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**Orge, R., McHenry, M.P. and de Leon, R.L. (2013) Modelling the carbonization process to develop a cost-effective, smokeless, continuous, down-draft rice husk carbonizer suitable for rice growing regions. In: Poullikka, A., (ed.) Renewable energy: economics, emerging technologies and global practices. Nova Science Publishers, Hauppauge, New York, pp. 267-280**

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### Book Chapter

## Modeling the carbonization process to develop a cost-effective, smokeless, continuous, down-draft rice husk carbonizer suitable for rice growing regions.

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### Abstract

This work discusses modeling of the operational processes occurring in a small-scale, down-draft, continuous rice husk (40 kg h<sup>-1</sup>) carbonizer suitable for application in poor rice growing regions. The model was used as a tool to optimize the performance of a constructed carbonizer using material and heat balances. The carbonizer technology operating principles are discussed in terms of four operational "zones" and the possible reactions occurring in each zone. The material balance model was used to determine the amounts of each participating material at each zone, and the energy balance was generated using the material balance solutions. The final output of the model for O<sub>2</sub>, CO, and CO<sub>2</sub> was reconciled with testing performance of the constructed carbonizer. The results suggested that 99.2% (weight basis) of the total CO produced during carbonization was burnt at the ignition chamber zone, resulting in only 0.8% CO emission from the chimney. The energy balance determined there was a high potential for the carbonizer to produce useful heat, for rice farm activities, with flue gasses calculated at 724°C. The material and heat balance models were successfully verified by prototype testing.

**Keywords:** Carbonizer; Rice husk; Energy; Model; Biochar.

### Nomenclature

RH	rice husk
CHR	carbonized rice husk
$R_p$	the matrix of the elemental composition (%) of the RH based on ultimate analyses
$A_p$	the matrix of the elemental composition of ambient air
$C_{crh}$	C content (%) of the carbonized RH produced by the carbonizer
$Q_r$	the input capacity of the carbonizer, (kg RH h <sup>-1</sup> )
$Q_a$	the flow rate of air entering the side opening of the carbonizer, (kg h <sup>-1</sup> )
$Q_b$	the flow rate of air entering the bottom opening of the carbonizer, (kg h <sup>-1</sup> ).
$R_w$	matrix of the kg of RH components entering the carbonizer

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Author's Copy, suggested citation: Orge R, McHenry MP & de Leon RL (2013) Modelling the carbonization process to develop a cost-effective, smokeless, continuous, down-draft rice husk carbonizer suitable for rice growing regions. In: Renewable energy: economics, emerging technologies and global practices. Ed. Poullikka A. Nova Science Publishers, Hauppauge, New York, USA. ISBN 978-1-62618-264-6.

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$A_{ws}$	matrix of the kg of air components entering the side opening
$A_{wb}$	matrix of the kg of air components entering the bottom opening
$t$	accounting period considered (one hour)
$C_{crh}$	portion of the C present in RH remaining in the charcoal after carbonization
$C_a$	the amount of gasified C taking part in the reaction
$R_w(1)$	the first element of the $R_w$ matrix (%C)
$y$	yield of CRH (a ratio of the weight of CRH to input RH, in decimal form)
$X_{air}$	X characteristic of the intake air
$X_{rh}$	X characteristic of the RH
$X_{crh}$	X characteristic of the CRH
$X_{fg}$	X characteristic of the flue gas
$m$	mass of the material
$C_p$	specific heat capacity, (J mole <sup>-1</sup> K <sup>-1</sup> )
$\Delta T$	difference between reference and final temperature, (°K)

