The modeling and simulation of a smoke-free firewood furnace designed for indirect heating adapted to mixing heating configuration

Modelagem e simulação de uma fornalha de lenha sem fumaça projetada para aquecimento indireto adaptada à configuração de aquecimento por mistura

Modelización y simulación de un horno de leña sin humos diseñado para calentamiento indirecto adaptado a la configuración de calentamiento por mezcla

DOI: 10.34188/bjaerv7n2-013

Submetido: 19/01/2024
Aprovado: 01/03/2024

Luís César da Silva
Doutor em Engenharia Agrícola pela
Universidade Federal de Viçosa / Kansas State University
Universidade Federal de Viçosa
Viçosa, MG. Brasil
E-mail: silvaluisc@ufv.br

Kamaldeen Ayinla Yusuf
Mestre em Engenharia Agrícola pela
Universidade Federal de Viçosa
Auchi Polytechnic
Auchi. Nigeria
E-mail: kamyuf@auchipoly.edu.ng

Evandro de Castro Melo
DS em Agronomia pela Universidad Politécnica de Madrid
Universidade Federal de Viçosa
Viçosa, MG. Brasil
E-mail: evandro@ufv.br

Sammy Fernandes Soares
Doutor em Agronomia pela Universidade Estadual Paulista - UNESP Embrapa Café/EPAMIG
Viçosa, MG. Brasil
E-mail: sammy.soares@embrapa.br

Juarez de Sousa e Silva
PhD em Engenharia Agrícola pela Michigan State University - USA Universidade Federal de Viçosa
Viçosa, MG. Brasil
E-mail: juarez@ufv.br

Sérgio Maurício Lopes Donzeles
Doutor em Engenharia Agrícola pela Universidade Federal de Viçosa Empresa de Pesquisa Agropecuária de Minas Gerais - EPAMIG
Viçosa, MG. Brasil
E-mail: sergio.donzeles@gmail.com

Douglas Gonzaga Vitor
Engenheiro Agrônomo pela Universidade Federal de Viçosa
Empresa de Pesquisa Agropecuária de Minas Gerais - EPAMIG
Viçosa, MG. Brasil
E-mail: dgonzagavitor@gmail.com

ABSTRACT

The use of wood furnaces for thermal energy applications in drying is common among coffee growers in Brazil. However, incomplete combustion of firewood and excessive use of damaged furnaces can lead to product contamination and negative environmental effects. To address this issue, a smoke-free wood furnace was designed, to heat the drying air utilizing a heat exchanger, and using a removable smoke-free combustion cell. The new furnace design was based on thermal energy ranging from 15 to 30 kW, drying airflow rates from 35 to 45 m³ min^{-1}, and drying air temperatures from 50 to 80 °C.

The design process considered the thermal energy required for heating air, furnace fuel consumption, combustion chamber volume, grate area, and heat exchanger dimensions. The performance of the adapted furnace data was monitored over time using a graphics statistical control (x-bar chart). Regression analysis of temperature and mass flow rate for the mixed heating configurations was carried out to develop quadratic models for the modified operation.

The models were used to create a simulation model using ExtendTM simulation language to predict the performance of the furnace, in mixed heating at the desired drying air temperature. The simulation was carried out under two different conditions, normal and controlled operation of the furnace. Five scenarios of working hours without refueling (119 min) drying temperature were carried out.

The simulation result indicates that the furnace operates at a maximum efficiency of approximately 40% irrespective of the desired drying temperature during normal operation. However, controlled operation with increased opening time of the mixing air inlet for admitting ambient air into the mixing chamber significantly improved the furnace's efficiency, with an optimum efficiency of 55% achieved at 90°C drying temperature.

The simulation reflects that the furnace operates at a maximum efficiency of 68% at a temperature of 90°C, which can be attained at 66.31 minutes of operation in mixed heating of 30 minutes and indirect heating configuration of 89 min during working hours without refueling of 119 min.

Keywords: modeling, firewood furnace, simulation, eucalyptus, combustion, indirect heating, mixed heating, and mass flow rate.

RESUMO

O uso de fornalhas a lenha para aplicações de energia térmica na secagem é comum entre os produtores de café no Brasil. Entretanto, a combustão incompleta da lenha e o uso excessivo de fornalhas danificadas podem levar à contaminação do produto e a efeitos ambientais negativos. Para resolver esse problema, foi projetada uma fornalha de madeira sem fumaça, para aquecer o ar de secagem utilizando um trocador de calor e uma célula de combustão removível sem fumaça. O projeto da nova fornalha baseou-se na energia térmica que varia de 15 a 30 kW, nas taxas de fluxo de ar de secagem de 35 a 45 m³ $^{min-1}$ e nas temperaturas do ar de secagem de 50 a 80 °C.

O processo de projeto considerou a energia térmica necessária para o aquecimento do ar, o consumo de combustível da fornalha, o volume da câmara de combustão, a área da grelha e as dimensões do trocador de calor. O desempenho dos dados da fornalha adaptada foi monitorado ao longo do tempo usando um controle estatístico gráfico (gráfico de barras x). A análise de regressão da temperatura e da taxa de fluxo de massa para as configurações de aquecimento misto foi realizada para desenvolver modelos quadráticos para a operação modificada.

Os modelos foram usados para criar um modelo de simulação usando a linguagem de simulação ExtendTM para prever o desempenho do forno, em aquecimento misto na temperatura desejada do ar de secagem. A simulação foi realizada em duas condições diferentes, operação normal e controlada do forno. Foram realizados cinco cenários de horas de trabalho sem reabastecimento (119 min) da temperatura de secagem.

O resultado da simulação indica que a fornalha opera com uma eficiência máxima de aproximadamente 40%, independentemente da temperatura de secagem desejada durante a operação normal. No entanto, a operação controlada com maior tempo de abertura da entrada de ar de mistura para admitir o ar ambiente na câmara de mistura melhorou significativamente a eficiência do forno, com uma eficiência ideal de 55% alcançada a uma temperatura de secagem de 90°C.

