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Study and Analysis of Energy Use Efficiency of a Local Gas Roasting Oven

Serge Wendsida Igo[1*], David Namoano[2], Abdoulaye Compaoré[1], Gaël Lassina Sawadogo[2], Drissa Ouedraogo[2] and Joseph Dieudonné Bathiebo[2]

[1]Institut de Recherche en Sciences Appliquées et Technologies (IRSAT/CNRST), Département Energie, Ouagadougou, Burkina Faso.
[2]Université Joseph KI-ZERBO, Laboratoire d'Energies Thermiques Renouvelables (LETRE), Ouagadougou, Burkina Faso.

Authors' contributions

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

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ABSTRACT

This work concerns the energy efficiency study and analysis of a gas roasting oven developed by a local craftsman. The oven energy efficiency was determined by the Water Boiling Test (WBT) method. The temperatures of the walls as well as the ambient temperature were recorded to evaluate the heat losses by convection towards the environment. The energy balance of the oven then allows to calculate the heat losses from the fumes. The results show that the heat losses by fumes through the chimney are the greatest (50% of the energy consumed). Losses through the walls are relatively low (15%). The oven efficiency is around 35%, which is relatively low. These results show that optimization work must be carried out in order to improve the energy efficiency of the equipment.

Keywords: Local gas roasting oven; LPG; energy balance; energy losses; energy efficiency.

**Corresponding author: E-mail: sergesigo@yahoo.fr;*

ABBREVIATIONS

Cp_v : *Specific Heat of Vessel, KJ. Kg^{-1}. K^{-1}*
Cp_w : *Specific Heat of Water, KJ. Kg^{-1}. K^{-1}*
E : *Oven Efficiency, %*
Eg : *Calorific Value of Fuel, KJ. Kg^{-1}*
h : *Natural Convection Coefficient, W. m^{-2}. K^{-1}*
LPG : *Liquefied Petroleum Gas*
M_w : *Quantity of Water, Kg*
Mg : *Mass of Gas Consumed, Kg*
M_v : *Weight of Vessel, Kg*
M_e : *Quantity of Water Evaporated, Kg*
L_w : *Latent Heat of Vaporization of Water, KJ. Kg^{-1}*
QB : *Energy Supplied by the Burner, KJ*
QF : *Energy Lost by Fumes, KJ*
QL : *Energy Consumed by the Load, KJ*
QW : *Energy Lost by Walls, KJ*
S : *External Walls Surface, m^2*
T_1 : *Initial Temperature of Water, °C*
T_2 : *Final Temperature of Water, °C*
T_a : *Ambient Temperature, °C*
T_w : *Walls Temperature, °C*
V : *Wind Speed, m.s^{-1}*

1. INTRODUCTION

Liquefied petroleum gas (LPG) is a popular energy source around the world. Its applications are numerous and cover the demand for domestic energy, trade, agriculture, industry but also transport [1,2,3]. Although it is a fossil fuel, it is classified in the category of clean fuels because of its low environmental impact [4,5,6,7].

In Burkina Faso, this energy resource is entirely imported and commonly used as fuel in households, food processing units (rotisserie, bakery, pastry, drying, etc.) and secondarily in some urban transport vehicles. Due to the rising cost of wood and the environmental problems caused by its use, LPG consumption is growing sharply in the country [8]. In 2007, the LPG penetration rate in urban areas was 20% but should have increased to 40% in 2020 [9]. This increase in consumption has implications at the economic level, especially at the level of the country's trade balance.

More and more, local craftsmen are developing ovens operating on LPG, but in the absence of regulations in this area, the energy efficiency of this equipment is not known. However, it is important that these equipments have good energy efficiency in order to not cause unnecessary losses in LPG.

In the literature, the energy efficiency of gas cookstoves and ovens is mainly linked to the efficiency of combustion, and therefore of burners. The burners always operate with an air/fuel ratio which must be optimized to properly burn the fuel. If there is not enough air, combustion will be incomplete and will generate toxic products such as CO and unburnt such as soot. Burner efficiency will be low due to unburned carbon. So there is always an excess of air compared to the stoichiometric air to avoid this problem. However, this excess air must be well controlled. Indeed, if the excess air is too large, the losses will also be significant through the chimney resulting in low efficiency of the burner. Controlling air/fuel ratio is therefore important to limit energy losses and emissions during combustion [10,11].

