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Research Note

Experimental Analysis of the Thermal Performance of a Metal Fired-wood Oven

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ABSTRACT

This work is devoted to the evaluation of the performance of a typical fired-wood oven commonly used in the rotisserie sector in Burkina Faso. The methodology used is based on the energy balance of the oven. For this purpose, 20 liters of water were heated up to 90 °C. The difference in water temperature at the start and at the end of the experiment makes it possible to calculate the amount of energy consumed by the load. The temperatures of the walls as well as that of the ambient were recorded to evaluate the losses by convection towards the environment. The losses through the fumes have been estimated from the energy balance. The results show that the dominant losses are those of fumes (about 55 % of the energy consumed). The losses through the walls are relatively large (26 %). The efficiency of the oven is around 19 %, which is very low. These results show that these equipment are inefficient and contribute significantly to the waste of wood at the national level.

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Nomenclature

t	time, s	E_F	energy lost by the flue gas, kJ
Cp_v	specific heat of vessel, kJ. kg^{-1}. K^{-1}	E	oven efficiency, %
Cp_w	specific heat of water, kJ. kg^{-1}. K^{-1}	T_1	initial temperature of water, °C
C_{Wd}	calorific value of wood, kJ. kg^{-1}	T_2	final temperature of water, °C
h	natural convection coefficient, W.m^{-2}.K^{-1}	T_w	walls temperature, °C
M_w	quantity of water, l	T_a	ambient temperature, °C
M_{wd}	mass of wood consumed, kg	V	wind speed, m.s^{-1}
E_{wd}	energy supplied by wood, k	L_w	latent heat of vaporization of water, kJ. kg^{-1}
E_L	energy consumed by the load, kJ	M_e	quantity of water vaporied, l
E_w	energy lost by walls, kJ		

INTRODUCTION

Meat rotisserie in Burkina Faso is a lucrative activity which provides substantial revenues to the actors. Unfortunately, most equipment has very low efficiency and we have highlighted this problem through a study carried out on grilling equipment [1]. This low efficiency represents a net loss of income for the players who spend more than necessary on fuel. At the national level, this situation leads to a waste of forest resources because most of this equipment operate with wood. However, the situation of forest resources in Burkina Faso is very worrying. Indeed, over the 1992-2002 period, the rate of decline in forest resources was estimated at 107,626 ha/year [2]. Moreover, 90.1 % of households use solid fuels (wood and derivatives) as the main source of cooking energy [3] and this situation should not change in the coming decades [4]. Also, several studies have shown the impact of the regression of forest areas on climate change [5–7].

The use of biomass (wood, charcoal, animal dung, agricultural residue, etc.) as energy source in cooking food also has other drawbacks. The major disadvantage is related to the degradation of the quality of ambient and

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households air due to emissions [8–10]. Emissions can be particles (particulate matter including black carbon: BC) or gaseous compounds (CH_4, CO_2, CO, NO_2, SO_x, NMHCs, VOCs, etc.) which have a negative impact on populations health [11–13]. Women and children are particularly vulnerable to this pollution [14, 15]. According to the World Health Organization (WHO), in 2016, globally, 7 million deaths were attributable to the joint effects of household and ambient air pollution and about 94% of these deaths occur in low and middle income countries [16].

At the environmental level, gaseous compounds such as CO_2, CH_4 and NO_2 are known to be greenhouse gases [17]. Several studies have also shown that BC and NMHCs have a negative impact on the climate [18–21].

In recent years, to control such problem, research has been directed towards the development of energy-efficient cooking technologies. Thus, from traditional 3-stone stoves which efficiency is 10-15 % [22], improved cookstoves have been developed [23–30]. However, the improvements were mainly concentrated in the household cookstoves. In Burkina Faso, commercial wood-fired cooking equipment such as rotisserie ovens has not received much attention. Most of them are still rudimentary and uninsulated. Also very few studies concerning them have been carried out. This is why the objective of this work is to study these devices with a view to highlight their thermal performance.