A simulação reflete que a fornalha opera com uma eficiência máxima de 68% a uma temperatura de 90°C, que pode ser alcançada em 66,31 minutos de operação em aquecimento misto de 30 minutos e configuração de aquecimento indireto de 89 minutos durante as horas de trabalho sem reabastecimento de 119 minutos.

Palavras-chave: modelagem, fornalha de lenha, simulação, eucalipto, combustão, aquecimento indireto, aquecimento misto e taxa de fluxo de massa.

RESUMEN

El uso de hornos de leña para aplicaciones de energía térmica en el secado es común entre los caficultores de Brasil. Sin embargo, la combustión incompleta de la leña y el uso excesivo de hornos dañados pueden provocar la contaminación del producto y efectos ambientales negativos. Para resolver este problema, se diseñó un horno de leña sin humo, para calentar el aire de secado utilizando un intercambiador de calor y empleando una célula de combustión sin humo desmontable. El nuevo diseño del horno se basó en una energía térmica de entre 15 y 30 kW, caudales de aire de secado de entre 35 y 45 m³ $^{min-1}$ y temperaturas del aire de secado de entre 50 y 80 °C$^{.}$

El proceso de diseño tuvo en cuenta la energía térmica necesaria para calentar el aire, el consumo de combustible del horno, el volumen de la cámara de combustión, la superficie de la parrilla y las dimensiones del intercambiador de calor. El rendimiento de los datos del horno adaptado se supervisó a lo largo del tiempo mediante un control estadístico gráfico (gráfico de barras x). Se llevó a cabo un análisis de regresión de la temperatura y el caudal másico para las configuraciones de calentamiento mixtas con el fin de desarrollar modelos cuadráticos para el funcionamiento modificado.

Los modelos se utilizaron para crear un modelo de simulación utilizando el lenguaje de simulación ExtendTM para predecir el rendimiento del horno, en calentamiento mixto a la temperatura deseada del aire de secado. La simulación se realizó en dos condiciones diferentes, funcionamiento normal y funcionamiento controlado del horno. Se realizaron cinco escenarios de horas de trabajo sin reabastecimiento (119 min) de temperatura de secado.

El resultado de la simulación indica que el horno funciona con un rendimiento máximo de aproximadamente el 40% independientemente de la temperatura de secado deseada durante el funcionamiento normal. Sin embargo, el funcionamiento controlado con un mayor tiempo de apertura de la entrada de aire de mezcla para admitir aire ambiente en la cámara de mezcla mejoró significativamente la eficiencia del horno, alcanzándose una eficiencia óptima del 55% a una temperatura de secado de 90°C.

La simulación refleja que el horno funciona con una eficiencia máxima del 68% a una temperatura de 90°C, que puede alcanzarse a los 66,31 minutos de funcionamiento en calentamiento mixto de 30 minutos y configuración de calentamiento indirecto de 89 min durante las horas de trabajo sin repostaje de 119 min.

Palabras clave: modelización, horno de leña, simulación, eucalipto, combustión, calentamiento indirecto, calentamiento mixto y caudal másico.

1 INTRODUCTION

After coffee harvesting farmer must avoid any process that accelerates the deterioration of the product. These precautions must be doubled, especially in the first three days after removing the coffee fruits from the tree. The best, and economic post harvesting process must be done to reduce the humidity of the fruits to 18% moisture content within the first three days of harvesting, that is considered safe for different ways for coffee drying (Silva et al. 2023). To reduce coffee moisture content in three days, using natural drying, can only be achieved under favorable climatic conditions or with the use of dryers that use air heated by furnaces to speed up the drying process without damaging the product. As there are several possibilities for heating the drying air, the coffee grower must pay attention and choose the most sustainable option to reduce energy consumption, maintain product quality and adapt to the environmental law enforcement.

Firewood fuels are renewable and a natural resource that are competitive in terms of quantities and pricing with GLP, in coffee producing areas. Firewood offers an attractive alternative due to their potential negative environmental impact, making them a safer and more eco-friendly option. Balat et al. (2009) and Bildirici et al. (2013) also support the use of biomass fuels as a viable solution for the energy crisis and Machado et al. 2020 show the possibility of producing coffee and trees in the Agroforestry System (SIF).

Understanding and correctly managing a well-designed heating system will mean that owners of some coffee farms will stop using high-consumption wood-burning furnaces, some of which are in poor condition, poorly sized and with excessive heat loss. Most of these furnaces used on coffee farms do not have a mechanism to control the combustion process and are generally operated inadequately and produce significant air pollution in the countryside and even close to urban centers. This fact has led the environmental police to prevent the operation of some production units, due to the amount of pollution caused, mainly, by the burning derived biomass, such as coffee husk.

The combustion of hydrocarbons found in fossil fuels or biomass generates carbon dioxide (CO_2), carbon monoxide (CO), and nitrogen oxides (NOx). These substances, if not completely burned, can cause negative environmental impacts.

In farm conditions, biomass is by far, the most significant source of renewable energy, and can be classified into various categories such as firewood, agricultural and wood processing residues, including wood chips, charcoal, coffee and rice husks, sugarcane bagasse, and manure, among others (Usmani et al., 2021).

In Brazil, a mix of firewood and coffee rusk is commonly used as fuel to dry coffee beans. However, this practice can lead to product quality depreciation and negative environmental impacts due to incomplete combustion in unappropriated furnaces that generate too much smoke.

To reduce the risk in coffee drying it is necessary to use well designed furnaces followed by a well-done furnace operation, good manutention along with good process control methodologies or automation resources to stabilize the drying air temperature and minimize CO and smoke emissions.