Apart from the air/fuel ratio, the other factors which influence the efficiency of the burners mainly concern their design. Brass burners have been shown to be more efficient than those made of cast iron [12]. Swirl flow burners also have better efficiency compared to radial flow burners [13,14,15,16].

The influence of the load on the efficiency of the burners has also been studied. Thus, studies have shown that the weight of the load as well as its distance from the flame have an effect on the efficiency of the burner [17,18]. In the case of ovens where the burner operates in a thermal envelope, losses can occur through it in particular when it is not well insulated. These energy losses also play on the excess air in the combustion chamber [19].

In our previous work, we have shown that grilling equipment lost almost half of the fuel consumed mainly through the walls [20]. We have also shown that the energy efficiency of fired-wood ovens used in Burkina Faso is low (around 19%) [21]. This research is a continuation of these works, and aims to study and analyze the energy efficiency of a local gas roasting oven.

2. MATERIALS AND METHODS

2.1 Materials

For this study, we used:

An experimental gas oven developed by a local craftsman: This oven is mainly intended for meat roasting and its average load is 20 kg. It has a parallelepiped shape (L x W x H = 1 m x 0.84 m x 0.72 m) surmounted by a chimney 12cm high and 5cm in diameter. Combustion is ensured by two radial burners made with steel. The walls are made of metal sheet 2 mm thick and insulated with a layer of glass wool 3 cm thick. The experimental prototype is illustrated in (Fig. 1).

Fig. 1. Experimental prototype
Source: Authors, 2020

A schematic view of the prototype is presented in (Fig. 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.

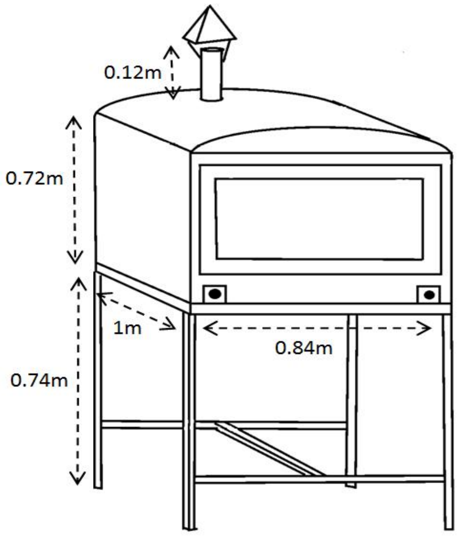

Fig. 2. Diagram of the prototype
Source: Authors, 2020

2.2 Methods

2.2.1 Oven efficiency

The method for calculating the oven efficiency is the water boiling test (WBT) used by other authors [22,23,24,25,26]. The experiments were carried out on 20 liters of water in a steel vessel. A 12.5 kg gas cylinder was used with a pressure of 28 mbar. The oven is turned on until the water reaches a temperature of 90°C and then is turned off. The mass of LPG consumed as well as that of the vaporized water is then noted. During the experiment, the internal and external temperatures of the oven as well as the ambient temperature are recorded using thermocouples. Recording continues until the water begins to cool. The measurements are repeated three times under the same conditions to have average values. The oven efficiency (E) is given by the formula:

$$E\ (\%) = 100 \times \frac{(A+B)(T_2-T_1)+M_eL_w}{Mg \times Eg} \tag{1}$$

Where:

$A = Cp_wM_w$
$B = Cp_v\ M_v$

M_w: Quantity of water (Kg)
Cp_w: Specific heat of water (KJ. Kg^{-1}. K^{-1})
T_1: Initial temperature of water (°C)
T_2: Final temperature reached by water (°C)
M_v: The weight of vessel (Kg)
Cp_v: Specific heat of vessel (KJ. Kg^{-1}. K^{-1})
M_e: Quantity of water evaporated (Kg)
L_w: Latent heat of vaporization of water (KJ. Kg^{-1})
Mg: Mass of gas consumed (Kg)
Eg: Calorific value of fuel (KJ.Kg^{-1})

2.2.2 Oven energy balance

To calculate the losses through the oven, an energy balance described in (Fig. 3) is necessary.