(a) (b)

Figure 1. a) Fired-wood oven used in the market; b) Experimental prototype

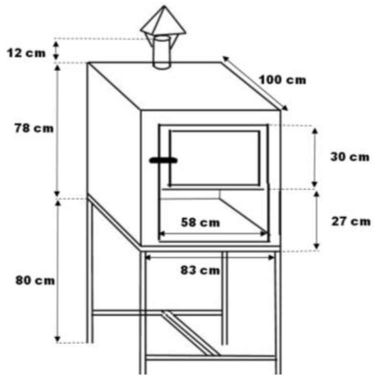

Figure 2. Diagram of the prototype

MATERIAL AND METHOD

Material

For this study, we used:

– An experimental prototype fired-wood oven: It was developed on the basis of models used in the market (Figure 1(a)). The experimental prototype is shown in Figure 1(b).

It has a parallelepiped shape (L x W x H = 1 m x 0.84 m x 0.78 m) surmounted by a chimney 12cm high and 9cm in diameter. The walls are made of metal sheet 2 mm thick and are uninsulated. A schematic view of the prototype is illustrated in Figure 2.

– Measuring equipment: They consist of K type thermocouples (precision: 1.5 °C) connected to a datalogger with a tolerance of: 0.05 % (read value) ± 1 °C, a balance with precision: ±1 g, and a moisture meter.

Methods

The methodology used to determine the performance of the oven is based on the energy balance. For this purpose, a steel vessel containing 20 liters of water is introduced into the oven, then the water is heated with 10 kg of wood to 90 °C on average. The 20 liters of water represent the average load of the oven. The humidity of the wood is determined before combustion. As the combustion of wood is random depending on the wind speed and the vessel fairly wide, when the average water temperature reaches 90 °C, part of the water reaching temperatures above 90 °C vaporizes. At the end of the experiment, the mass of water in the vessel is again weighed to determine the mass of water vaporized. Likewise, the remaining mass of wood is weighed to calculate the mass of wood consumed. The experimental setup is illustrated in Figure 3.

During the experimental run, the internal and external temperatures of the oven, the ambient temperature as well as the water temperature are recorded using thermocouples. The thermocouple recording the water temperature is placed in the middle of the vessel. The measurements are repeated three times under the same conditions to have average values.

The energy balance of the oven is summarized in the Figure 4. The heat balance of the oven can then be written:

$$E_{wd} = E_L + E_w + E_F \quad (1)$$

where,

E_{wd}: Energy supplied by wood

E_L: Energy consumed by the load

E_w: Energy lost by walls

E_F: Energy lost through the flue gas

Figure 3. Experimental setup

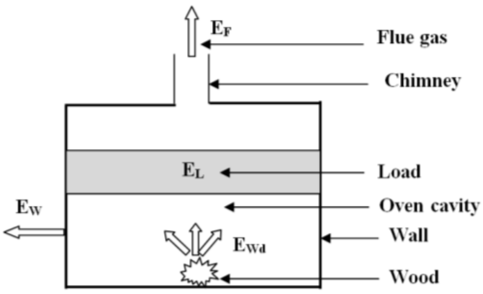

Figure 4. Energy balance diagram

The different amounts of energy can be calculated as follows:

– The energy supplied by wood (E_{wd}) is calculated by making a mass balance of the gas before and after each experiment to obtain the mass of wood consumed (M_{wd}). The energy supplied by wood is then:

$$E_{wd} = M_{wd}C_{wd} \quad (2)$$

where, M_{wd} is the mass of wood consumed (kg) and C_{wd} is the calorific value of wood (kJ.kg^{-1}).

– The energy consumed by the load (EL) is that stored by the water and the vessel to which the vaporization energy of part of the water is added:

$$E_L = (M_w Cp_w + M_v Cp_v)(T_2 - T_1) + M_e L_w \quad (2)$$

where,
M_w: Quantity of water (l)
M_e: Quantity of water evaporated (l)
L_w: Latent heat of vaporization of water (kJ. kg^{-1})
Cp_w: Specific heat of water (kJ. kg^{-1}. K^{-1})
T_1: Initial temperature of water (°C)
T_2: Final average temperature reached by water (°C)
M_v: Weight of vessel (kg)
Cp_v: Specific heat of vessel (kJ. kg^{-1}. K^{-1})

