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Numerical Study of the Performance of a Double-Insulated Barbecue Oven: Implication for Energy Savings and Thermal Comfort

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Authors' contributions

This work was carried out in collaboration among all authors. Author SWI designed the study, wrote the protocol and the first draft of the manuscript. Author GLS performed the numerical simulations. Authors AC and JDB managed the analyses of the study. Authors DO and DN managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

This work is devoted to a numerical study of the performance of a double insulated barbecue oven using terracotta bricks and plywood. The numerical methodology is based on the nodal method and the heat transfer equations have been established by performing an energy balance on each node. The equations obtained were then discretized using an implicit finite difference scheme and solved by the Gauss algorithm. The numerical results validated by the experiment show that this double insulation considerably reduces the energy losses through the walls of the oven. However, the addition of plywood does not significantly change the energy savings compared to simple terracotta insulation but does drop the external wall temperatures. Thus, for 4 cm of thickness of terracotta bricks and 1 cm of plywood, the energy savings (compared to the non-insulated oven) are of the order of 70% and the temperature of the outer walls of the oven does not exceed not 60°C, which ensures better thermal comfort for users.

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Keywords: Barbecue oven; double-insulation; terracotta bricks; plywood; energy savings; thermal comfort.

ABBREVIATIONS

ε : Wall Emissivity
λ : Thermal conductivity $(W.m^{-1}.K^{-1})$
ρ : *Density (kg.m^{-3})*
F : Form factor
ν : *Kinematic viscosity of air (m^2.s^{-1})*
σ : Stefan Boltzmann constant $(5{,}67.10^{-8}m^{-2}K^{-4})$
μ : *Dynamic viscosity (Kg.m^{-1}.s^{-1})*
e : Characteristic thickness (m)
C_i : *Material heat capacity (kJ/kg.K)*
D : Hydraulic diameter (m)
F : Sky form factor
$g_{i,j}$: *Thermal conductance at nodes i and j (W.K^{-1})*
h : Convection heat transfer coefficient $(W.m^{-2}.K^{-1})$
h_r : *Radiative conductance* $(W.m^{-2}.K^{-1})$
h_a^e : *Enthalpy of air entering the node (J)*
h_a^s : *Enthalpy of air outing the node (J)*
m_i : *Mass of node i (Kg)*
$\dot{m}_{ai}^e$: *Mass air entering in the node i (Kg)*
$\dot{m}_{ai}^s$: *Mass air outing of the node i (Kg)*
Nu : Nusselt number
P : Perimeter (m)
Re : Reynolds number
S : Surface (m^2)
$T_{i,j}$: *Temperature at nodes i and j (K)*
T_{ext} : *Ambient temperature (K)*
T_{sky} : *Sky temperature (K)*
V : Air velocity (m/s)
Qi : Heat source at node i (J)
λ_{char} : *Thermal conductivity of charcoal,*
e_{char} : *Charcoal thickness*
L : Oven length (m)
H : Oven height (m)
W : Oven width (m)

1. INTRODUCTION

Thermal insulation is very important to save energy and avoid thermal discomfort in different sectors (buildings, industry, etc.). The influence of the thermal envelope on the energy efficiency of buildings has been very well studied. In the building, the thermal envelope (walls, openings, roofing, etc.) plays an essential role in the energy consumption of housing [1,2,3]. Energy losses can occur through walls, roof, windows, air infiltration, etc. [4]. In particular for walls, the heat losses are mainly due to heat transfers by conduction and the thermal properties of the materials constituting the walls strongly influence these losses [5]. A good wall insulation reduces these losses [6,7,8,9].

In Burkina Faso, the major problem with grilling ovens is linked to their thermal envelope which does not play its role as a thermal barrier between the interior of the oven and the external environment. In our previous work, we have shown that non-insulated barbecue ovens lost almost 50% of the energy consumed through the walls [10]. This low energy efficiency of equipment has a negative impact on economic activity but also on the environment. Indeed, it leads to a waste of energy resources for the country but also of financial resources for the actors. On the environmental side, it is well known that low-efficient cookstoves contribute more to deforestation and emit more pollutants compared to improved stoves [11,12,13].

The negative impact on the health of workers exposed to high temperatures should also be emphasized, as well as the short lifetime of equipment also subject to very high temperatures.