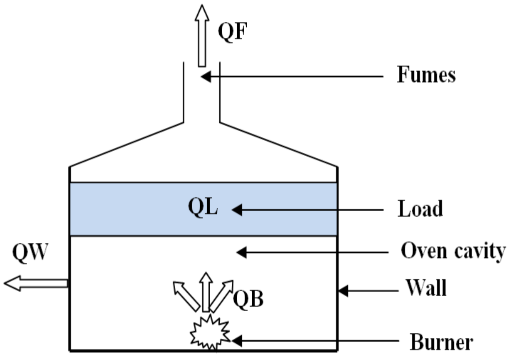

Fig.3. Energy balance diagram
Source: Authors, 2020

In this energy balance, we consider the other types of losses as negligible (losses when the burner stops or starts, losses by air renewal, etc).

QB: Energy supplied by the burner;
QL: Energy consumed by the load;
QW: Energy lost by walls;
QF: Energy lost through the fumes.

The heat balance of the oven can then be written:

$$QB = QL + QW + QF \quad (2)$$

From equation (2), energy lost by fumes can be calculated:

$$QF = QB - QL - QW \quad (3)$$

The different amounts of energy can be calculated as follows:

The energy supplied by the burner (QB) is calculated by making a mass balance of the gas before and after each experiment to obtain the mass of gas consumed (Mg). The energy supplied by the burner is then:

$$QB = Mg \times Eg \quad (4)$$

The energy consumed by the load (QL) is:

$$QL = (A + B)(T_2 - T_1) + M_e L_w \quad (5)$$

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

$$QW = \int_0^t hS(T_w - T_a)dt \quad (6)$$

Where T_w is the walls temperature, T_a 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 [27]:

$$h = 5.7 + 3.8 \times V \quad (7)$$

Where V is the wind speed.

Considering the wind speed constant, equation (6) becomes:

$$QW = S \times (5.7 + 3.8 \times V) \int_0^t (T_w - T_a)dt \quad (8)$$

This integral is then evaluated by numerical approximation methods.

3. RESULTS AND DISCUSSION

3.1 Oven Temperatures Evolution

Figs. 4, 5, and 6 show the evolution of the oven internal and external temperatures.

It is noted that as soon as the burners are ignited, the temperature of the oven cavity as well as that of the water increases similarly until the flame goes out at 90°C. This is the temperature gradient between these two environments which allows water to gradually store energy. As soon as the flame goes out, the temperature of the oven cavity drops suddenly while that of the water decreases slowly due to the stored energy. The ambient temperature remains practically constant at 42°C. The duration of heating the water to 90°C is approximately 36 minutes.