A furnace is a piece of equipment designed to convert chemical energy from fuels into thermal energy through combustion reactions. Since fuels can be solids, liquids, gases, or powders, it is important to use the appropriate furnace to ensure complete combustion.

When utilizing firewood in grain dryers, three distinct types of furnaces can be employed to heat the drying air: direct, indirect, or mixed heating. In the direct heating furnace, the gases generated by combustion are amalgamated with the surrounding air and subsequently blown by a fan directly into the grain mass. In indirect heating, the drying air is heated as it passes through a heat exchanger, without contact with the combustion gases. In mixed heating, the furnace works with the combination of the two first options.

Many coffee producers, in Brazil, use the supposed indirect heating furnaces fired with firewood to dry their coffee beans. However, often these furnaces operate inefficiently, suffers serious heat damage and leading to excessive smoke emission that harms the environment, nearby cities, traffic on roads, and workers' health. Due to these issues, the environmental inspection authorities have established rules and penalties, sometimes resulting in the sealing of coffee processing facilities.

Thus, this study aimed to use the evaluation result of one smoke-less furnace for indirect heating adapted for mixed heating of the air. The actual furnace design and adaptation was developed by the research group.

2 MATERIALS AND METHODS

2.1 SYSTEM DESCRIPTION AND CHARACTERIZATION

The wood furnace was analyzed under the following specifications: thermal energy ranging from 15 to 30 kW (13,898 to 25,795 kcal) h^{-1}), drying air flow rate from 35 to 45 m^3 min^{-1}, drying air temperature from 50 to 80 °C. The prototype was constructed at Santa Luzia Farm, situated at an altitude of 774 meters above sea level, in the municipality of São Geraldo in Minas Gerais State, Brazil.

The real furnace presents two operational options, namely indirect and mixed heating due to smoke less operation. For recommending operational procedures, a simulation model was developed according to experimental data.

The methodology employed in the design of the wood furnace comprises of the following calculations: the thermal energy required to heat air, (ii) furnace fuel consumption, (iii) combustion chamber volume, (iv) grate area, and (v) heat exchanger dimensions.

The useful energy to heat the air, was calculated considering the specific heat of the air constant, and equivalent to 1.0035 kJ kg $^{-1}$ ^{o}C $^{-1}$ (Ceviz and Kaymaz, 2005). For the atmospheric pressure calculated for the local where the furnace was evaluated (92.37 kPa. for 774 meters of altitude). The thermal energy required for heating the air was 18.41 kW (66,264 kcal h^{-1}). The consumption of firewood was determined as 0.0020 kg s^{-1} (7.03 kg h^{-1}) based on the thermal energy obtained, energy required 18,41 kW , and estimated efficiency of the furnace as 60%.

The volume of the combustion chamber in the present case was calculated as; approximately, 0.30 m$^{3.}$ for a firewood consumption of 0.0020 kg s^{-1}, lower calorific value equal 15,533.31 kJ kg^{-1} and VTT of 177 kW m^{-3} (Silva *et al.* (1991).

The total grate area and grate free area of the furnace are 0.247 m^{2} and 0.035 m^{2}, respectively, considering: fuel loading rate equal to 47 kg h^{-1}m^{2}, fuel mass flow rate of 0.0032 kg s^{-1}, theoretical volume of air to burn 1kg of fuel equal 15.533m^{3} kg^{-1}, relation factor between the total and free grate areas as 0.14.

The heat exchanger (HE) surface area is 1.70 m^{2}, based on the combustion chamber volume and the Global Temperature Coefficient (GTC) of 30 W m $^{-2}$ ^{o}C $^{-1}$.

2.2 FURNACE WORKING SYSTEM

The evaluated furnace consists of five compartments: (1) combustion chamber, (2) preheating of the drying air, (3) heat exchanger, (3) direct heating mixing chamber, and (5) drying air mixing chamber.

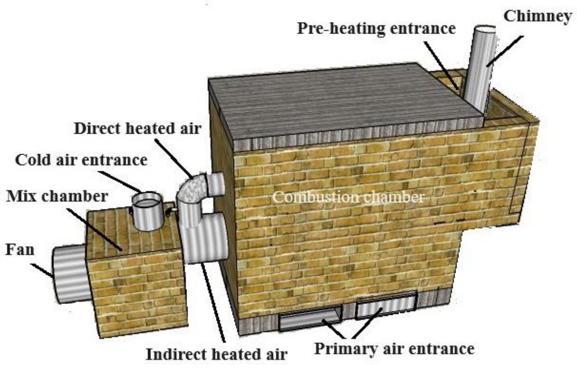
The combustion chamber consists of a grate, a removal combustion cell scheduled to be changed every two hours. To heat the pre-heated ambient air that passes around the chimney, a fan coupled to the furnace in the mix chamber forces the air to cross the surface of the heat exchanger (Figure 1).

The heat exchanger, constructed in steel plate, was mounted on the topo of the combustion chamber, and the air exits through a duct connected to the drying air mixing chamber. Using only the heat exchanger, the furnace operates as indirect heating.

Figure 2, also shows the direct heating mixing compartment, which consists of the T-shaped connection of the ducts in which the combustion gases and ambient airflow, respectively, are contained. In this connection, the flows are mixed if the valve located in the initial duct is open, which is a prerequisite for the furnace to work as mixed heating operation. Otherwise, only ambient air is permitted to enter the drying air mixing chamber.