In recent years, efforts have been made to improve the energy efficiency of households cookstoves in order to reduce emissions and energy consumption [14,15,16]. In most cases, local materials (clay bricks, mud bricks, sun-dried bricks, etc.) have been used in the design of the stoves to improve their energy efficiency [17,18,19]. However, the artisanal agri-foodstuffs equipment were not taken into account, particularly in Burkina Faso. Commercial equipment such as grilling ovens remained rudimentary and did not receive any improvement in terms of energy efficiency. In order to provide a solution to this problem, we have modeled and simulated an insulated barbecue oven with terracotta bricks. The results obtained show that losses through the walls can be reduced by 60 to 70% [20]. This study also revealed that the optimal thickness of terracotta bricks to simultaneously have thermal comfort and good energy saving varied between 3 and 4 cm. However, for these thicknesses, the temperatures of the outer walls of the oven sometimes exceed 100°C, which can be dangerous for users. Therefore, the main objective of this work is to improve the thermal comfort of users by lowering the external wall temperatures of the oven by adding a second insulation material, in this case plywood. We will also analyze the impact of this modification on the energy savings achieved by the new oven.

2. PROBLEM FORMULATION

2.1 Physical Model

The casing of the oven is made with 2mm iron sheets. Inside the combustion chamber were placed 4cm thick terracotta bricks assembled using a mortar made of a mixture of ash and cement. The plywood is placed between the terracotta bricks and the metallic casing.The Fig. 1 shows an overview of the oven.

2.2 Mathematical Model

Fig. 2. shows the configuration of the furnace combustion chamber.

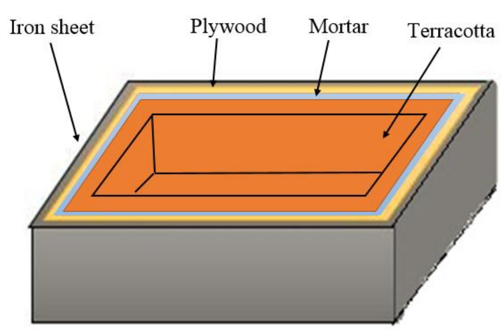

Fig. 1. Oven combustion chamber configuration

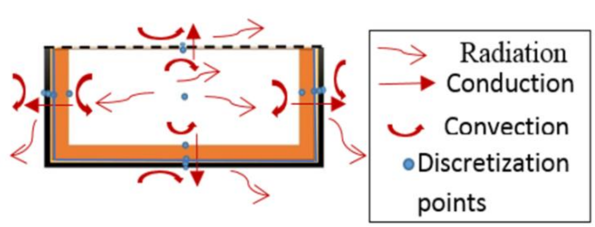

Fig. 2. Oven heat transfer model and discretization points

The internal walls exchange heat by conduction, convection and radiation with the fuel. Heat transfers take place by conduction between the different layers of the oven walls. The outer walls of the oven exchange heat by convection and radiation with the outside environment. Simplifying assumptions:

- The physical properties of the materials used for the design of the furnace are almost constant;
- The ambient temperature is the same everywhere outside the oven;
- The heat distribution is homogeneous inside the oven;
- The properties of air depend on the speed outside and inside they depend on speed and temperature.

The determination of the global thermal behavior of the oven goes through the determination of the temperatures at the various nodes presented in Fig. 2. The equation for the energy balance of node i is as follows [21]:

$$m_i c_i \frac{\partial T_i}{\partial t} = \sum_{i \neq j} g_{i,j}(T_j - T_i) + \dot{m}_{ai}^e h_a^e - \dot{m}_{ai}^s h_a^s + Q_i \quad (1)$$

Where,

m_i: Mass of node i,
C_i: Material heat capacity,
$T_{i,j}$: Temperature at nodes i and j,
$g_{i,j}$: Thermal conductance at nodes i and j,
$\dot{m}_{ai}^e$: Mass air entering in the node i,
$\dot{m}_{ai}^s$: Mass air outing the node i,
h_a^e: Enthalpy of air entering the node,
h_a^s: Enthalpy of air outing the node,
Qi: Heat source at node i

According to the heat transfer mode, the following equations are adopted:

- The conductive conductance:

$$g_{i,j} = \frac{\lambda S}{e} \quad (2)$$

Where,

λ : Thermal conductivity,
S: Surface,
e : Characteristic thickness

- The convective conductance:

$$h_c = h.S \quad (3)$$

Where,

h is the convection heat transfer coefficient

- The radiative conductance:

$$h_r = \varepsilon.F.\sigma.S.(T_j + T_i)(T_j^2 + T_i^2) \quad (4)$$

ε: Emissivity of the wall,
F: Form factor,
σ: StefanBoltzmannconstant $(5{,}67.\,10^{-8}\mathrm{m}^{-2}\mathrm{K}^{-4})$

- Correlations and materials thermophysical properties: Table 1 summarizes the termophysical properties of oven construction materials.

