# Design of Combustion Equipment for Residual Biomass at Laboratory Scale

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## 1 Introduction

Currently, around 100 million tons of rice husk are produced annually worldwide [1]. In addition, one of the main characteristics of rice husk is the low level of biodegradation, which can last up to 5 years, accumulating it in the soil, generating large amounts of methane CH4—one of the leading causes of the greenhouse effect. It should also be said that rice husk is one of the greatest biomasses with the availability and possibility to generate energy. According to the Ministry of Agriculture, Livestock, Aquaculture, and Fisheries (MAGAP, acronym in Spanish), Ecuador produces around 1.71 tons per year, ranking fifth in Latin America as a rice producer. This occupies 15.34% of the area for planting and is considered a self-sustaining agricultural product, as it satisfies the national demand for consumption. Its production is focused on the provinces of Guayas and Los Ríos, with 60% and 34%, respectively, corresponding to approximately 94% of the planting that corresponds to the Costa region, according to the National Institute of Statistics and Censuses (INEC, acronym in Spanish).

In Ecuador, the large rice mill plants use husk as fuel for drying rice, being one of the processes that require the highest energy demand because the percentage of water associated with the product and the humidity of the surface must be extracted [2]. This industry sells the waste to cogeneration plants [3]. Analyzing the rice mill plants during the study, it is estimated that 50% of the husk is used as fuel, in exceptional cases 100% of it, but 35% of the husk is used in other production processes [4]. The technology of combustion furnaces coupled to dryers handles

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many failures in the combustion process, generating CO2 emissions, unprocessed products (100% ash is not produced), silica in furnaces, and particulate matter. The amount of ash generated from combustion corresponds to 14–25% depending on the region's variety, climate, and soil [5]. It is composed of silica, potassium, carbon, calcium, phosphorus, and other elements [6]. Being considered harmful to the employee's health, it is essential to maintain controlled combustion of the system.

Concerning the medium-scale industry, few rice milling plants have changed their technology. Currently, industrial LPG is the primary source of fuel, not being competitive for the national market due to the cost of fuel for a drying time from 12 to 16 h. Other problems in the sector are thermal losses, flame temperature, flow, and temperature air of hot ranging between 35 °C and 80 °C, generating a problem in terms of the final quality of the product because of the range temperature that the dryer must reach is between 40 °C and 50 °C.

From the mentioned problems, to carry out the study of the combustion process of this biomass source, the design and construction of a controlled furnace at laboratory-scale are proposed, taking advantage of the energy value of biomass. Among the analysis, properties are flame temperature, flow and operating temperature, emission control, and ash control.

## 2 Methods

Several problems were detected from different studies using drying technology through biomass furnace: nonuniform drying air temperature, diesel fuel consumption for husk ignition, inadequate sizing of the air extractor, heat losses in the chamber, and smoke in the area. Based on the limitations found in the study area and the user's requirements, some essential parameters have been raised for the design of laboratory equipment [7].

(a) *Type of biomass:* It is necessary to consider the chemical composition, calorific value, biomass combustion temperature, effects on the environment, and amount of ash.
(b) *Operating conditions:* Requirements for the correct operation of the equipment, the dimensions of the feeder, combustion chamber, external temperature, humidity, radiation, and operating temperature were considered.
(c) *Energy efficiency:* Relationship between the heat generated by the burner and the calorific value of the fuel so that the oven's percentage amount takes advantage of the chemical energy of the rice husk to convert into proper heat. The physicochemical decomposition of the husk occurs in three stages: desiccation, pyrolysis, and combustion. The final phase of combustion occurs at temperatures above 500 °C.
(d) *Temperature control:* A temperature control inside the combustion chamber is necessary to control the complete incineration point of the rice husk.

(e) *Market accessibility:* The components, materials, and equipment will be manufactured and can be purchased in the local market.
(f) Maintenance: The equipment to be designed must be easy to operate and maintain.
(g) *Accessibility of materials in the market:* The design requires to be built with materials available in the national market.
(h) *Safety for operators:* The design must ensure safety for workers, preventing the flame from being outdoors.
(i) *Costs:* Materials and parts for the construction of laboratory equipment are intended to be used as recycled or reusable material to lower the equipment cost.

