mathrm{M}) = \vec{0}\mathrm{m/s}$; $\mathrm{T}(0,\mathrm{M}) = \mathrm{T}_0 = 27°C$ and p(0, M)=1013hPa
- At $t > 0s$;

Hydrodynamic condition:

$\vec{V}(t,\mathrm{M}) = \vec{0}\mathrm{m/s}$: no-slip condition on the wall

Thermal conditions:

- The heat source is modeled as a heated surface, corresponding to the upper surface of the base:

$$-\lambda\left(\vec{n}.\vec{\nabla}\right)T = q \quad (5)$$

where q is the heat flux, and $\vec{n}$ the normal vector to the wall.

- Lower surface of the base (adiabatic):

$$\left(\left(\vec{n}.\vec{\nabla}\right)T\right) = 0 \quad (6)$$

- Inner surface of the enclosure:

$$F\varepsilon\sigma\left(T_{up}^4 - T_P^4\right) = -\lambda\left(\vec{n}.\vec{\nabla}\right)T\big|_P \quad (7)$$

where T_{up} is the temperature at the upper surface of the base (or the heat source temperature), F is the view factor, and P denotes a point located on the inner wall.

- External surface of the enclosure:

$$-\lambda\left(\vec{n}.\vec{\nabla}\right)T\big|_P = h(T_P - T_a) + \varepsilon\sigma\left(T_P^4 - T_a^4\right) \quad (8)$$

- Fluid-solid coupling

$$T_f\big|_P = T_w\big|_P, -\lambda\left(\vec{n}.\vec{\nabla}\right)T\big|_P = -\lambda_w\left(\vec{n}.\vec{\nabla}\right)T\big|_P \quad (9)$$

Where T_f , T_P and T_a are respectively the temperature of the air inside the oven, the temperature at a point P located on the inner or outer surface of the spherical enclosure, and the ambient temperature.

2.2. Simulation Parameter Properties

The above equations were solved numerically using COMSOL Multiphysics, which is based on the finite element method. The following parameters were used:

Table 1.

Physical properties	λ (W/(K.m)	c_p (J/(kg.K)	ρ (kg/m^3)	ε
Clay [14,15]	0.45	701	1500	0.9
Air	0.026	1005	1.2	0
$\dot{q}$	117kW/m^3			

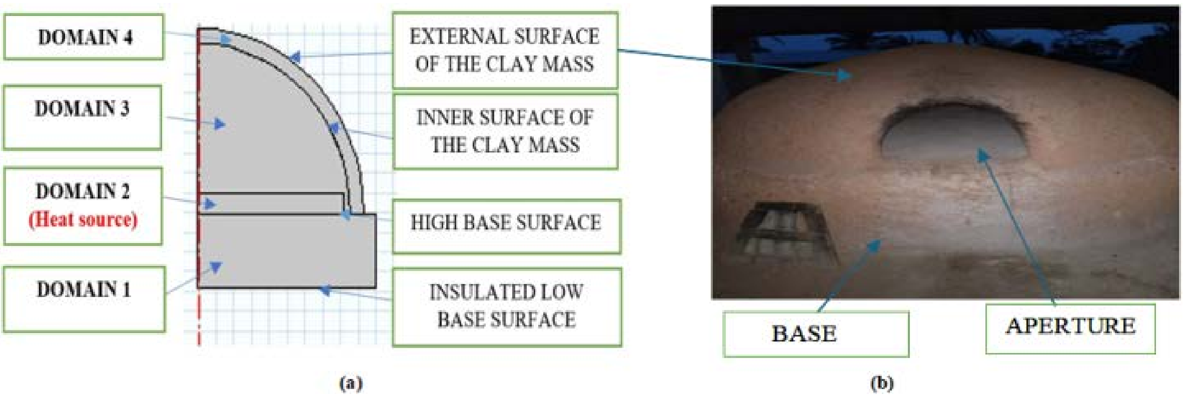

Figure 1. Simulated system (a) and Physical system (b) of the clay mass oven

3. Results and Discussions

3.1. Temperature Field Analysis

The following figures illustrate the spatial and temporal temperature distribution, providing a clearer understanding of both the heating dynamics and thermal relaxation within the studied system. Figure 2 presents the three-dimensional spatial temperature distribution at times t = 7200 s (heating phase) and t = 25,200 s (relaxation phase), highlighting the axisymmetric nature of the system under investigation.