The following correlations are used to determine the coefficient of heat transfer by convection inside the combustion chamber [22]:

$$Nu = 0.5(1.6\,\mathrm{Re}^{0.5} + 2.733\,\mathrm{Re}^{0.59}) \qquad (5)$$

Where,

$\mathrm{Re} = \frac{\rho \times v \times D}{\mu}$ is the Reynolds number and

$D = \frac{4 \times S}{P}$ the hydraulic diameter

ρ is the air density, v the kinematic viscosity of air and μ the dynamic viscosity of air

Outside the oven the Mc Adam relationship is used [23]:

$$h_c = 5{,}7 + 3{,}8V \qquad (6)$$

Where V is the air velocity (m/s)
The thermophysical properties of air are determined by the following correlations [24]:

Massive heat:

$$C_p = 0{,}9362 + 0{,}0002 \times T \quad \text{(kJ/kg.K)} \qquad (7)$$

Thermal conductivity:

$$\lambda = 0{,}00031847 \times T^{0.7775} \quad \text{(W/m.K)} \qquad (8)$$

Kinematic viscosity:

$$v = (0{,}0000644 \times T^2 + 0{,}0631 \times T - 9{,}54).10^{-6}\ (\mathrm{m^2/s}) \qquad (9)$$

Dynamic viscosity:

$$\mu = 0{,}0447 * 10^{-5} * T^{0{,}7775} \quad \text{(kg/m.s)} \qquad (10)$$

Density:

$$\rho = 353 / T \quad (\mathrm{kg/m^3}) \qquad (11)$$

$$\mathrm{Pr} = 0{,}685 \text{(Constant)} \qquad (12)$$

Radiant heat transfer coefficients are determined by the following correlations [25,26]:

$$h_r = \frac{\sigma}{\frac{1}{\varepsilon} + \frac{1}{F_{sky}} - 1}(T_i^2 + T_{sky}^2)(T_t + T_{sky}) \qquad (13)$$

$$\text{With : } F_{sky} = \frac{3\pi + 2b}{2\pi(3 + b)} \qquad (14)$$

Where,

b is a function of the anisotropy of the sky. For an isotropic sky (b = 0), the radiative form factor corresponds to 0.5.

$$T_{sky} = 0.0552 T_{ext}^{1.5} \qquad (15)$$

$$F_c = \frac{(L^2 + 2(H+W)^2 - 2(H+W)\sqrt{L^2 + (H+W)^2})}{L^2} \qquad (16)$$

Where,

L : Oven length,
H : Oven height,
W : Oven width

The energy stored by walls is expressed by:

$$E_{st} = m_i c_i \left(\frac{T_{f-\mathrm{int}} + T_{f-ext}}{2} - T_{ext}\right) \qquad (17)$$

Where,

$T_{f-\mathrm{int}}$: Temperature of the internal face of the material

T_{f-ext} : Temperature of the external face of the material

The energy lost by convection and radiation is expressed by:

$$E_{cv} = \sum_0^t (g_{i,ext}(T_i - T_{ext}) \times \Delta t + g_{i,sky}(T_i - T_{sky}) \times \Delta t) \qquad (18)$$

The total energy lost by the oven walls is :

$$E_p = E_{st} + E_{cv} \qquad (19)$$

Table 1. Materials thermophysical properties

Materials	Heat capacity $J.kg^{-1}.K^{-1}$	Density $Kg.m^{-3}$	Thermal conductivity $W.m^{-1}.K^{-1}$
Terracotta brick	878	1800	1.8
Plywood	1600	500	0.12
Mortar	500	1515	1.13
Iron sheet	478	7850	70

2.3 Numerical Method

The outer walls exchange heat by convection and radiation with the external environment, which gives the following relation:

$$m_i c_i \frac{\partial T_i}{\partial t} = g_{i,j}(T_i - T_j) + g_{i,ext}(T_{ext} - T_i) + g_{i,sky}(T_{sky} - T_i) \tag{20}$$

With,

$g_{i,ext} = (h\ )S_{i,ext}$ and $g_{i,sky} = h_r S_{i,sky}$

T_{sky}: Sky temperature (K),
T_{ext}: Ambient temperature (K)

The heat exchanged by the air inlets and outlets at the grid is expressed by :

$$m_i c_i \frac{\partial T_i}{\partial t} = \sum_{i \neq j} g_{i,j}(T_j - T_i) + \dot{m}_{ai}^e h_a^e - \dot{m}_{ai}^s h_a^s \tag{21}$$

The heat exchanged by the air inlets and outlets at the combustion chamber with the heat source is expressed by :

$$m_m c_m \frac{\partial T_m}{\partial t} = \sum_{m \neq j} g_{m,j}(T_j - T_m) + \dot{m}_{am}^e h_a^e - \dot{m}_{am}^s h_a^s + Q_m \tag{22}$$