## 2.1 Alternatives for Design Selection

There are several models of combustion furnaces, but for this process, the fluidized bed and grill-type models were analyzed. The method to make the selection consisted of a decision matrix where a range between 1 and 10 was established to give value to each design parameter, giving a percentage to the essential requirements so that the most viable alternative was obtained. Table 1 shows the decision matrix.

It was determined that the grill-type oven is the most viable option because it had a relatively low power range concerning the fluidized bed. The combustion of the rice husk produces high ash content; therefore, the grill must be tilted for better control of the feeding zone, combustion, and ash deposit [8].

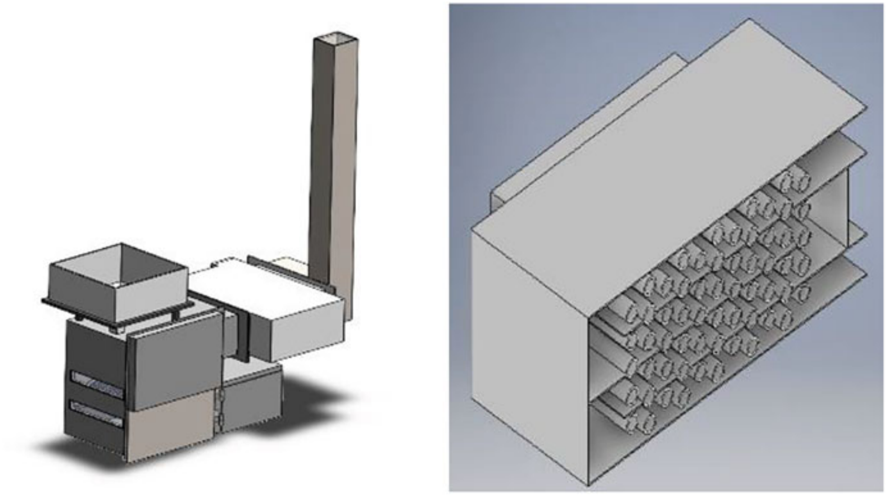
To exchange heat between the hot gas from combustion and the heat transfer fluid that will enter the dryer, it is necessary to design a heat exchanger, which allows an easy cleaning from silica that can be formed by husk combustion. Safety, temperature control, and ease of construction need to be considered. Table 2 discusses the design criteria and models of exchangers.

**Table 1** Decision matrix for oven type selection

| | | Furnaces | |
|---|---|---|---|
| Parameters | Weight | Fluidized bed | Grill type |
| Safety | 10% | 8 | 8 |
| Type of biomass | 5% | 10 | 9 |
| Cost | 15% | 5 | 10 |
| Maintenance | 10% | 7 | 8 |
| Ease of use | 5% | 8 | 7 |
| Temperature control | 20% | 9 | 8 |
| Ash extraction | 15% | 6 | 7 |
| Energy efficiency | 15% | 7 | 9 |
| Environmental conservation | 5% | 7 | 8 |
| Total | 100% | 7.25 | 8.3 |

**Table 2** Decision matrix for heat exchanger selection

| Criteria | Weight | Heat exchanger (one pass) | Heat exchanger (three pass) | Heat exchanger (four pass) |
|---|---|---|---|---|
| Easy to use | 20% | 8 | 6 | 9 |
| Safety | 15% | 5 | 8 | 7 |
| Production costs | 30% | 8 | 5 | 8 |
| Maintenance | 10% | 5 | 6 | 8 |
| Temperature control | 25% | 7 | 8 | 8 |
| Total | 100% | 6.75% | 6.5% | 8.05% |



a) b)

**Fig. 1** (**a**) Biomass furnace shape design. (**b**) Heat exchanger

As a result of this analysis, the viability of the four-step heat exchanger with the internal gas flow is determined. It is essential to mention that the biomass oven has the advantage that can use rice husk, pruning log residues, or mixtures with pellets as biomass sources which makes the process cheaper. In addition, as an initial process of ignition of the biomass, it will be intended to use an electrical resistance, considered less polluting than diesel. The heat exchanger will be coupled to one side of the combustion furnace. The flue gases will pass internally in the exchanger tubes to clean the unquenched material, and the airflow from a fan will pass through the outside of the tubes (Fig. 1).