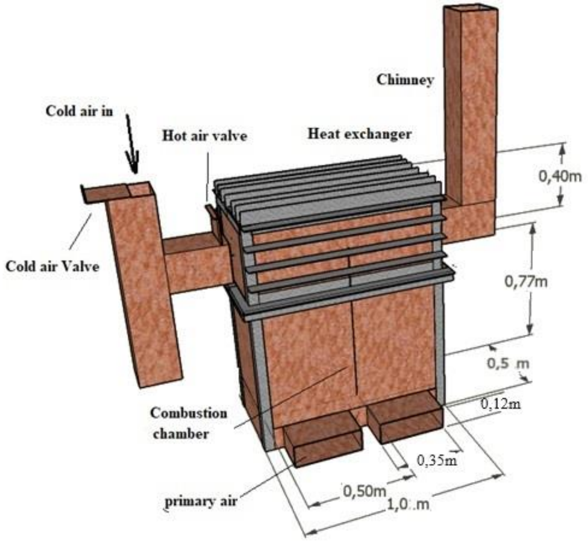
The chamber for the mixing of drying air comprises of one outlet and two inlets. The outlet is equipped with a centrifugal fan that has two functions: one involves blowing the heated drying air, while the second involves sucking the flows from the heat exchanger to mix with direct heating compartment. Hence, in the case of indirect firing, the mixing chamber in the drying chamber is characterized by the mixing of ambient air with the airflow from the heat exchanger. However, in the mixing drying air chamber, if the valve in the direct heating duct is open, the airflow from the heat exchanger is mixed with the airflow from direct heating. In this circumstance, the furnace's operation is referred to as a mixed heating operation.

Figure 1: The furnace working system depicts the flow of gases within the furnace



(Source: Authors)

Figure 2- Internal and metallic component of the mix heating furnace



(Source: Authors).

During furnace performance evaluation, several tests were carried out for the mixed configuration. It was measured: the firewood weight charge before the switched-on of the centrifugal fan, for an average of two hours. For each test, repeated four times, were measured the primary air speed, the drying air speed, mixing air speed, flue gasses speed outlet at the chimney, inlet air speed at the heat exchanger, temperature, and ambient relative humidity, burning flame temperature, temperature of the gases inside the furnace, heat exchanger and drying air temperatures were monitored at time intervals. The ratio of CO and CO_2 in the exhaust of the drying air and the exhaust of flue gasses was also monitored.

2.3 MODELING AND FURNACE PERFORMANCE SIMULATION

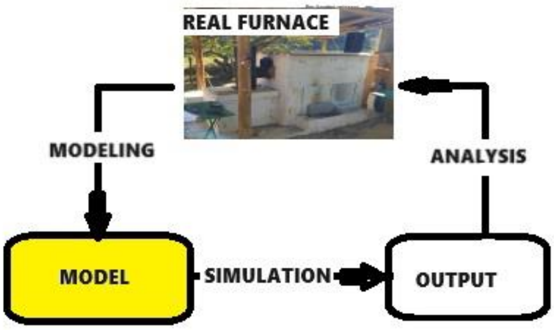
After adjusting the regressions for temperature and airflow (Tables 1 and 2), the regression analysis of the drying temperature data obtained at various points of measurement T1 to T10, per unit time, was carried out and fitted with a quadratic model as Equation 1, and a dynamic, continuous, and stochastic model was devised to simulate the operational scenario, considering drying air temperatures ranging from 50 to 80°C, and furnaces operating in indirect or mixed heating. The software ExtendTM, a simulation language, was used to develop the model, based on the scheme (Figure 3).

$$Tp = Yo + a.t_{ct} + b.t_{ct}^2 \qquad (1)$$

Where,

Tp = temperature at a point, 0C
Yo = constant
a = coefficient of circle time
b = coefficient of square of circle time

Figure 3 – Real versus simulated model scheme



(Source: Authors).

Table 1- Fitted models, adjusted coefficients of determination (R^2_{adj}), and standard error of estimate (S) for temperature measurement points for mixed heating configuration.

Measure point	Yo	a	b	R^2_{adj}	S
Ambient air temperature	25.4416	-2.3748	2.0923	0.000	0.6811
Drying air temperature – T1	56.1617	-10.0247	56.7682	0.9788	2.9337
Combustion cell - T2	582.8277	156.65	82.0585	0.7095	54.2479
Heat exchanger – T3	58.037	286.2842	11.7798	0.9382	26.4683
Temperature out of heat. Exchanger – T6	67.5268	155.1689	53.813	0.9413	18.6847
Temperature of fin plate – T7	56.2852	197.5867	14.1351	0.909	23.2223
Preheated air for heat exchanger – T8	61.873	-84.7375	90.8602	0.9646	2.2518
Chimney temperature – T9	70.4327	-107.712	242.5843	0.9866	7.468
Furnace wall temperature – T10	49.4503	-86.4939	114.7643	0.9955	1.3274
Ambient air temperature	56.0446	-262.472	473.2525	0.9166	32.7007
Drying air temperature – T1	48.777	-18.0483	11.3999	0.304	2.7988

A continuous model was developed with a block named "Control" whose main function is to control the advance of the time variable called "cycle Time" whose maximum value corresponds to the time without refueling. At increments of one minute, the cycle time advances.

In the dialog windows of the "Control Block," is necessary for the user to specify the working time without refueling, namely h, and the period during which the furnace operated as an indirect and mixed heating. This will ensure that at each minute of the advance, the Control Block will report the "cycle-time" value, and if the furnace is operating as indirect or mixed heating.

Additionally, the user is required to input altitude - m, and specific heat of air - kJ. Kg^{-1}. K^{-1}. This information is continually provided to the other blocks in the model.

Other variables made available by 'Control Block' are ambient air temperature and relative humidity. These variables are obtained from time series, which correspond to the moving average of experimental data.

The remaining components of the model comprise the "Combustion Chamber", "Pre-Heating", "Heat Exchanger", "Air Pre-Mixing", "Mixing Chamber," and "Efficiency."

According to the value of the 'Cycle Time' and operation option, at each minute advance, the temperature in the removable combustion cell, the temperature of gases in the chimney, the temperature in the combustion chamber, and the temperature of gases in the direct heating duct are calculated (Kamalgeem theses).