Figure 3 presents the temperature distribution inside the oven during the heating process. Through conduction, fluid layers in the immediate vicinity of the heat source are heated. Once they acquire sufficient kinetic energy, they move upward toward the top wall, generating concentric isotherms that are characteristic of upward natural convection. The fluid domain (Domain 3) can be subdivided into several distinct thermal regions. In the vicinity of the heat source, the isotherms are highly concentrated and follow its shape, indicating strong temperature gradients (see Figures 3(a) and 3(b)). The lower right corner also exhibits relatively high temperatures, whereas the central region, which remains comparatively cooler, is characterized by more widely spaced concentric isotherms (see Figures 3(b) and 3(c)). Overall, this configuration represents a strongly convective yet thermally stratified flow. As time progresses, the domain gradually warms up and tends toward a quasi-steady state, with the maximum temperature of approximately 450 °C (see Figures 3(c) and 3(d)), indicating a significant contribution of thermal radiation. The establishment time of this regime is relatively long, estimated at around 5 hours. This slow evolution can be attributed to thermal stratification, which limits heat exchange between fluid layers, as well as to energy accumulation within the clay wall or thermal losses through it. Indeed, the temperature of the enclosure reaches nearly 300°C at t = 18,000 s, indicating heat dissipation to the external environment. Significant heat losses are also observed toward the lower part of the system (Domain 1).

Figure 4 illustrates the spatio-temporal evolution of the thermal field following the extinction of the heat source at t = 18,000 s. A marked antagonistic dynamic is observed, characterized by a gradual yet significant decrease in the maximum temperature, which drops from 450 °C to 80 °C by Δt = 46,800 s. This evolution reflects a thermal relaxation process of the system toward a new equilibrium state (see Figures 4(e)–4(h)). The analysis of the spatial temperature distribution reveals that the central region of the domain retains a significantly higher temperature compared to the peripheral zones. This thermal gradient generates heat transfers mainly governed by convective movements, as evidenced by the concentric isotherms, which gradually become more widely spaced as they move away from the center. Simultaneously, conductive heat transfers occur towards the base, whose temperature exceeds the peak values reached during the heating phase (Figures 4(g) and 4(h)), as well as towards the external envelope. The latter exchanges heat with the surrounding air mainly through natural convection and thermal radiation. Similar to the heating phase, the cooling stage extends over a relatively long period, highlighting the thermal stability of the system. This pronounced thermal inertia results from the thermophysical properties of clay, notably its high heat capacity and low thermal diffusivity, which result in a slow response time for both energy absorption and release.

3.2. Average Heat Fluxes and Mean Temperatures

Figure 5 shows the temporal evolution of the heat flux through the oven envelope for various wall thicknesses ranging from 5 to 30 cm. In all cases, the initial heating phase is characterized by significant heat losses, followed by a gradual decline in thermal flux until a quasi-steady regime is reached.

The influence of wall thickness is clearly evident from the resulting curves. Thinner walls (5 cm and 10 cm) exhibit high negative heat fluxes, reaching peak values of approximately –3000 W/m² and –2000 W/m², respectively. Conversely, increasing the wall thickness substantially reduces these losses: for a thickness of 30 cm, the flux remains close to zero throughout the process, suggesting that such thickness may effectively insulate the oven from its external environment. This behavior can be explained by Fourier's law, according to which heat flux is inversely proportional to wall thickness. Thus, greater thickness leads to slower thermal exchange with the surroundings, implying a higher insulating capacity. One might therefore expect that domain 3 maintains a higher average fluid temperature during the relaxation phase, since during heating phase this temperature is nearly independent of thickness (see Figure 6).