## 2.2 Mathematical Analysis

Combustion. Fossil fuels have a high content of carbon (C), hydrogen (H), and oxygen (O), in addition to other elements in smaller proportions such as sulfur (S) and nitrogen (N).

The general formula for fossil fuels was expressed below (Eq. 1) [8] [9].

$$\begin{aligned} &CH_{\frac{y}{x}}S_{\frac{w}{x}}O_{\frac{z}{x}}N_{\frac{u}{x}} + (1+EA)\left(1+\frac{y}{4x}+\frac{w}{x}+\frac{u}{x}-\frac{z}{2x}\right)(3.76N_2+O_2) \\ &\rightarrow CO_2 + \frac{y}{2x}H_2O + (1+EA)\left(1+\frac{y}{4x}+\frac{w}{x}+\frac{u}{x}-\frac{z}{2x}\right)(3.76N_2) \\ &+ EA\left(1+\frac{y}{4x}+\frac{w}{x}+\frac{u}{x}-\frac{z}{2x}\right)O_2 + \frac{w}{x}SO_2 + \frac{u}{x}NO_2 \end{aligned} \tag{1}$$

The relationships$y/_x$, $w/_x$, $z/_x$ y $u/_x$ represent the ratio of hydrogen, sulfur, oxygen, and nitrogen atoms to each carbon atom, respectively. EA is the air in excess.

There is the formula of fuel and air on the left side, with an excess of the latter, and on the right side are the combustion products [8] [7].

$$\frac{y}{x} = \frac{M_c * m_H}{M_H * m_c} \tag{2}$$

The subscript $y/_x$, $w/_x$, $z/_x$ y $u/_x$ is the ratio of the mass M of the elements and m their percentage present in the compound.

To determine the subscripts that correspond to each element, it is necessary to know the chemical composition of the fuel. The composition of the rice husk is shown with the percentages assigned to each element: C = 47,029%, H = 5.02%, N = 0.18%, O = 47.45%, and S = 0.05% [4].

**Theoretical Air-Fuel Ratio** It is expressed as the amount of air ($m_{aire}$) by fuel quantity ($m_{combustible}$). Eq. 3:

$$m_{\left(\frac{a}{f}\right),t} = \frac{m_{aire}}{m_{combustible}} \tag{3}$$

The mass was determined. Eq. 4:

$$m = n * M \tag{4}$$

Number of moles(n), molar mass M.

**Real Air-Fuel Ratio** For the determination of the value of the actual air-fuel ratio, it was necessary to consider the excess air needed and is determined by the following equation:

$$m_{\left(\frac{a}{f}\right)r} = m_{\left(\frac{a}{f}\right)t} * (1 + EA) \tag{5}$$

where EA represents the excess air and has a value of 20%.

**Rice Husk Flow for Continuous Combustion** To maintain continuous combustion, it was necessary to calculate the flow of the rice husk; from the simulation, the airflow was obtained, and with the total air-fuel ratio, it could be calculated from the expression:

$$\dot{m}_{CA} = \dot{m}_{aire} * m_{\left(a/f\right)_{real}} \tag{6}$$

**Flue Gas Flow** It was required to establish a mass balance between the mass flow of the air, the flue gases, and the ashes that were produced due to the combustion process, according to Eq. 7:

$$\sum \dot{m}_{entrada} = \sum \dot{m}_{salida.}$$
$$\dot{m}_{CA} + \dot{m}_{aire-blower1} + \dot{m}_{aire-blower2} = \dot{m}_{combustion} + \dot{m}_{cenizas} \tag{7}$$

Therefore, the total heat of combustion is determined from the relation between the amount of mass flow of the rice husk entering the chamber and its corresponding calorific value; it was determined from the following equation:

$$Q_{CA} = \dot{m}_{CA} * P_c \tag{8}$$

where $P_c$ = calorific power of the husk kJ/kg.