## Introduction

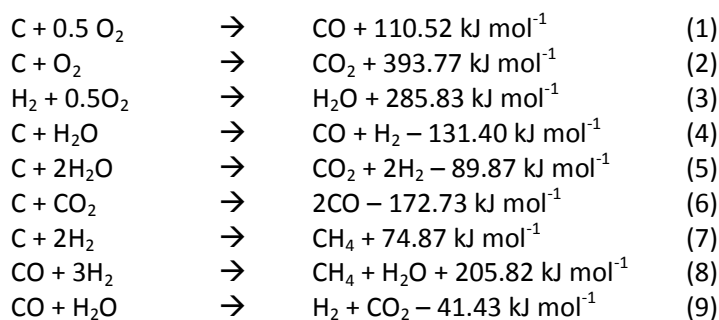
Carbonization is a complex process [1, 2] with some published literature equating carbonization with pyrolysis [3-5], while others consider pyrolysis a distinct process to accomplish carbonization [6-11], or as a sub-processes similar to gasification [12]. Several models describing the carbonization process have been developed [13-16], although no literature is currently available that sufficiently describes how the chemical elements in rice husk (RH) and air interact in the numerous reactions involved in the carbonization process. This work incorporates Hien's [17] research on RH combustion systems, both Vinluan's [18], and Rezaiyan and Cheremisinoff's [5] research on gasification technologies, Basu's [19] work on combustion and gasification, and Reed and Das's [12] work on downdraft combustion systems to simplify the problem to equations to predict the behavior of a thermal system like a carbonizer [20]. Reed and Das [12] reported that adjusting the equivalence ratio of a gasifier at a level lower than 0.25 favors the production of carbonized rice husk (CRH). This means a carbonizer is able to operate as a gasifier if an optimal equivalence ratio for gasification is achieved by influencing air intakes. This paper uses a combination of gasification and combustion theory to model the various chemical reactions taking place in the operation of a smokeless RH carbonizer, and how these elements interact during the process. The predictive model produced suitable quantitative inputs for assisting the design and optimization of the carbonization process and carbonizer. The results were tested by constructing a small-scale, motor-less downdraft RH carbonizer in the Philippines, designed to enable future retrofitting of heat recovery components. The resultant carbonizer overcame many limitations of the batch carbonizers currently used in the region, including low heat recovery capability, and in particular the unacceptable operator emission/smoke exposures.

## Carbonizer operating principles

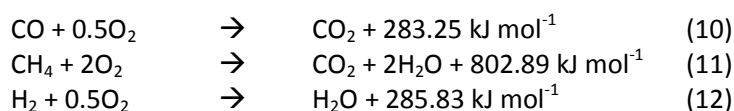
RH is initially fed into the top of the carbonizer, filling the hopper, which is then tightly closed (Fig. 1). The model assumes that hopper cover and all of the hopper joints and connections are perfectly

sealed so ambient air taking part in the carbonization process enters only through the side opening where a portion of the RH bed is exposed. Once the carbonizer is ignited and starts to operate by itself, the model assumes the carbonizer operates with the same processes and reactions as that of a gasifier, since both systems operate with limited (below stoichiometric) levels of air. The flow of materials (RH, air, and CRH) entering and leaving the carbonizer is represented in Fig. 2.

The RHs inside the hopper undergo changes in various zones, the boundaries of which overlap in practice [17], but are clearly divided diagrammatically for the discussion. Furthermore, the size of each zone will vary for each operation, primarily due to the changes in RH agitation frequency which is undertaken to allow the CRH to collect in the bottom chamber. In the drying zone the RHs are heated from the ambient temperature to pyrolysis temperatures of around 230°C [17]. In the immediate vicinity of the chimney's base and the upper portion of the ignition chamber is the pyrolysis zone. The RHs are exposed to high temperatures in the absence of air as the air does not flow through this region of the carbonizer. Thus, the RHs lying in this region are 'cooked', transforming them into three products - solid (CRH), liquid (tar), and gas. The region in the immediate vicinity of the ignition chamber is the reduction zone. This zone lies along the path of the air wherein the following reactions are expected to occur in a similar manner as that of a gasifier [12]:



Reactions four and five are the water-gas reactions, reaction six is the Boudouard reaction, reaction seven is the methanation or hydro-gasification and reaction nine is the shift conversion or water-gas shift [5,19]. The combustion zone is bound by the walls of the ignition chamber. It is where secondary air entering through the bottom opening is introduced to the combustible gases. The reactions can be described as follows:



In addition to the N<sub>2</sub> component of air which did not play a reactionary role, gases entering into the combustion zone could be any or all of the following products of reactions one to nine: H<sub>2</sub>, CO, CO<sub>2</sub>, H<sub>2</sub>O, and CH<sub>4</sub>. As some of these products are reactants of the other reactions, some of the combustible gases may be consumed while in the reduction zone.