However, the analysis of the curves in Figure 6 reveals a more complex dynamic following the heat source extinction. Contrary to the previous assumption, it is the 15 cm wall thickness that maintains a significantly higher average fluid temperature during the relaxation period. Very thick walls (30 cm) tend to store a substantial amount of heat in the form of sensible energy, which is subsequently released to the external environment. This explains the moderate increase in average heat flux (or of the heat loss) observed for this thickness after the source is turned off.

For a spherical wall thickness of 15 cm, Figure 7 illustrates the variations in average temperatures recorded on different oven surfaces: the inner and outer surfaces of the spherical cap, the upper surface of the base (in direct contact with the heat source), as well as the lower surface of the base, which is maintained at the initial temperature of 27 °C. The analysis reveals that the maximum temperature reached by the outer surface of the spherical cap is approximately 75°C, representing a maximum temperature difference of 48°C relative to the initial temperature. Following the shutdown of the heat source, this temperature gradually decreases, approaching thermal equilibrium with the ambient environment. This evolution highlights limited heat exchange with the exterior, due to the low temperature gradient between the outer wall and the surroundings. This thermal behavior thus confirms that a 15 cm thickness constitutes an appropriate choice, ensuring both effective heat retention inside the oven and a significant reduction in energy losses to the exterior.

4. Conclusion

This study presented a numerical model of a traditional clay bread oven, represented as a closed spherical dome resting on a thick base, to evaluate the effect of wall thickness on thermal exchanges with the environment. Simulations conducted using COMSOL Multiphysics identified an optimal wall thickness of 15 cm, which enables higher average internal temperatures to be maintained during the thermal relaxation phase while minimizing heat losses. The oven's thermal inertia, attributed to the thermophysical properties of clay—particularly its high heat capacity and low thermal diffusivity—proves beneficial for sustaining the heat required during baking. Even in the absence of real-time temperature sensors, it is possible to estimate the internal temperature following combustion. Furthermore, the observed spatial temperature gradients within the oven highlight the need for strategic placement of bread, considering mass and initial moisture content, to prevent uneven baking and improve overall efficiency.