**Thermal Analysis of the Combustion Furnace** The furnace wall is considered a composite material; therefore, the heat stored in the steel and insulation was calculated separately. During the heat transfer process, a fraction is stored on the walls of the furnace and in the insulator, increasing the internal temperature; this amount was calculated from the following equation:

$$Q_{ac} = m_{ac} c_{p_{ac}} \left(T_{p_{int}} - T_{m_p}\right) \tag{9}$$

where $m_{ac}$ is the total mass of steel [Kg], $c_{p_{ac}}$ is the specific heat of steel $\left[\frac{J}{Kg\ K}\right]$, $T_{p_{int}}$ is the internal wall temperature [K], $T_{m_p}$ is the average wall temperature [K], and $T_{p_{out}}$ is the external wall temperature [K].

During the combustion process, a fraction of the heat is used for the decomposition of the husk into ash; if 14% [10] of the total value of the mass of the rice husk is transformed into ash, the value is determined with the following expression:

$$Q_{cz} = m_{cz} c_{p_{cz}} (T_{cz} - T_{out}) \quad (10)$$

where $m_{cz}$ is the mass of ash [Kg], $c_{p_{cz}}$ is the specific heat of ash $\left[\frac{J}{Kg\ K}\right]$,$T_{cz}$ is ash temperature[K], and $T_{out}$ is the environmental temperature [K].

It is necessary to indicate that the furnace design was based on the API 560 standard, where the minimum requirements and recommendations for manufacturing a fuel burner furnace are established.

**Heat Exchanger Design Analysis** Input and output temperatures were defined for the exchanger design. The flow of air and flue gases entering the heat exchanger was determined. Flue gas inlet temperature [K] Thi (250 °C); flue gas outlet temperature [K] Tho (120 °C), inlet air temperature [K] $T_{ci}$: (27 °C) y the outlet air temperature [K] Tco (50 °C).

Subsequently, the system's energy balance is made to determine the flow of the combustion gases and the flow of hot air necessary to dry; for this, Eqs. 11 and 12 must be equalized:

$$q = \dot{m}_c * C_{pc} * (T_{ci} - T_{co}) \quad (11)$$

$$q = \dot{m}_h * C_{ph} * (T_{hi} - T_{ho}) \quad (12)$$

where $\dot{\mathbf{m}}_\mathbf{h}$ is the mass flow of gases [Kg/s], $\dot{\mathbf{m}}_\mathbf{c}$ is the air mass flow [Kg/s], Cpc is the specific heat of air [J/Kg. K], and y Cph is the specific heat of gases [J/Kg. K].

The total heat transfer heat between both fluids is determined through Eq. 13:

$$Q = U^* \pi^* \ Di^* L^* NT^* \Delta Tml \quad (13)$$

where U is the global heat transfer coefficient [W/$m^2$ K], Di pipe is the inner diameter [m], L is the pipe length [m], Nt is the number of pipe, and y ΔTml is the difference in average logarithmic temperatures [K].

The overall heat transfer coefficient is determined through the internal convection coefficient hi and the external ho; it depends on the Nusselt number, k the thermal conductivity [W/$m^2$ K], and the pipe diameter [m] [10]. It was open to considering that the Nusselt number is a geometry function as well as the Reynolds number (Re) and the Prandtl number (Pr). Therefore, the equation used to determine the Reynolds number in internal flow is presented in Eq. 14, and the representative equation to determine the external Reynolds number is presented in Eq. 15:

$$\mathbf{Re}_{\mathbf{D}} = \frac{\mathbf{4\dot{m}_h}}{\boldsymbol{\pi} * \mathbf{D_i} * \boldsymbol{\mu}_{\mathbf{gas}} * \mathbf{N_T}} \tag{14}$$

$$\mathbf{Re}_{\mathbf{D\ max}} = \frac{\boldsymbol{\rho}_{\mathbf{aire}} * \mathbf{V_{max}} * \mathbf{D}}{\boldsymbol{\mu}_{\mathbf{aire}}} \tag{15}$$

where $\rho_{aire}$, density of air [Kg/m$^3$]; $\mu_{aire}$, dynamic air viscosity [N.s/m$^2$]; and $V_{max}$, maximum speed on the tube bank [m/s].

Finally, the drop pressure of the tube bank is determined where NL represents the number of lines, x the correlation factor, and f the friction factor (Eq. 16):

$$\boldsymbol{\Delta}\mathbf{p} = \mathbf{N_L} * \mathbf{x} * \left(\frac{\boldsymbol{\rho} * \mathbf{V}^2_{\mathbf{max}}}{\mathbf{2}}\right) * \mathbf{f} \tag{16}$$

# 3 Results

## *3.1 Theoretical Results*

The corresponding mass flows at the input and outlet were determined for complete combustion of the rice husk, using the general equation for combustion (Eq. 1). The mass flow of the air was iterated until obtaining a temperature between 50 and 60 °C at the outlet of the exchanger. The blowers must have located at the bottom of the grill with an airflow of 70 CFM (cubic feet per minute), the top of the grill reaches the 30 CFM. With the data obtained, the mass flows of the husk and the combustion gases were calculated. The total heat of combustion of the rice husk was calculated considering a percentage of humidity of 10.33% [11]. The amount of heat that can be extracted for the established husk flow is determined to be 74.39 [kW].

In relation to the results of the analysis of the lost in the combustion chamber, the coefficient of conduction, radiation, and convection of the furnace was considered, assuming the grill as a homogeneous plate, isothermal, and with an inclination of 70° with respect to the Y-axis. In addition, free convection was assumed for the inner and outer surface of the furnace; for the calculation of the radiation coefficient, grilling was considered as a heat source with an emissivity of 0.8. The result was 1.46 [kW]. For the calculation of the heat stored in the steel walls and the insulator, the average temperature between the outside and inside of the furnace was determined, opening a loss of 2.64 [kW] as heat stored in the steel wall and 5.29 [kW] as heat stored in the insulator. For the calculation of heat transferred to ash, 14% of the total mass of rice husk that decomposes into ash was considered, and its result was 0.015 [kW], being a very small value concerning the other results obtained and can be disregarded without affecting the results. Finally, the total heat of combustion that is transferred

**Table 3** Results of the combustion furnace design

| Equation | Nomenclature | Symbology | Unit | Result |
|---|---|---|---|---|
| 3 | Actual air-fuel ratio | $m_{\left(\frac{a}{f}\right)r}$ | dimensionless | 13.83 |
| – | Air inlet flow | $\dot{m}_{aire-\mathrm{blower1}}$ | kg/h | 138.13 |
| | | $\dot{m}_{aire-\mathrm{blower2}}$ | kg/h | 59.19 |
| | | $\dot{m}_{aire-\mathrm{blower3}}$ | kg/h | 138.13 |
| 6 | Scale flow into the chamber | $\dot{m}_{CA}$ | kg/h | 15.18 |
| 7 | Mass flow of combustion gases | $\dot{m}_{\mathrm{combustion}}$ | kg/h | 209.80 |
| 8 | Heat of combustion | $Q_{CA}$ | [kW] | 74.39 |
| 9 | Heat stored in the walls | $Q_{ac}$ | $[kW]$ | 2.64 |
| – | Heat stored in insulation | $Q_{ais}$ | $[kW]$ | 5.29 |
| – | Heat given to the ashes | $Q_{cz}$ | $[kW]$ | 0.015 |
| | Total heat lost from the system | $Q_t$ | [kW] | 9.41 |