The discretization of these equations gives for the external walls :

$$m_i c_i \frac{T_i^{t+\Delta t} - T_i^t}{\Delta t} = g_{i,j}(T_j^{t+\Delta t} - T_i^{t+\Delta t}) + g_{i,ext}(T_{ext} - T_i^{t+\Delta t}) + g_{i,sky}(T_{sky} - T_i^{t+\Delta t}) \tag{23}$$

Which gives:

$$(1 + \alpha_{i,j} + \alpha_{i,ext} + \alpha_{i,sky})T_i^{t+\Delta t} - \alpha_{i,j} T_j^{t+\Delta t} = T_i^t + \alpha_{i,ext} T_{ext} + \alpha_{i,sky} T_{sky} \tag{24}$$

With,

$\alpha_{i,j} = \frac{\Delta t \times g_{i,j}}{m_i \times c_i}$, $\alpha_{i,ext} = \frac{\Delta t \times g_{i,ext}}{m_i \times c_i}$ and $\alpha_{i,sky} = \frac{\Delta t \times g_{i,sky}}{m_i \times c_i}$.Δt is the step time

Likewise at the internal walls, we have:

$$(1 + \alpha_{i,j} + \alpha_{i,m})T_i^{t+\Delta t} - \alpha_{i,j} T_j^{t+\Delta t} - \alpha_{i,m} T_m^{t+\Delta t} = T_i^t \tag{25}$$

At time t_0, the temperatures of the different parts of the oven are initialized at 314.15K corresponding to the ambient temperature, then we calculate the different coefficients of heat transfer by conduction, convection and radiation. At $t_0+\Delta t$, where Δt is the step time, the resolution of the system of algebraic equations using Gauss algorithm (20-25) leads to new values of the temperature of the different parts of oven which are compared with the arbitrary values. If the difference between these two temperatures is greater than the desired precision, the values of the calculated temperatures replace the arbitrary value and the procedure described below is repeated until the convergence is obtained. The convergence was obtained when the following criterion was satisfied:

$$\frac{T^{t+\Delta t} - T^{t}}{T^{t+\Delta t}} \leq 10^{-3} \tag{26}$$

3. RESULTS AND DISCUSSIONS

3.1. Model Validation

The mathematical model was validated by comparing the numerical and experimental results. The oven has been built with the dimensions L = 70cm, W = 50cm and H = 20 cm. 4 cm thick terracotta bricks were assembled by a mortar made from cement, sand and ash. 1 cm of plywood has been placed between terracotta bricks and metallic casing. Measuring equipment consist of K type thermocouples connected to a datalogger (Omega) with precision : 1.5°C and a balance with precision : ±1g. The experimental setup is shown in the Fig. 3.

Fig. 4. and 5. present the temporal evolutions of the numerical and experimental external wall temperatures of the oven.

The preceding figures show that the numerical and experimental profiles of the temperatures of the external walls of the oven are similar. At the start of combustion, the temperatures are almost invariable because the heat flow generated by the fuel is blocked by the insulation effect of the furnace. The temperature of the outer wall rises slightly after 40 minutes, but throughout the experiment it does not exceed the limit of 60°C set outside by the numerical study. The maximum relative errors ($100 \times \frac{|T_{exp}-T_{num}|}{T_{exp}}$) between theoretical and experimental study are of the order of 5%. This difference is explained by the correlations used in the numerical study to approximate the heat exchange coefficients. In addition, the experimental results are very sensitive to external conditions (ambient temperature, wind speed and direction, etc).

In the rest of the study, we consider a thickness of 4 cm for terracotta bricks.