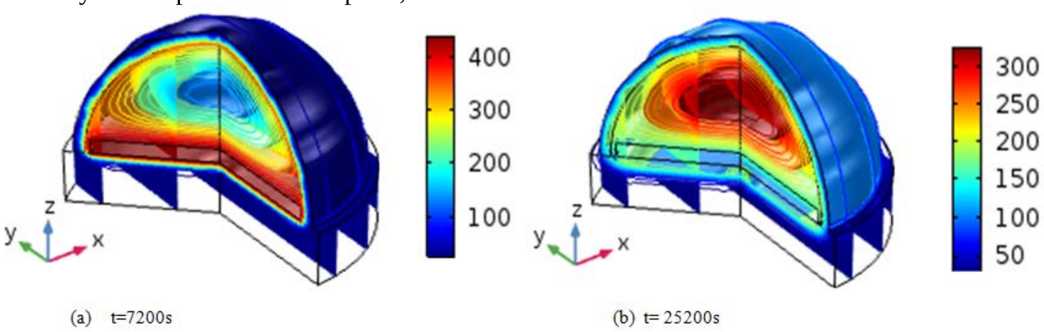

Figure 2. 3D temperature distribution for thickness 15 cm

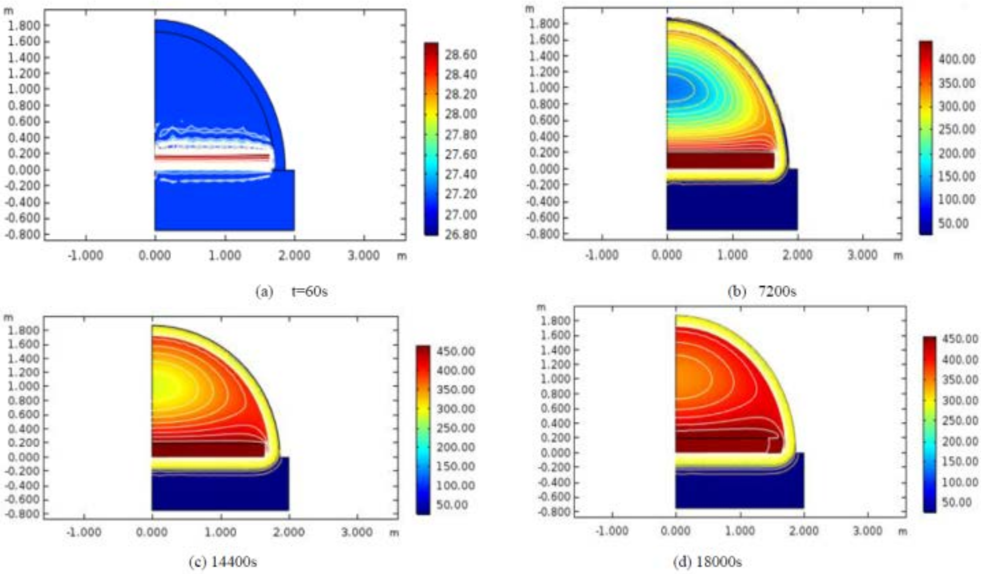

Figure 3. Temperature distribution during the heating phase

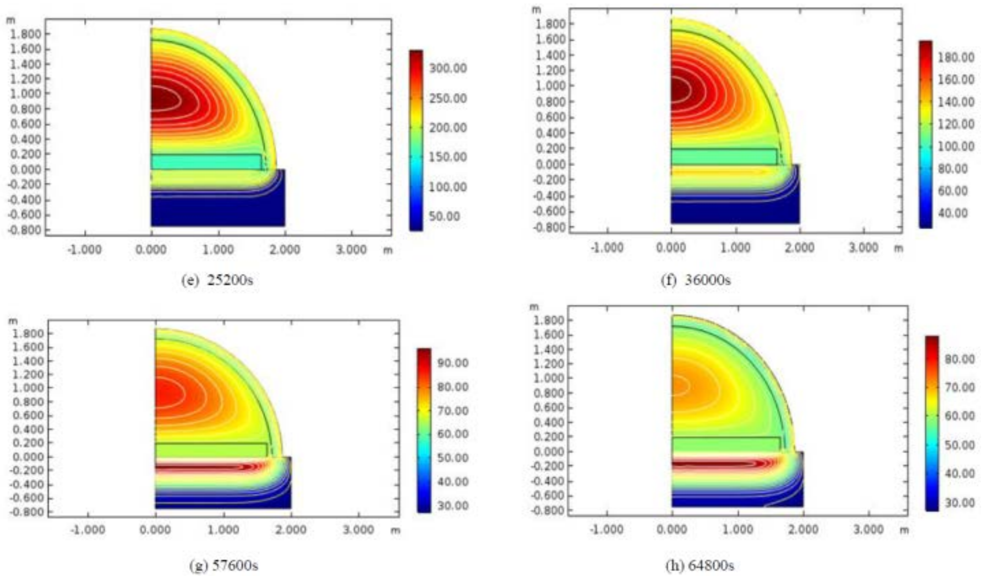

Figure 4. Temperature distribution during the relaxation phase