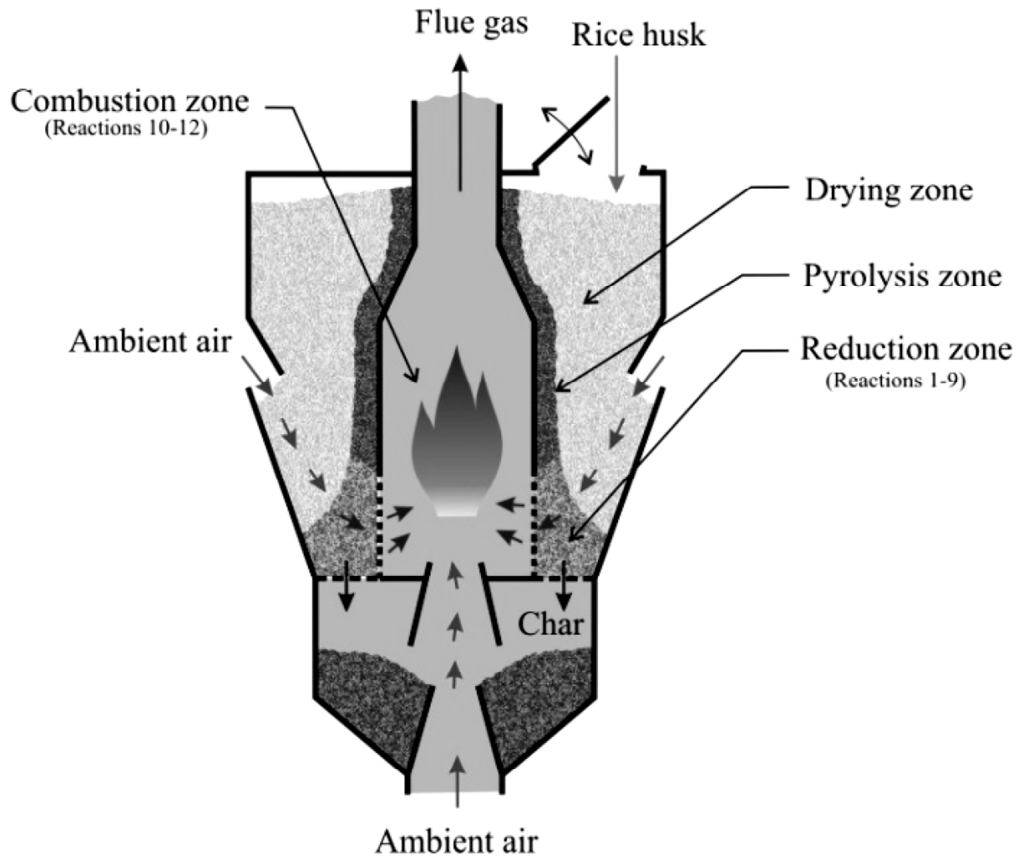


Fig. 1. Cross section representing material flows into and out of the carbonizer.

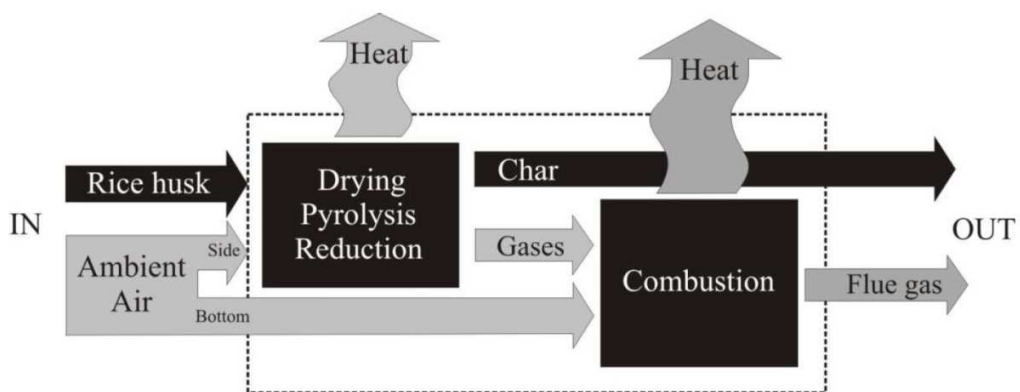


Fig. 2. Flow of materials into and out of the carbonizer in a process diagram.

## Methods

The carbonization process was modeled based on the concept of material balance. As matter cannot be created nor destroyed, the total materials that constitute the RH and the ambient air taking place in the carbonization process remains the same at the point of entry and exit of the carbonizer. MATLAB<sup>®</sup> was used to develop a program to model the carbonization process to account for reactions one to twelve to determine a condition wherein a 'material balance' exists, based on the zone boundary conditions. The program output displays a list of the materials and their relative amounts at the point of entry and exit in the carbonizer, and for each zone. Since the carbonizer is a continuous design, the program uses an accounting period of one hour. Thus, the amount of RH considered is equal to the carbonizer's input capacity ( $\text{kg RH h}^{-1}$ ) multiplied by one hour.