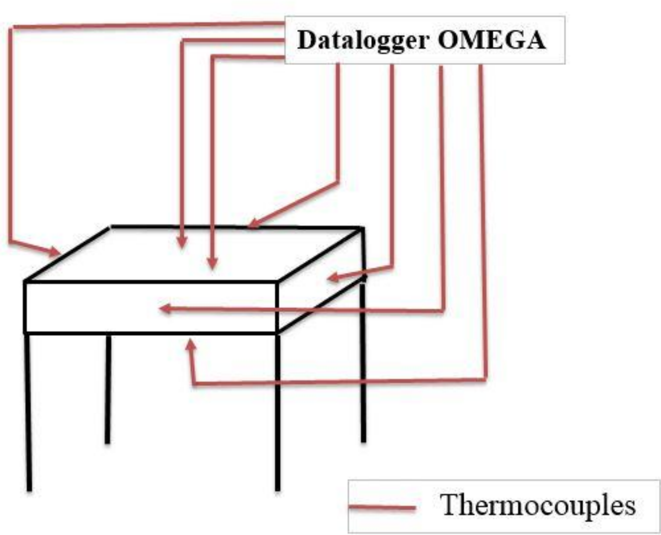

Fig. 3. Experimental setup

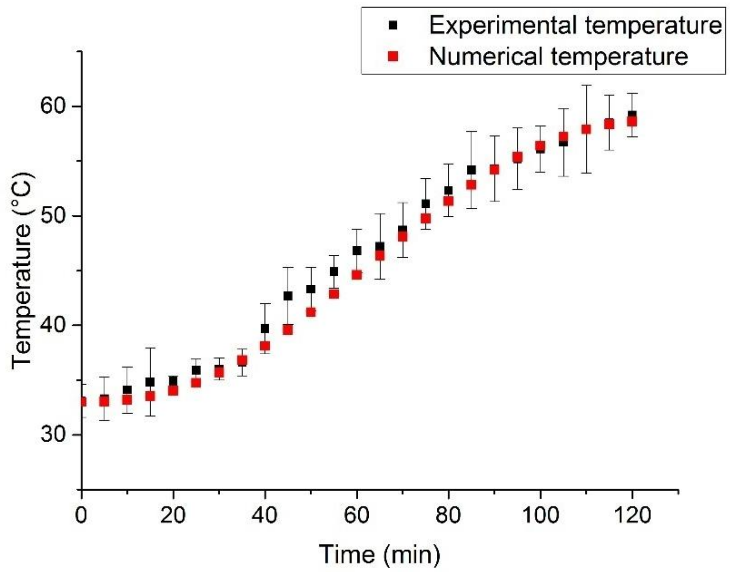

Fig. 4. Experimental and numerical lateral walls temperature

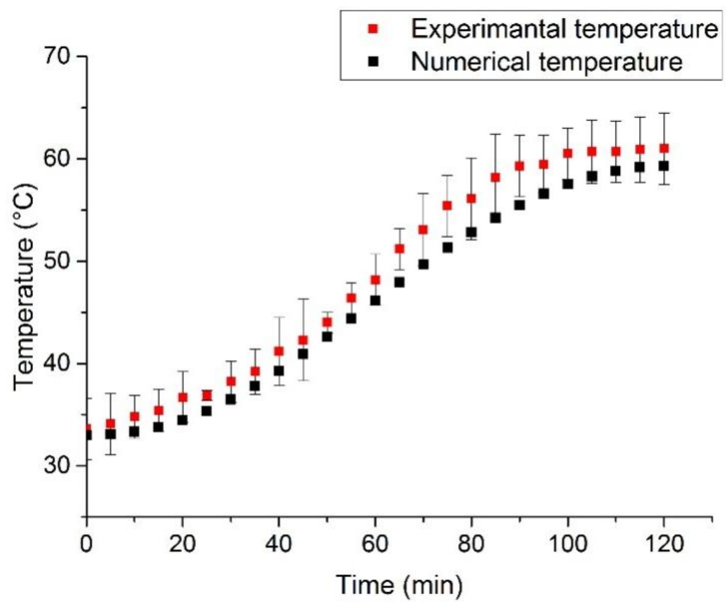

Fig. 5. Experimental and numerical bottom wall temperature

3.2 Plywood Influence on Heat Transfers

Figs. 6 and 7 show the influence of the thickness of the plywood on the temperatures of the outer walls of the oven.

The results show that without plywood (e = 0), the temperatures increase to exceed 100°C, in particular for the bottom walls. It is obvious that at these temperatures, there is a risk of burns for users. However, as the thickness of the plywood increases, the temperatures of the exterior walls of the oven gradually decrease. At the beginning, a small increase in the thickness of the plywood causes a considerable drop in wall temperatures and then from a thickness of 10 mm the temperatures decrease slightly even if the increase in the thickness of the plywood is considerable. This result is mainly due to the low thermal conductivity of the plywood which prevents the transmission of heat from the inside to the outside of the oven. This insulating effect confines heat inside the combustion chamber and reduces energy loss through convection and radiation. The convergence of transfers obtained from plywood 10 mm thick shows that this thickness is sufficient to solve the problem. Overall, when the temperatures of the outer walls of the oven are compared between single and double insulation, it is found that the addition of plywood considerably improves the thermal comfort of users since the temperatures obtained do not exceed 60°C as shown in Fig. 8.