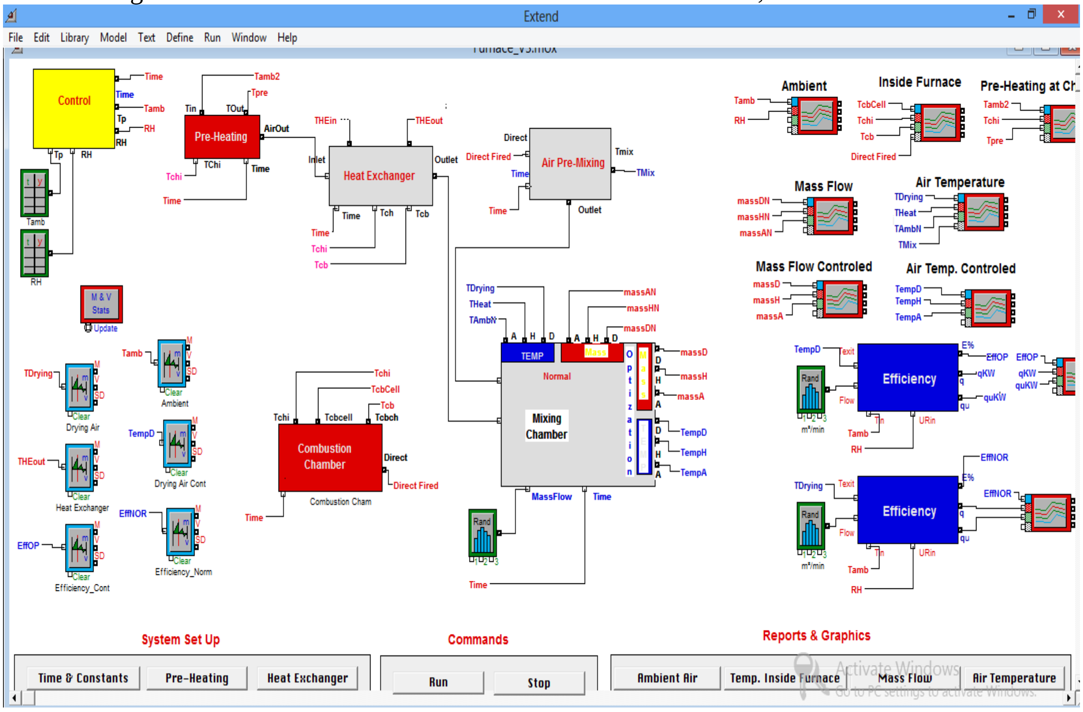
"*Heat Exchanger Block*" –The outlet temperature of the heat exchanger is calculated at each minute advance of 'cycle-time' and operation option.

The "Air Pre-Mixing Block" is a block where the air outlet temperature and mass flow are simulated. This airflow is directed towards the drying air mixing chamber. The outlet airflow of the furnace option, when it is operated as indirect heating, corresponds to the ambient air condition. Otherwise, it simulates the mixing of ambient and combustion chamber gases. This simulation uses the ambient air temperature and mass flow rate, the temperature of the gases from the combustion chamber, and the temperature of airflow after mixing. It is therefore possible to calculate the mass flow rate after the mixing process using mass and heat balance equations.

“Mixing chamber Block” This block simulates the mixing of air flows in the drying air mixing chamber, which has two inlets and one outlet. In the simulation, the temperature and mass flow rate of air emanating from the direct heating mixing chamber the temperature of airflow emanating from the heat exchanger, and the temperature and mass flow rate of the drying air at the outlet were determined. The calculation of the mass flow rate generated by the heat exchanger is based on the utilization of mass and heat balance. This block considers two situations without control, and one with control, when the user needs to inform the desired drying air temperature. Hence, during the simulation, this block provides information regarding the moment when the inlet of ambient air in the direct heating mixing chamber should be opened, as well as the mass flow rates and temperatures of air in the inlets and outlets.

The "Efficiency Block" refers to the psychometric properties of both ambient air and drying air, which are continuously calculated during the simulation. It is simulated at each increment, the efficiency is a % ratio between the flow rate energy supplied by combustion (kW), and the useful energy flow rate (kW). The pictorial view of the main window of the Extend^{TM}, a simulation model developed is shown on Figure 4

Figure 4: Pictorial view of the main window of the Extend^{TM}, a simulation model



(Source: Author)

3 RESULTS AND DISCUSSION

3.1 THEORETICAL AND ACTUAL FURNACE DIMENSIONS

The theoretical furnace's dimensions have been recalculated based on the measurement obtained during the furnace evaluation and compared with the dimensions that were originally designed for the prototype. However, the actual values are depicted in Table 2 and the actual theoretical (simulated) value is shown e Table 3.

Table 2: Obtained data used for the calculation of the actual values.

Properties	Units	Value
Thermal energy required for heating the air		
Drying mass flow rate	kg s^{-1}	0.68
Air density	kg m^{-3}	1.012668
Specific heat of air	kJ kg^{-1} ^{0}C	1.00400
Drying air temperature	^{0}C	73.81
Ambient air temperature (preheated)	^{0}C	47
Firewood Consumption and volume of combustion chamber		
Thermal energy required for heating the air	kW	18.3
Lower heating value	kJ kg^{-1}	15533.31
Estimated efficiency of furnace	%	0.6
Firewood consumption	kg s^{-1}	0.0020
VTT	kW m^{-3}	177
Grate area and grate free area		
FLR	kg h^{-1} m^{2}	47
$\dot{m}_{fuel}$	kg s^{-1}	0.0032
V_T^{air}	m^{3} kg^{-1}	15533.31
fa	(0.14 to 0.25)	0.14
Surface area of heat exchanger		
Global Temperature Coefficient	W m $^{-2}$ ºC $^{-1}$	30
T_{in_ha}	ºC	660.42
T_{out_a}	ºC	246.38
T_{in_a}	ºC	47
T_{out_a}	ºC	73.81
ΔT_1	ºC	313.45
ΔT_2	ºC	-73.78
$\Delta \mathrm{T}_{la}$	ºC	85.67