**Table 4** Theoretical results of heat exchanger analysis

| Nomenclature | Unit | Result |
|---|---|---|
| Total heat transfer in the heat exchanger | W | 2180.70 |
| Global heat transfer coefficient | $W/m^2$ K | 6.15 |
| Internal convection coefficient | $W/m^2$ K | 6.79 |
| Maximum speed on the tube bank | m/s | 4.8 |
| Wind speed at dryer inlet (exchanger outlet) | m/s | 2.1 |
| Pressure drop in pipe bank | Pa | 67.28 |

to the airflow was obtained considering the system's losses; its result was 64.98 [kW]. In Table 3, from the established equations, the results are shown.

In Table 4, the theoretical results of the heat exchanger obtained when using the proposed methodology are shown. Through simulation, these results were validated.

Therefore, the design of the heat exchanger will be 76 cm in length, 30 cm in height, and 50 cm in width, with four steps and 60 tubes distributed in a staggered way. For the analysis both fluids (hot combustion gas and air from a fan) were analyzed in perpendicular trajectories (crossflow). The materials selected were 1inch diameter schedule 40 tubes and ASTM A36 steel plates for the housing.

## 3.2 *Combustion Furnace Simulation*

The materials used for the walls, roof, and base of the furnace structure were 6 mm thick ASTM A36 steel, coated with 100 mm of fiberglass insulation to prevent thermal losses. The material of the gates was ASTM A36 steel 3 mm thick with the difference that in the main gate it had a layer of 100 mm thick fiberglass insulation. The parts that made up the system were designed separately and joined in a single assembly and then used the SolidWorks "Flow Simulation" tool, which works with

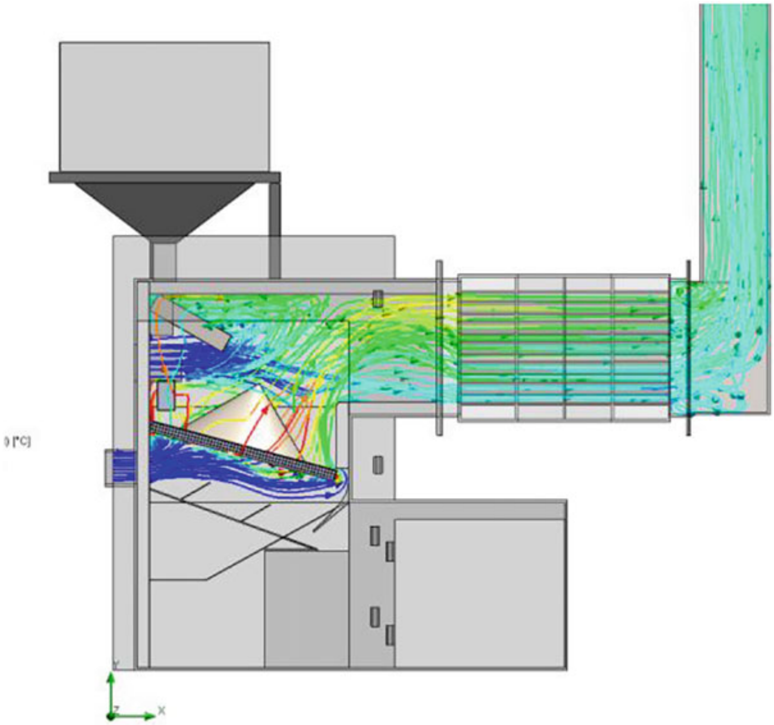


**Fig. 2** Flow lines inside the combustion chamber

computational fluid dynamics or CFD in which, through simulated iterations, allowed to validate the design before the construction of the prototype.

An iterative process of trial and error was followed, modifying the internal geometry of the combustion chamber with the initial conditions to obtain the best possible result. Alternatives were considered a change of flow direction by baffles and different air inlets to the chamber.

In Fig. 2, the results of the simulation of the final geometry are shown. The orientation of the grill was changed, and baffles were included under the hole where the air entered the combustion chamber, which served to redirect the flow, so it did not go to the ash collection chamber.