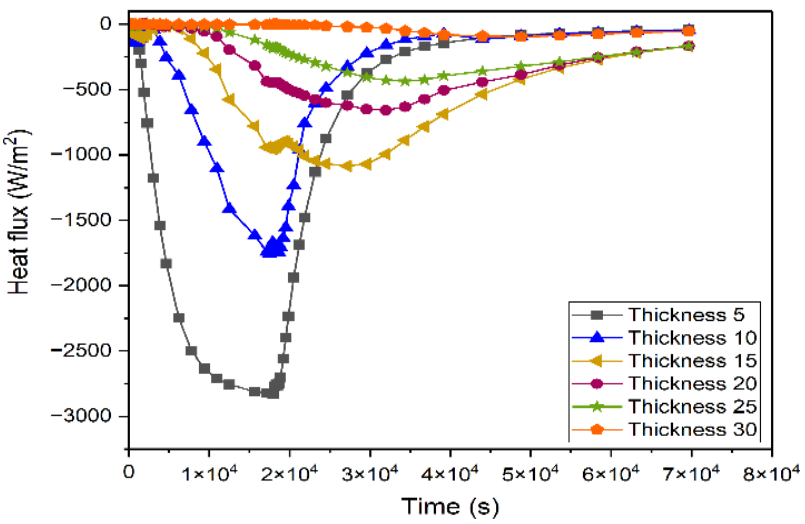

Figure 5. Heat flux loss for different thicknesses

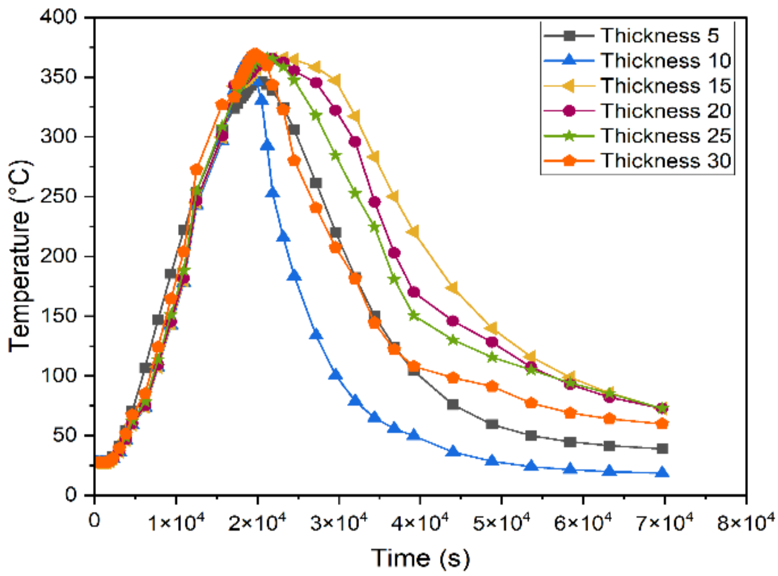

Figure 6. Average Fluid Temperature (Domain 3) for Different Thicknesses

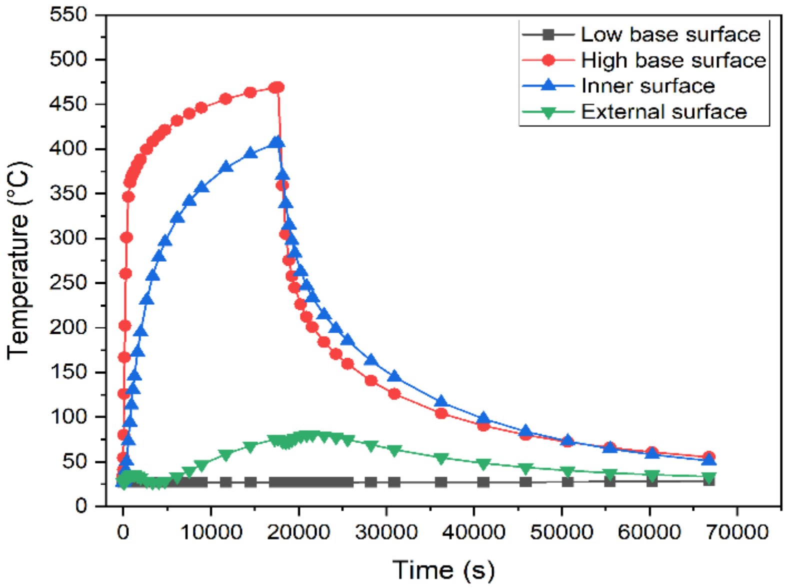

Figure 7. Average surface temperature

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