– Energy lost by the walls (EW) takes place essentially by convection from external walls to the environment. As the walls temperature varies over time, EW can be estimated using the following formula:

$$E_w = \int_0^t hS(T_w - T_a)dt \quad (4)$$

where, T_w is the walls temperature, T_a is the ambient temperature, S is the surface of the walls, t corresponds to the duration of the water heating and h the natural convection coefficient between the walls and the external environment. For side walls, h can be estimated using the Mac Adams correlation [31]:

$$h = 5.7 + 3.8 \times V \quad (5)$$

where V is the wind speed (m.s^{-1}).

Considering the wind speed constant, Equation (4) becomes:

$$E_W = S \times (5.7 + 3.8 \times V) \int_0^t (T_w - T_a)dt \quad (6)$$

This integral is evaluated by numerical approximation.

– The energy lost through the flue gas (EF):
From Equation (1), energy lost by flue gas can be calculated:

$$E_F = E_{wd} - E_L - E_w \quad (7)$$

The oven efficiency is given by the formula:

$$E\ (\%) = 100 \times \frac{(M_w \times Cp_w + Cp_v \times M_v)(T_2 - T_1) + M_e \times L_w}{M_{wd} \times E_{wd}} \quad (8)$$

RESULTS AND DISCUSSION

Evolution of oven temerature

Figure 5 shows the evolution of the oven cavity, water and external walls temperature. It can be seen that the temperature of the oven cavity as well as that of the walls changes in the same way. In fact, part of the heat inside the oven cavity reaches the internal wall of the oven by convection, crosses the metal casing by conduction and then reaches the outside wall of the oven. These temperatures are low the first 25 minutes because of the combustion of the wood which is in the starting phase. Due to fluctuations in wood combustion, the water temperature changes slowly to 90 ° on average and this

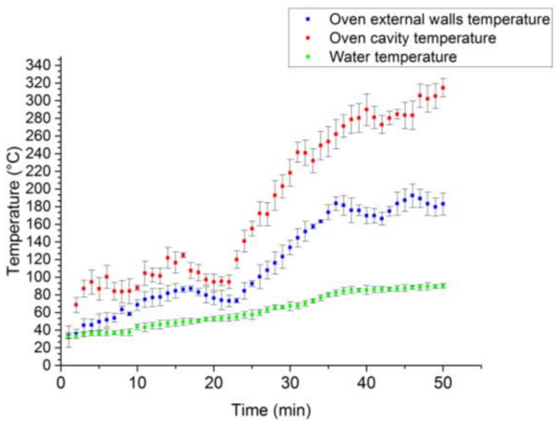

Figure 5. Oven cavity and external walls temperature evolution

in about 50 minutes. The temperatures of the external walls are high compared to the ambient temperature due to the absence of thermal insulation as shown in Figure 6. This large difference in temperature compared to the ambient obviously results in huge losses of energy to the outside environment.

Energy balance outcome

The constants used for the oven efficiency calculations are shown in Table 1. The calorific value of wood was calculated from its moisture content (10%) using the curve of the net calorific value of wood as a function of humidity [32]. The different measured values are summarized in Table 2.

The above average values are used for the calculation of the energy balance. The calculated values are stated in Table 3 and Figure 7.

It can be seen that the most significant losses are those of fumes. These losses are explained by the design of the oven of which the open combustion chamber admits too much primary air for the combustion of organic matter and very little secondary air for the combustion of gases and other unburnt matter. Finally, these hot gases leave the oven without being burnt, which causes losses. At the same time, the excess of primary air accelerates the combustion of the organic matter. The losses through the walls are explained by their non-insulation, thus facilitating the transfer of heat to the surrounding environment. These huge losses explain the low efficiency of the oven which is around 19%. This efficiency is not very far from that of traditional domestic cookstoves (10-15%). This very low efficiency obviously translates into a waste wood; therefore, financial resources for the actors but also of forest resources for the country.