Below are the temperature profiles of the outer walls of the combustion chamber, which do not exceed 90 °C. This means that the system is safe for the operator and the constituted material is in the thermal operating range (Fig. 3a). Fig. 3b shows the flow inside the heat exchanger chamber, where it can be seen that the temperature at the outlet is 60 °C, ideal for drying the rice grain.

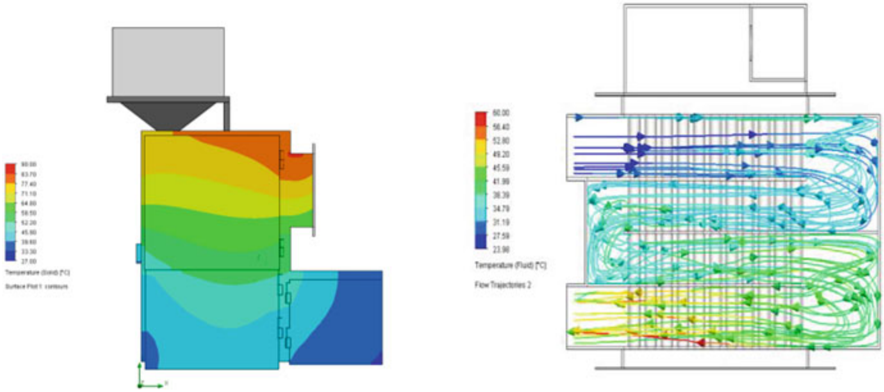


**Fig. 3** (**a**) External chamber temperature. (**b**) Flowlines inside the heat exchanger

**Fig. 4** Laboratory equipment prototype

## *3.3 Theoretical Results*

Once the experimental equipment was built, the experimental tests were carried out using 180 kg of rice husk, with a duration of 4 hours [12]. Temperature measurements were made at various points in the furnace chamber, heat exchanger, and chimney, to determine the thermal efficiency of the equipment. Fig. 4 shows the laboratory-scale equipment designed for 136 kg of wet products such as rice, corn, coffee, and other cereals.

During the tests the proper functioning of the equipment was evidenced, with few heat losses, smoke through the doors and chimney, from the control of the air flow inlet to the chamber, and the temperature reached 230 °C, with a percentage of ash