The model included input data from the input RHs and actual operation of the carbonizer. For the materials entering the carbonizer, the data were derived from elemental (ultimate) and proximate analyses of the RHs (Table 1). The data for the exiting materials were obtained during testing of the carbonizer (see Table 2 for testing results). The calculations in program were based on the following assumptions:

1. The processes involved do not change with time (steady state) and are carried out at constant pressure (isobaric);
2. Each reaction from one to nine took place during the carbonization process, and each of the C-consuming reactions (such as reactions one, two, four, five, six, and seven) receive equal chance of obtaining carbon (C) from RH (as the main source), although each reaction may obtain unequal amounts depending on where material balance is attained. This assumption also applies to chemical substances/compounds which are produced in one reaction but are also utilized as reactants in another reaction;
3. CO, a product of reactions one, four, and six, and reactant of reactions eight and nine, was allowed to exit the chimney unburnt. This was introduced to find a material balance solution to the measured CO gas at the chimney, in addition to satisfying the C allocation flexibility described in assumption 2 above;
4. Both  $\text{H}_2$  and  $\text{CH}_4$ , being more combustible than CO, were assumed to be completely burned before leaving the chimney. The  $\text{H}_2$  was assumed to be totally combusted in the reduction zone as its auto-ignition temperature is  $400^\circ\text{C}$  [21], well above reduction zone temperatures obtained in the performance tests results. The  $\text{CH}_4$  was assumed to be totally burnt by the time it exits the ignition chamber to pass through the carbonizer's chimney.

Table 1. RH data used in the material and heat balance analysis.

Parameter	Value
Proximate Analysis	
Moisture, %	7.8
Ash, %	18.1
Volatile, %	55.5
Fixed C, %	18.6
Ultimate Analysis	
C, %	38.2
Hydrogen, %	5.5
Oxygen, %	35.2
Nitrogen, %	0.9
Ash, %	20.2

Table 2. Performance of the carbonizer.

Performance Parameter	Prototype
Ignition time, min	3.2
Total amount of RH consumed, kg	164.5
Total operating time, h	4.1
Input capacity, kg RH h <sup>-1</sup>	40.12
Char yield, %	40.3
Maximum temperature attained, °C	898.7
Attendance time, % of total operating time	21.3
Reloading with RH, %	8.6
Agitation, %	8.6
Collection of CRH, %	4.1
Purity of CRH output, %	99.1
Emission	
O <sub>2</sub> , %	8.9
CO, ppm	431
CO <sub>2</sub> , %	7.4

Fig. 4 provides a visual representation of the sources and destinations of the materials involved in the carbonization process. The nine rows in each of the two grids represent the reactions occurring at the reduction zone (with the number designations indicated at the left). The columns represent the participating elements and compounds including N<sub>2</sub>. A shaded box where columns and rows intersect indicate the presence of an element or compound in a particular reaction. The main sources of these

elements/compounds are RH and ambient air which are displayed at the leftmost side as two independent sources. The only source of C was the RH, which were allocated to the six C-consuming reactions. This was the net amount of C after subtracting the C content of the CRH. In the model, one of the two reactants from each row was an independent reactant, and one considered as the independent reactant (the leftmost end of the row in Fig. 4. The calculated dependent reactant was subtracted from the input RH or ambient air material flows, and also the measured output products. Any excess reactant will proceed to the combustion zone, or if not utilized was considered as carbonizer emission gas.

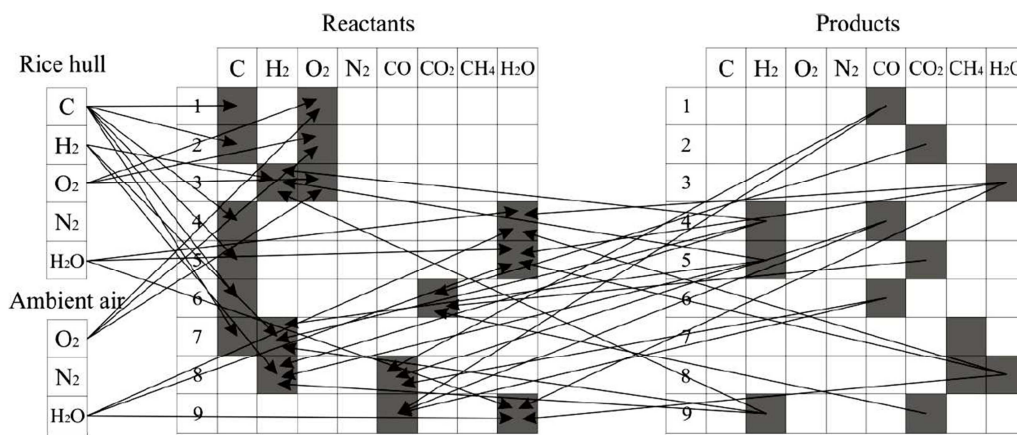


Fig. 3. Sources and possible destinations of reduction zone elements and compounds.