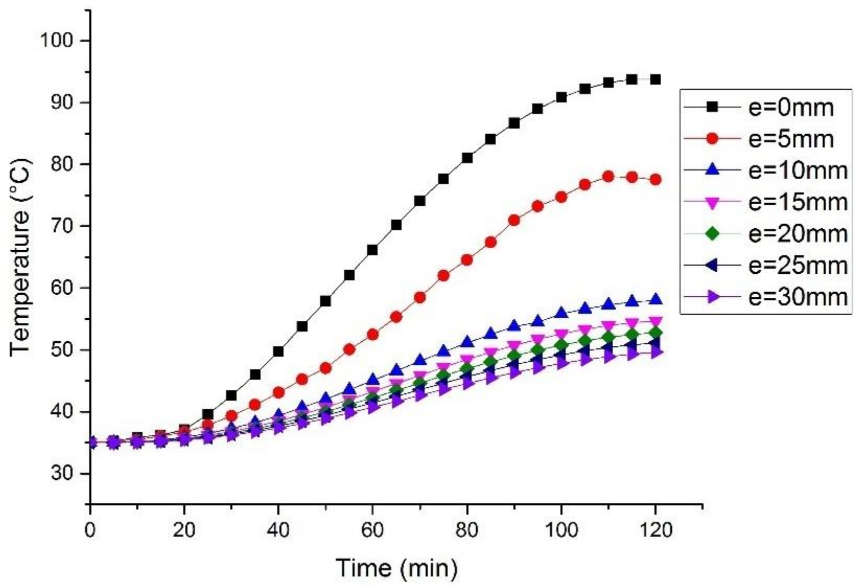

Fig. 6. Influence of plywood thickness on the external oven lateral walls temperatures

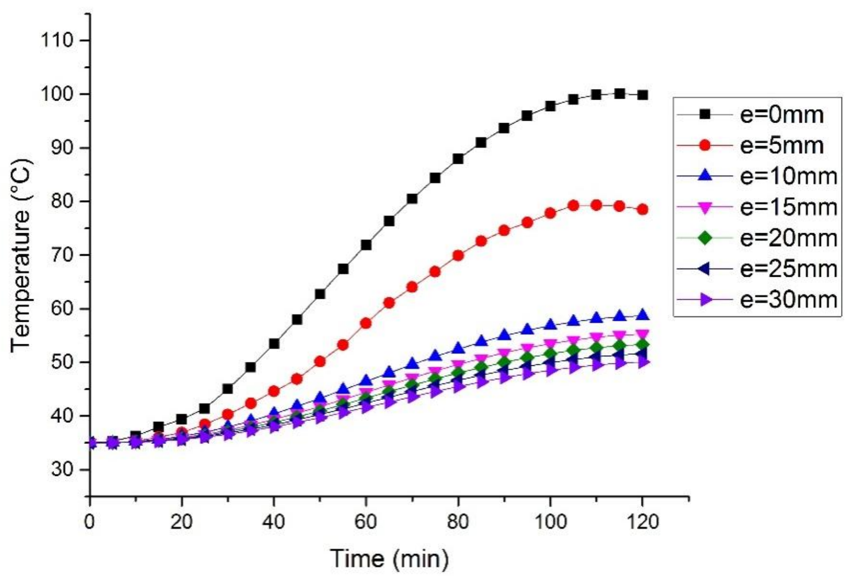

Fig. 7. Influence of plywood thickness on the external oven bottom wall temperatures

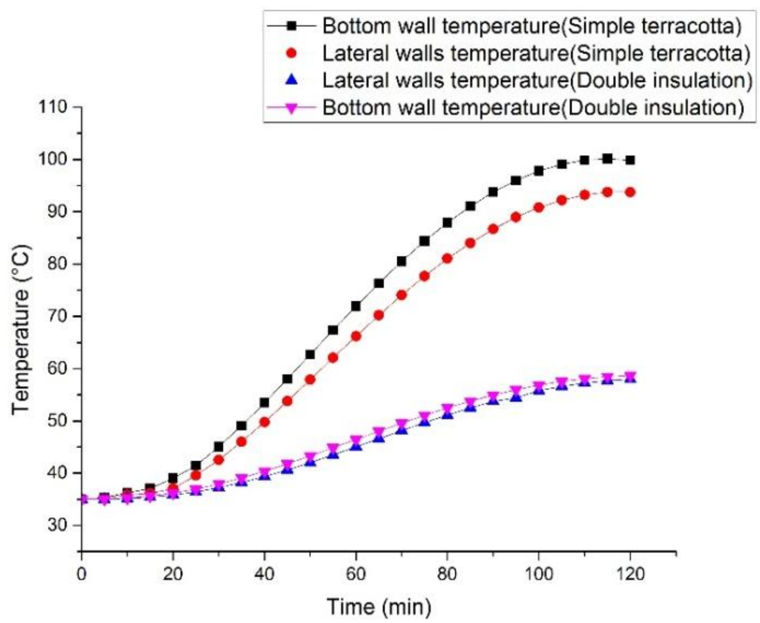

Fig. 8. Temperature evolution of the exterior walls for single and double insulation