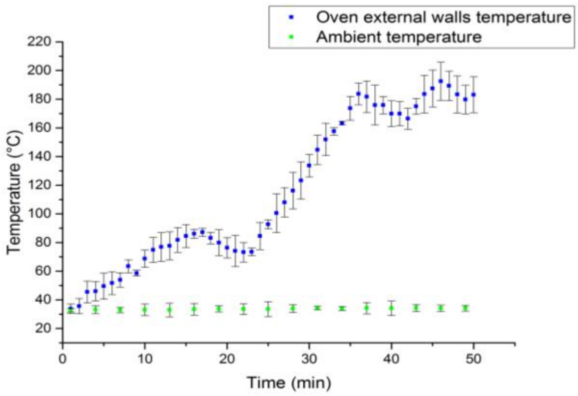

Figure 6. External walls and ambient temperature evolution

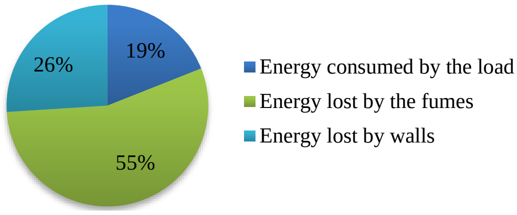

Figure 7. Oven energy balance

TABLE 1. Constants used for calculations

M_w	Cp_w	C_{wd}	Lw	M_V	Cp_v	V
20	4.18	16 400	2260	9.15	0.46	3

TABLE 2. Measured values

Test	T_1 (°C)	T_2 (°C)	M_{wd} (kg)	M_e(l)
1	35	90	4.2	3.3
2	36	90	4.5	4.4
3	35.5	90	4.8	5.1
Average	35.5±0.5	90	4.5±0.3	4±1.1

TABLE 3. Energy balance results

Energy	E_{wd} (KJ)	E_L (kJ)	E_W (kJ)	E_F (kJ)
kJ	73800	13826	19306	40668
%	100	19	26	55

CONCLUSIONS

In this work, we evaluated the performance of a wood oven commonly used in the rotisserie sector in Burkina Faso. The methodology used is based on energy balance of the oven. For this purpose, 20 liters of water were heated up to 90°C. The difference in water temperature at the start and at the end of the experiment allows to calculate the amount of energy consumed by the load. Recording the temperature of the walls alows to calculate the losses by convection to the surrounding environment. The losses through the fumes were estimated from the energy balance. The main results are summarized as follows:

- The most significant losses are those through the fumes towards the outside environment (about 55% of the energy consumed). These losses are mainly due to the design of the oven which does not allow good combustion of the wood,
- The losses through the walls are relatively large (26% of the energy consumed), mainly due to the lack of thermal insulation,
- The efficiency of the oven is around 19%, which is close to that of traditional domestic cookstoves.

These results showed that the use of these equipment contributes more to the waste wood at the national level. Like traditional stoves, these equipment need to be improved. Meanwhile, regulation needs to be developed for their use.

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Persian Abstract

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چکیده

این پژوهش به ارزیابی عملکرد یک اجاق گاز هیزمی معمولی از چوب که معمولاً در بخش روتاری در بورکینا فاسو استفاده می‌شود اختصاص یافته است. روش استفاده شده براساس موازنه انرژی اجاق گاز است. برای این منظور ۲۰ لیتر آب تا ۹۰ درجه سانتیگراد گرم شده است. تفاوت دمای آب در شروع و در پایان آزمایش برای محاسبه مقدار انرژی مصرفی محاسبه می‌شود. درجه حرارت دیوارها و همچنین محیط برای ارزیابی خسارات ناشی از هدر رفت به محیط ثبت شده است. اتلاف انرژی ناشی از دود از تراز انرژی تخمین زده می‌شود. نتایج نشان می‌دهد که ضررهای عمده آن مربوط به دود (حدود ۵۵٪ از انرژی مصرفی) است. اتلاف انرژی ازطریق دیوارها نسبتاً زیاد است (۲۶٪). راندمان فر حدود ۱۹٪ است که بسیارپایین است. این نتایج نشان می‌دهد که این تجهیزات ناکارآمد بوده و به میزان قابل توجهی در هدر رفتن چوب در سطح ملی نقش دارند