Table 3: Theoretical and actual values of the furnace dimensions

Properties	Units	Theoretical value	Actual value
Thermal energy required for heating the air	kW	18.41	18.31
Firewood consumption	kg h^{-1}	7.03	7.0719
Volume of the combustion chamber	m^{3}	0.30	0.30
Furnace grate area	m^{2}	0.247	0.247
Grate free area	m^{2}	0.035	0.035
Surface area of heat exchanger	m^{2}	1.70	1.70

Table 3 indicates that there is no significant difference between the theoretical values calculated and the actual value obtained from the results of the evaluation. Thus, the design has been validated and demonstrated that the prototype constructed is a genuine representation of the designed furnace.

3.2 PROCESS CONTROL

3.2.1 Process control for temperature data

Tables 4 provide the process control for the data obtained for the combustion temperature, heat exchanger temperature, and temperature of gases out of the heat exchanger, as well as the drying air temperature and other various measurement positions. The maximum, mean, minimum, and standard deviation were obtained at a 95% confidence interval (CI).

Table 4: Temperature control data for operational position mixed heating for a cycle time of 67.2 minutes (1.12 h)

Temperatures (^0C)	Max	Average	Min	StaDiv	95% CI
Ambient air temperature	25.07	25.00	23.57	0.67	5.00 ± 0.33
Drying air temperature – T1	114.00	75.41	53.03	20.13	75.41 ± 9.87
Combustion cell - T2	875.00	708.70	515.00	100.64	708.70 ± 49.42
Heat exchanger – T3	392.50	227.24	91.00	106.50	227.24 ± 52.18
Temperature of air direct from comb. –T4	332.00	180.11	81.00	77.13	180.11 ± 37.79
Temperature of air mixed with Ambt. T5	329.00	175.71	67.50	76.99	175.71 ± 37.33
Temperature out of heat. Exchanger – T6	77.00	53.32	42.00	11.97	53.32 ± 5.87
Temperature of fin plate – T7	242.00	115.51	53.33	64.62	115.51 ± 31.66
Preheated air for heat exchanger – T8	96.00	50.42	32.67	19.83	50.42 ± 9.72
Chimney temperature – T9	297.00	114.00	26.67	113.20	114.00 ± 55.47
Furnace wall temperature – T10	51.60	48.46	37.93	3.35	48.46 1.64

The process control data presented in Tables 4 indicate that the average temperatures recorded at various points during mixed heating operations are significantly higher than the recorded and evaluation verified when the furnace worked as indirect heating operations, except for the heat exchanger temperature, preheated air for the heat exchanger, and the temperature of the chimney. This is because in mixed heating operations, the heat energy generated by the combustion chamber is transferred directly to the mixing chamber without any significant impact on the heat exchanger.

3.3 FURNACE PERFORMANCE

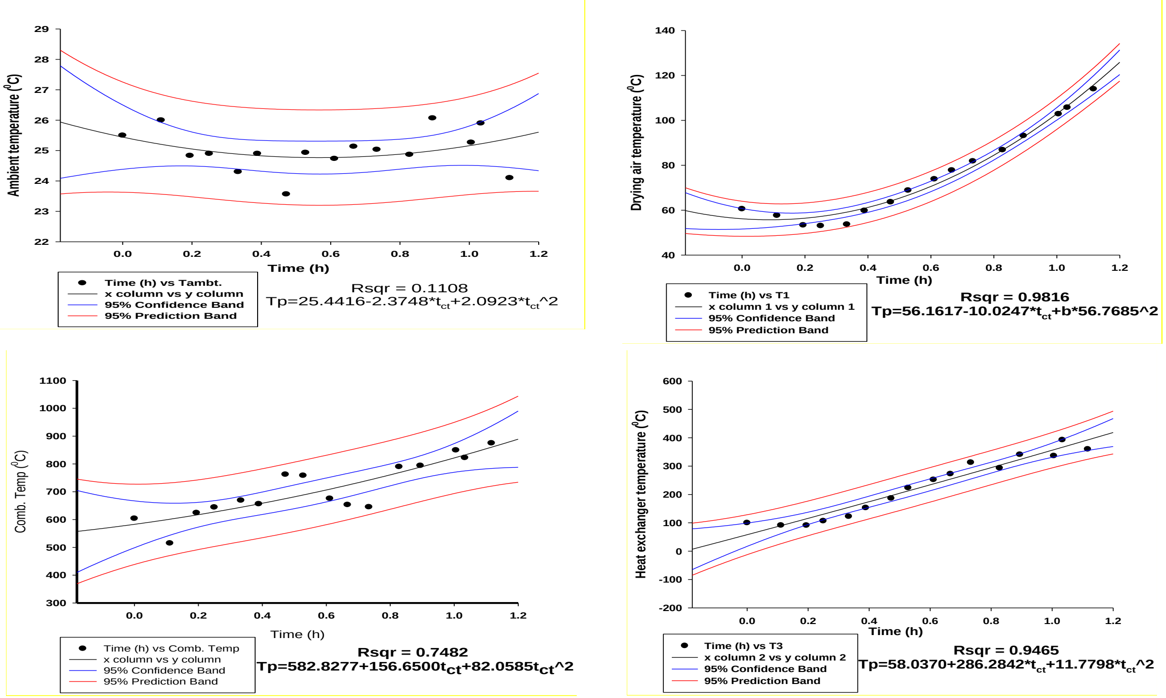
The furnace performance working during mixed heating of the air was studied by stabilizing the drying air temperature between 60 and 70^oC. The valve for the configuration for mixed heating of the air was opened for about 60 minutes to convert the system. The combustion temperature, the temperature of the gases out of the combustion chamber, the temperature of the gases mixed with ambient air, and the drying air temperature per unit time were investigated.