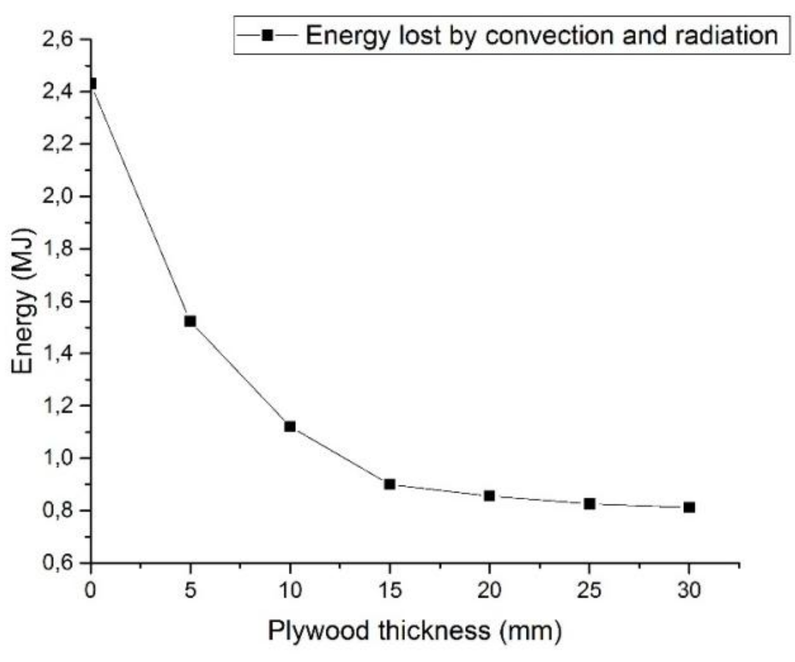

Fig. 9. Energy lost by convection and radiation with ambient

3.3 Plywood Thickness Influence on Energy Savings

Figs. 9 to 11 show respectively the influence of the thickness of the plywood thickness on the energy losses by convection and radiation with the external environment, on losses by storage in the oven walls and the total energy losses which is the sum of the two forms of energy previously cited.