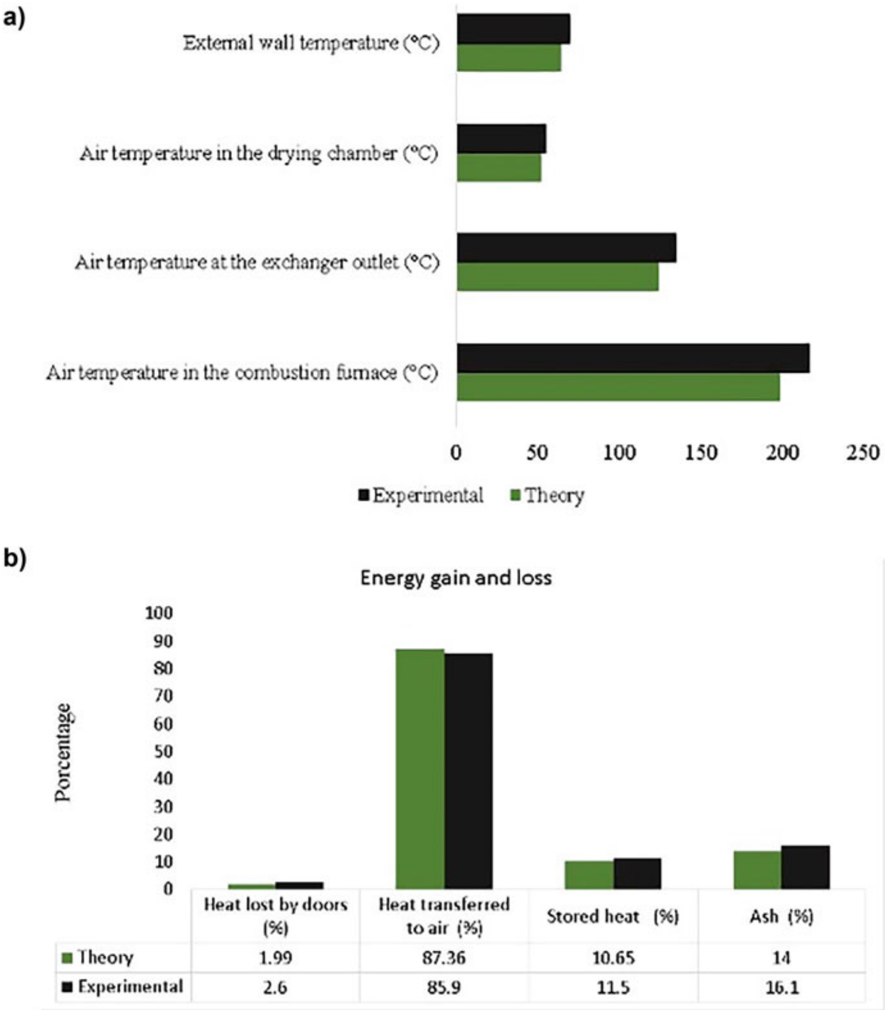



**Fig. 5** (**a**) Comparison of experimental and simulated tests (temperature). (**b**) Comparison of experimental and simulated tests (energy gain and loss)

around 16% about the total weight of the shell [3]. It became clear that pellet compaction of the biomass in the furnace in the form of pellets would have improved the combustion of the equipment and reached a higher temperature. For future tests, it is provided to make mixtures of various types of biomasses. Fig. 5a and b presents the comparison of the simulated theoretical results with the experimental results (90.95 kg of husks were used for the experiment).

## 4 Discussion

The areas of Ecuador with the highest rice production are the province of Guayas and Los Ríos, representing an approximate total of 95% of the production at the regional level, representing an excellent availability of rice husk that should be used for internal energy generation of rice processors.

Currently solid biomass such as husk is only used in large rice processing plants. It will be of interest at the local level to adapt existing technologies in small and medium production plants to these combustion chambers that allow taking advantage of the waste for heat generation; with this, the consumption of LPG that is used daily for the drying of rice is reduced. The proposed design to be laboratory equipment will not reflect the real consumption of biomass for large industrials, but a staggering of production, energy consumption, and failures due to the inadequate combustion of the rice husk with the possible environmental and maintenance problems of the equipment is determined.

## 5 Conclusions

The most suitable type of furnace for the combustion of rice husk was the grill type This is because the equipment operates in a relatively low power range for the use of the fluidized bed and is designed for a husk supply of 90.95 kg. In addition, the project is intended for the drying of rice in sectors where production is from small to medium scale; thus, there is a low operating and investment cost.

The combustion chamber was optimized, relocating the grille to an angle of 70° with respect to the vertical, allowing a greater amount of airflow through the grill and is directed toward the inlet of the heat exchanger; in addition, baffles were in the main air inlet at an angle of 30° with respect to the horizontal, so they redirect the air flow upward and not toward the ash chamber preventing a lifting of particulate matter within the combustion chamber.

The outside temperature of the walls of the combustion chamber reached a range between 50 and 70 °C This was achieved by increasing the thickness of the insulator to 100 mm, decreasing heat losses in the walls.

The baffles located for the redirection of the inlet airflow will also serve to direct the ash resulting from combustion to the bottom of the chamber, where it will be easier to handle. It is important that there is a correct arrangement of ash; it is considered a highly polluting material.

STM A36 Steel was selected as a material because the maximum temperature in the furnace is 650 °C ensuring that the equipment operates without modifying the mechanical properties. In addition, fiberglass was selected as an insulating material since it has a low thermal conductivity which makes heat conservation and can be transferred to air, and it is essential to mention that these materials are easily found in the national market.

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