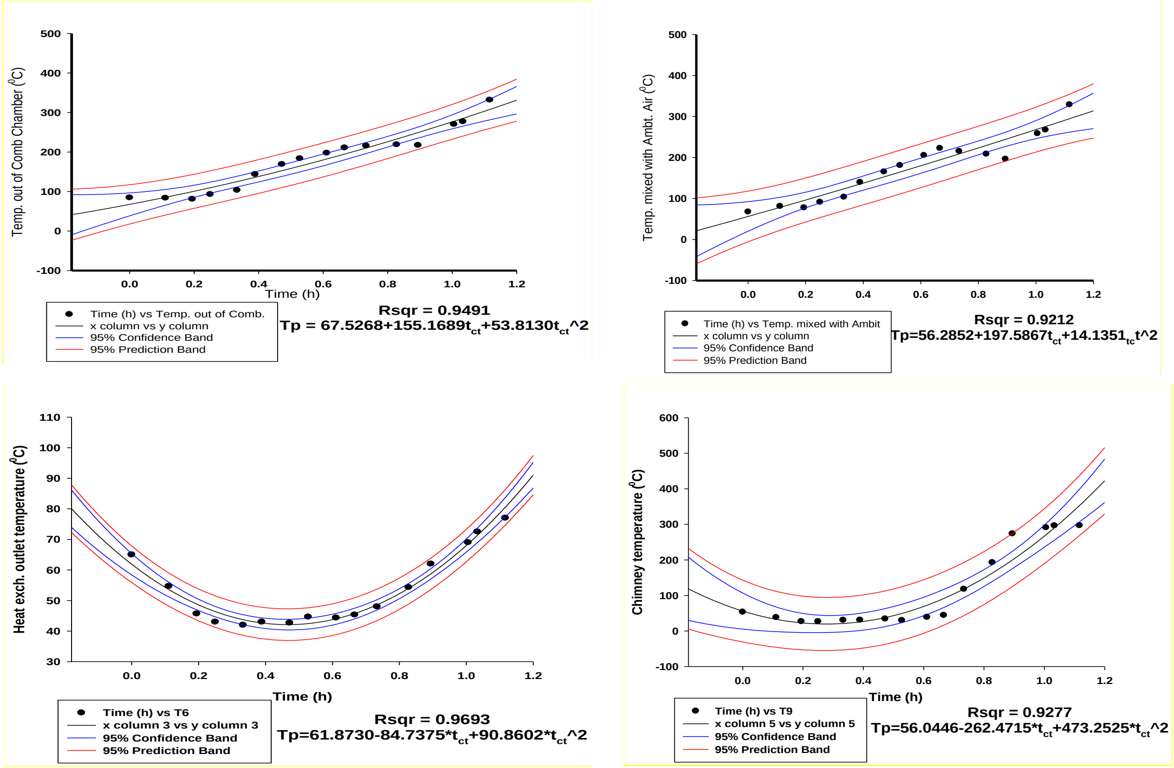
Table 1 shows the fitted models, adjusted coefficients of determination, and standard error of estimate for temperature measurement points during a circle time of 1.21 hours in mixed heating operation.

The relationship between the operation time and the ambient air, drying air, combustion, heat exchanger, outlet air from the combustion chamber, outlet air mixed with ambient, outlet heated air from the heat exchanger, and chimney is shown in Figure 5. The analysis of the data employed non-linear regression analysis of the data that was fitted with the quadratic model. The figure shows that there was no relationship between the operation time and ambient air temperature (R^2=0.0), all other temperatures showed a positive linear relationship with the operation time, except for the outlet heat exchanger and chimney temperature, which showed a negative correlation with the operation time. During this period, the maximum combustion cell temperature reached an approximate value of 875 ^{o}C, which is relatively higher than the value obtained for indirect heating (835 ^{0}C).

The regression analysis revealed a significant correlation between the operation time and the drying air, combustion, heat exchanger, outlet air from the combustion chamber, outlet mixed with ambient, outlet heated air from the heat exchanger, and chimney within a 95% confidence interval, with R^2 values of 0.9816, 0.7482, 0.9465, 0.9491, 0.9212, 0.9693, and 0.9277, respectively. It implies that the models significantly predict the behavior of various parameters at a given time.

Figure 5: Effects of operating time on the furnace performance for mixed heating of the drying air.





3.4 QUALITY ANALYSIS OF THE COMBUSTION GASSES

Table 5 shows the analysis results of the composition of the flue gases proportion present in the drying air and chimney during mixed heating operations. During the first 10 minutes of the indirect heating operation, there was no significant presence of CO in the drying air from the beginning to the end of the operation cycle and only 2.0 PPM of CO was present in the chimney gasses. While there was a greater proportion of CO (385 PPM) present in the drying air at the beginning of operation in a mixed heating configuration, the chimney air was free from CO contaminations.

In the table, Iit can be observed that regardless of the furnace configuration, the proportion of CO_2 present in the drying air is significantly higher than the one obtained at the chimney and gradually decreases as the operating duration increases.

Table 5: proportion of flue gases composition in the chimney and in the drying air for mixed heating operation

Operation time (minute)	Proportion CO (PPM)		Proportion of CO_2 (PPM)	
	Chimney air	Drying air	Chimney air	Drying air
10	0.00	385	924	1851
30	0.00	153	892	1191
50	0.00	148	724	956
60	0.00	109	702	845

With 0.0 ppm of CO and the concentrations of CO_2 detected at the chimney and drying air were significantly lower than the recommended limit of 20,000 PPM for CO_2 in the environment OSHA (2013).