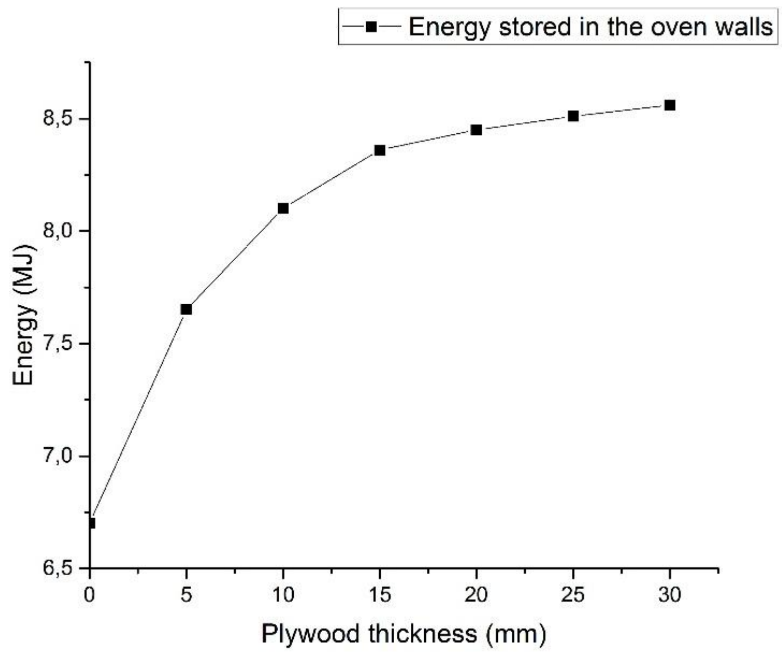

Fig. 10. Energy stored in the oven walls

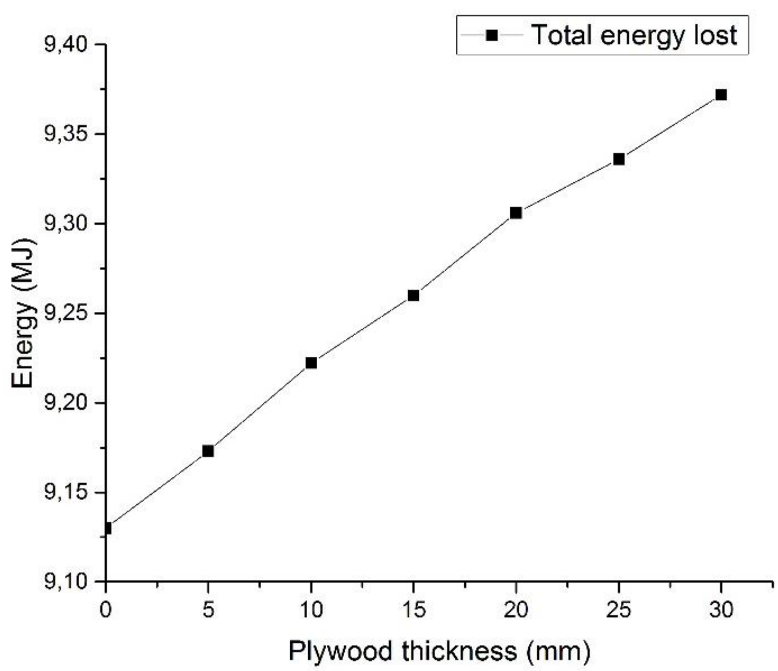

Fig. 11. Total energy lost with the oven walls

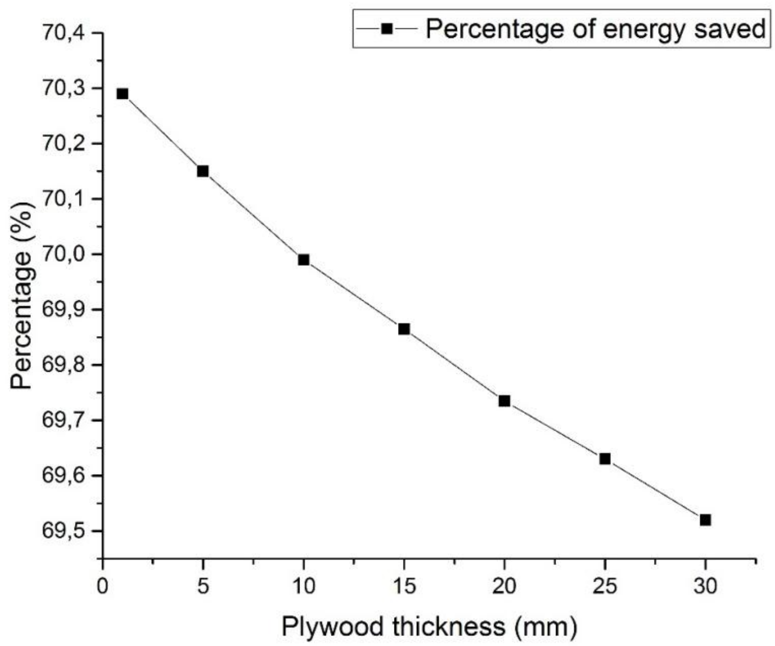

Fig. 12. Influence of plywood thickness on energy savings

The results show that as the thickness of the plywood increases, the energy lost through convection and radiation decreases. This energy decreases because it is related to the gradient between the temperatures of the external wall of the oven and the ambient temperature. The increase in the thickness of the plywood causes a gradual drop in the temperatures of the outer walls of the oven which decreases the temperature gradient between the walls and the environment, thus causing the reduction of energy losses by convection and radiation. The reduction of energy losses with the surrounding environment confines the heat inside the combustion chamber thus raising its temperature. The increase in the temperature of the combustion chamber causes an increase in the temperatures of the internal walls (terracotta) thus increasing the energy storage in the walls of the oven. The total energy lost which is the sum of the two forms of energy increases slightly with the thickness of the plywood because the losses by storage outweigh the losses by convection and radiation.

Fig. 12 shows the influence of plywood thickness on energy saved with oven walls insulation.

The results show that the energy saved with the double insulation is about 70%, which is not far from that of the oven isolated simply with 4 cm thick terracotta bricks (68%) obtained during our previous works [20]. The results also show that the energy savings decrease slightly with increasing plywood thickness. These results are explained by the increase in storage losses, which compensates the reduction of convective and radiative losses due to the introduction of plywood as explained above.

4. CONCLUSION

In this work, we conducted a numerical study of a double-insulated oven using terracotta bricks and plywood. The numerical methodology is based on the nodal method and the equations obtained were discretized using an implicit finite difference scheme, then solved by the Gauss algorithm. The main results are summarized as follows:

- The double insulation (terracotta bricks and plywood) makes it possible to achieve significant energy savings compared to the non-insulated oven. However, the addition of plywood does not significantly change the level of energy savings compared to simple terracotta insulation. For 4 cm thick terracotta bricks and 1 cm thick plywood, the energy savings is about 70%,

- The addition of plywood reduces the convective and radiative losses but increases storage losses in terracotta bricks,
- The addition of plywood allows the temperatures of the outer walls of the oven to be lowered up to 60°C, which is less dangerous for users compared to the temperatures achieved with simple terracotta insulation.

These results highlight the importance of double insulation (terracotta and plywood) in reducing energy consumption in the grilling sector while protecting the health of users. They will subsequently make it possible to develop a commercial prototype for the market players.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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