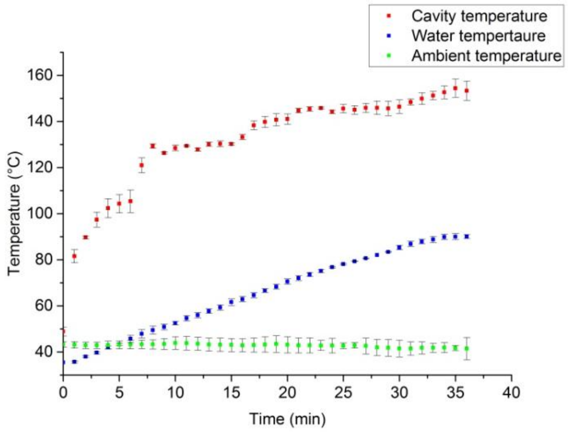

Fig. 4. Oven internal temperature evolution
Source: Authors, 2020

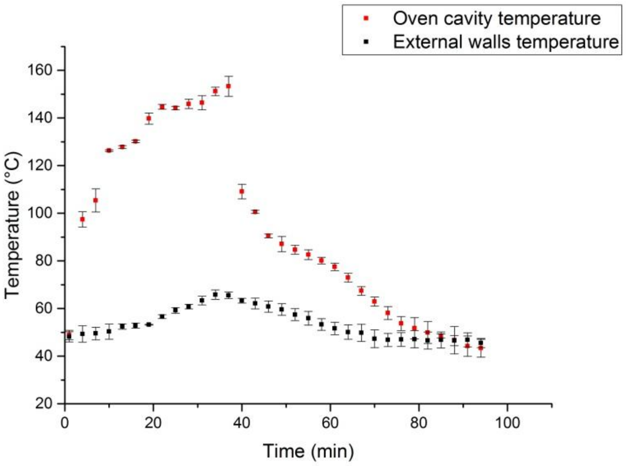

Fig. 5. Oven cavity and walls temperature evolution
Source: Authors, 2020

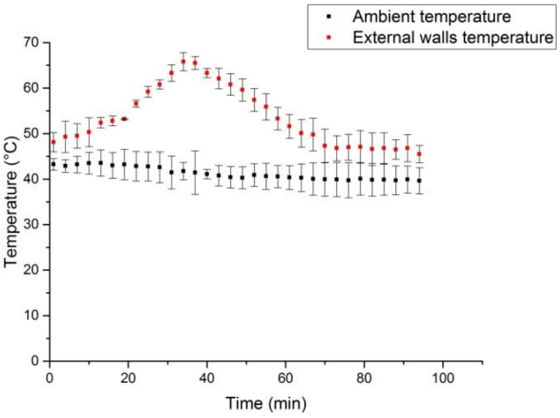

Fig. 6. External walls and ambient temperature evolution
Source: Authors, 2020

Fig. 5 shows that at the start of the experiment, the temperature of the walls is slightly higher than the ambient temperature because of the sunshine which hits the metal walls. But as soon as the burners are ignited, the temperature of the walls increases with the temperature of the oven cavity. Indeed, part of the heat inside the oven cavity passes by conduction through the internal wall and the insulating layer, then finally reaches the exterior wall. Walls temperatures are relatively low due to the glass wool insulation. Although not so important, they are nevertheless above room temperature as shown in Fig. 6, which indicates a convective heat transfer to the outside environment.

3.2 Oven Efficiency

The constants used for the oven efficiency calculations are shown in (Table 1).

Table 1. Constants used for calculations.

M_w	Cp_w	Eg	Mv	Cp_v	L_w	V
20	4.18	49 000	8	0.46	2260	3

Where:

M_w: Quantity of water (Kg)
Cp_w: Specific heat of water (KJ. Kg^{-1}. K^{-1})
Eg: Calorific value of fuel (KJ.Kg^{-1})
M_v: Weight of vessel (Kg)
Cp_v: Specific heat of vessel (KJ. Kg^{-1}. K^{-1})
L_w: Latent heat of vaporization of water (KJ. Kg^{-1})
V: Wind speed (m.s^{-1})

The energy efficiency of the oven as well as the parameters used for its calculation are shown in (Table 2).

Table 2. Oven efficiency calculations

Experiment	T_1	T_2	Mg	L_w	E
1	36	90	0.30	0.1	34
2	36.5	90	0.32	0.2	33
3	36.5	90	0.27	0.2	39
Average	36	90	0.30	0.17	35 ± 4

Where:

T_1: Initial temperature of water (°C)
T_2: Final temperature reached by water (°C)
Mg: Mass of gas consumed (Kg)
L_w: Latent heat of vaporization of water (KJ. Kg^{-1})
E: Oven efficiency (%)

3.3 Energy Balance Results

The results of the oven energy balance established from the above average values are shown in (Table 3).

Table 3. Energy balance results

Energy	QB	QL	QW	QF
Energy (KJ)	14700	5097	2196	7407
Energy (%)	100%	35%	15%	50%

Where:

QB: Energy supplied by the burner
QL: Energy consumed by the load
QW: Energy lost by walls
QF: Energy lost through the fumes

The energy efficiency of the oven is around 35% (Table 2). This efficiency corresponds to that of a standard gas oven. Indeed, the standard efficiency of gas ovens is between 30 and 40% and that of optimized ovens of the order of 40 to 50% [28].

From the energy balance results (Table 3), it can be seen that the most significant losses are those of fumes. These huge losses explain the low energy efficiency of the oven observed above and can be due to many factors (unsuitable burner, oven design, unoptimized air/fuel ratio, fuel quality, etc.). This low energy efficiency obviously results in an overconsumption of LPG. The losses through the walls are relatively low due to the thermal insulation of the glass wool, but can be reduced by reinforcing the insulation.

4. CONCLUSION

In this work, we evaluated the energy efficiency of a gas roasting oven developed by a local craftsman and commonly used in commercial activities. The oven efficiency was calculated by the Water Boiling Test (WBT) method. The wall temperatures as well as the ambient temperature were recorded to evaluate the heat losses by convection to the outside environment. The smoke losses were calculated from the energy balance of the oven. The results obtained are summarized as follows:

- The dominant energy losses are those from smoke (about 50% of the energy consumed),

- The losses through the walls are relatively low (about 15% of the energy consumed),
- The overall efficiency of the oven is 35%, which is relatively low and involves overconsumption of LPG.

These results indicate that the oven must be energy-optimized to reduce its consumption of LPG.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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