3.5 MODELING AND SIMULATION RESULTS

The furnace efficiency in mixed heating of the air was optimized using Extend simulation software, which was used to develop simulation models from quadratic models obtained from the analysis of experimental data. The conventional method of operation, which involves the absence of control, and the regulation of the opening time for mixing ambient air inlet and the regulation of drying air temperature during working hours without refueling (1.98 h or 119 min), was considered for optimal efficiency.

Six (6) distinct scenarios were analyzed at varying drying temperatures to ascertain the normal and controlled efficiency of the furnace and the opening time of the mixing chamber inlet for a controlled setting, and was performed for five distinct times, namely 5, 10, 15, 20, and 30 minutes after the valve opening, to convert the original furnace's configuration into mixed heating configuration, considering identical drying air temperatures of 50, 60, 70, and 80 ^{o}C.

The simulation results pertaining to the average thermal efficiency of the furnace under both normal and controlled conditions, at various temperatures and desired temperatures, are presented in Table 6. The average efficiency and percentage of operation time of the furnace at the desired temperature for the controlled system at a drying air flow rate of 43 m^3 min^{-1} are shown in the table.

Table 6: Simulated results for percentage of operation time of the furnace in the desired temperature for the controlled system at drying air flow rate of 43 m^3 min^{-1}

Scenarios	Desired drying air temperature (^{0}C)	Efficiency (with control) (%)	% Operating time in the desired temperature
I – Indirect fired (119 min.) Standard scenario	50	32.8	81.4
	60	44.0	71.6
	70	54.8	60.3
	80	65.0	43.3
II - 5 min at Indirect heating and (114 min) mixed heating	50	32.8	99.2
	60	44.0	98.4
	70	55.0	95.9
	80	65.0	43.3
III – 10 min at Indirect heating and (109 min) mixed heating	50	32.5	99.2
	60	44.4	98.4
	70	55.6	95.9
	80	64.9	93.5
IV - 15 min at Indirect heating and (104 min) mixed heating	50	32.5	99.2
	60	44.8	98.4
	70	54.8	95.9
	80	65.4	93.5
V - 20 min at Indirect heating and (99 min)	50	32.6	99.2
	60	43.8	98.4

mixed heating	70	55.6	95.9
	80	65.2	93.5
VI - 30 min at Indirect heating and (89 min) mixed heating	50	32.6	99.2
	60	43.8	98.4
	70	55.6	95.9
	80	65.2	93.5

It can be inferred from the figure that the furnace efficiency increases with an increase in the temperature of the drying air. Furthermore, the efficiency levels are approximately equivalent at the same drying air temperature, irrespective of the furnace configurations. The maximum efficiency of the furnace can be achieved at a temperature of 80 ^{o}C using any of the configurations.

Therefore, from Table 6, Scenario II, comprising indirect heating for 5 minutes and mixed heating 114 minutes, is accepted as the optimal scenario for drying air temperatures of 50°C (efficiency 32% - during 99.2 % of operating time), 60°C (efficiency 44% - during 98.4 % of operating time), and 70°C (efficiency 55% - during 95.5 % of operating time). However, for drying air temperature of 80 °C, scenario III with indirect heating for 10 min and mixed heating of 109 min is considered the best because it yielded the furnace thermal efficiency of 64 % during 93.5 % of operating time.

Furthermore, to improve the furnaces thermal efficiency at 50 ^{o}C drying air temperature during indirect heating operation, the volume of the combustion chamber, surface area of the heat exchanger, and area of the ambient air inlet must be reduced. This will increase the thermal energy generated at the combustion chamber and will increase the heat transfer from the heat exchanger to the mixing chamber.

For mixed heating operations, the thermal efficiency of the furnaces at 50 ^{o}C drying air temperature and its quality can be improved by creating another mixing chamber (in the form of a cyclone) for direct heating air from the combustion chamber. It is imperative to augment the rate of ambient air flow, considering the modification of the present fan.

4 CONCLUSIONS

An air heating smokeless furnace was designed, built, and evaluated. The optimization of the furnace efficiency was achieved by utilizing EXTEND simulation software, which was derived from the quadratic models obtained through the analysis of experimental data. The conventional operational procedure involves the control of the drying air temperature without any control over the opening time for the ambient air inlet at the mixing chamber, once the drying air temperature reaches a desired value during the working hours without any refueling (1.98 hours or 119 minutes)

Based on the results of the evaluation carried out, it was possible to conclude:

- The fuel combustion was incomplete when the ignition temperature was not full achieved within the first 10 minutes of operation, causing the flue gasses from the chimney outlet to contain a small proportion of CO. During this period, with clean drying air in the indirect heating configuration. For mixed heating configurations, the greater proportion of CO produced during the initial combustion period must be avoided.
- When operated normally, the furnace's efficiency was approximately uniform, regardless of the drying temperature. The drying efficiency increases with an increase in drying temperature with a controlled system.

According to the simulation results, it has been determined that scenario II, comprising of indirect heating for 5 minutes and mixed heating for 114 minutes, is deemed the optimal scenario for drying air temperatures of 50°C (efficiency 32% - during 99.2 % of the operating time), 60°C (efficiency 44% - during 98.4 % of the operating time), and 70°C (efficiency 55% - during 95.5 % of the operating time). But for drying air temperatures of 80 °C, scenario III with indirect heating of 10 min and mixed heating of 109 min is considered the best because it yielded a furnace thermal efficiency of 64 % during 93.5 % of operating time.

Because the simulation results were derived from the quadratic models obtained through the analysis of experimental data from a unica furnace size, it is not secure to use for furnace sizes too far from the furnace size analyzed.

It is recommended to analyze larger furnaces and, if possible, utilize three combustion cells for future works. This measure would guarantee that one cell is removed after the complete insertion of the second cell in steady work, thereby preventing temperature peaks.

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