The development of the model for the carbonization process followed the general algorithm shown in Fig. 4. The “balanced” condition was determined as when the modeled carbonizer emissions matched the measured emission data within a margin of error. The two loops created to filter the possible solution included one that varied the percentage of CO completely burnt at the ignition chamber, and the other was the allocation of C for the C-consuming reactions.

The calculations in the computer model are described in this section. Let:

- $R_p$  = the matrix of the elemental composition (%) of the RH based from the results of the ultimate analysis = [%C, %H<sub>2</sub>, %O<sub>2</sub>, %N<sub>2</sub>, %H<sub>2</sub>O, %Ash];
- $A_p$  = the matrix of the elemental composition of ambient air = [%O<sub>2</sub>, %N<sub>2</sub>, %H<sub>2</sub>O];
- $C_{crh}$  = C content (%) of the carbonized RH produced by the carbonizer;
- $Q_r$  = the input capacity of the carbonizer, (kg RH h<sup>-1</sup>);
- $Q_a$  = the flow rate of air entering the side opening of the carbonizer, (kg h<sup>-1</sup>);
- $Q_b$  = flow rate of air entering the bottom opening of the carbonizer, (kg h<sup>-1</sup>);



Then the matrix of input quantities (kg) of RH components, and side and bottom air may be derived from:

$$R_w = Q_r \times R_p \times t \times 100^{-1} \quad (13)$$

$$A_{ws} = Q_a \times A_p \times t \times 100^{-1} \quad (14)$$

$$A_{wb} = Q_b \times A_p \times t \times 100^{-1} \quad (15)$$

where:  $R_w$  = matrix of the kg of RH components entering the carbonizer;  
 $A_{ws}$  = matrix of the kg of air components entering the side opening;  
 $A_{wb}$  = matrix of the kg of air components entering the bottom opening;  
 $t$  = accounting period considered (one hour).

A portion of the C present in RH remains in the charcoal after the carbonization process, defined as equal to  $C_{crh}$  in the model. Therefore, the amount of gasified C ( $C_a$ ) that took part in reactions one to nine is the difference in the amount of C present in the RH, and in the CRH:

$$C_a = R_w(1) - (Q_r \times y \times t \times C_{crh} \times 100^{-1}) \quad (16)$$

where:  $R_w(1)$  = the first element of the  $R_w$  matrix (%C);  
 $y$  = yield of CRH (the ratio of the weight of CRH recovered after the carbonization process, and the total weight of the input RH, in decimal form).

The amounts of gasified C were allocated among the six C-consuming reactions (reactions one, two, four, five, six, and seven). The program itself generated C-allocation cases (up to 3,040,000) for use in the calculations. Each case was a vector of nine elements, representing the nine reactions occurring at the reduction zone. Three of these nine reactions (reactions three, eight and nine) had a zero C-allocation throughout the generated cases. With the substitution of values for C, the other reactant and product amounts were calculable, following the procedure discussed by Joel [22].

Vectors of the same size as the C-allocation matrix were created for each other participating element or compound. In cases where a particular element or compound was both a reactant in one reaction and a product in another, two unique vectors were created. The elements or compounds that proceeded to the ignition chamber in the model were those that remained after subtraction of all the reactants from the products. For combustible gases, such as  $H_2$ ,  $CO$ , and  $CH_4$  entering the ignition chamber, the introduction of air results in  $H_2O$  and  $CO_2$  as described in reactions 12 to 14. This finally consolidated the calculated amounts of all the emitted gases from the chimney. For an allocation case to be accepted (and be considered realistic), the difference between the calculated emissions for  $O_2$ ,  $CO$ , and  $CO_2$  and those gathered from the carbonizer tests, should be equal to, or less than that the set margin of error. Any allocation case that yields an error equal to or less than the set value was displayed by the program. In cases where the program displayed more than one solution, the margin of error was lowered until only one solution was displayed.

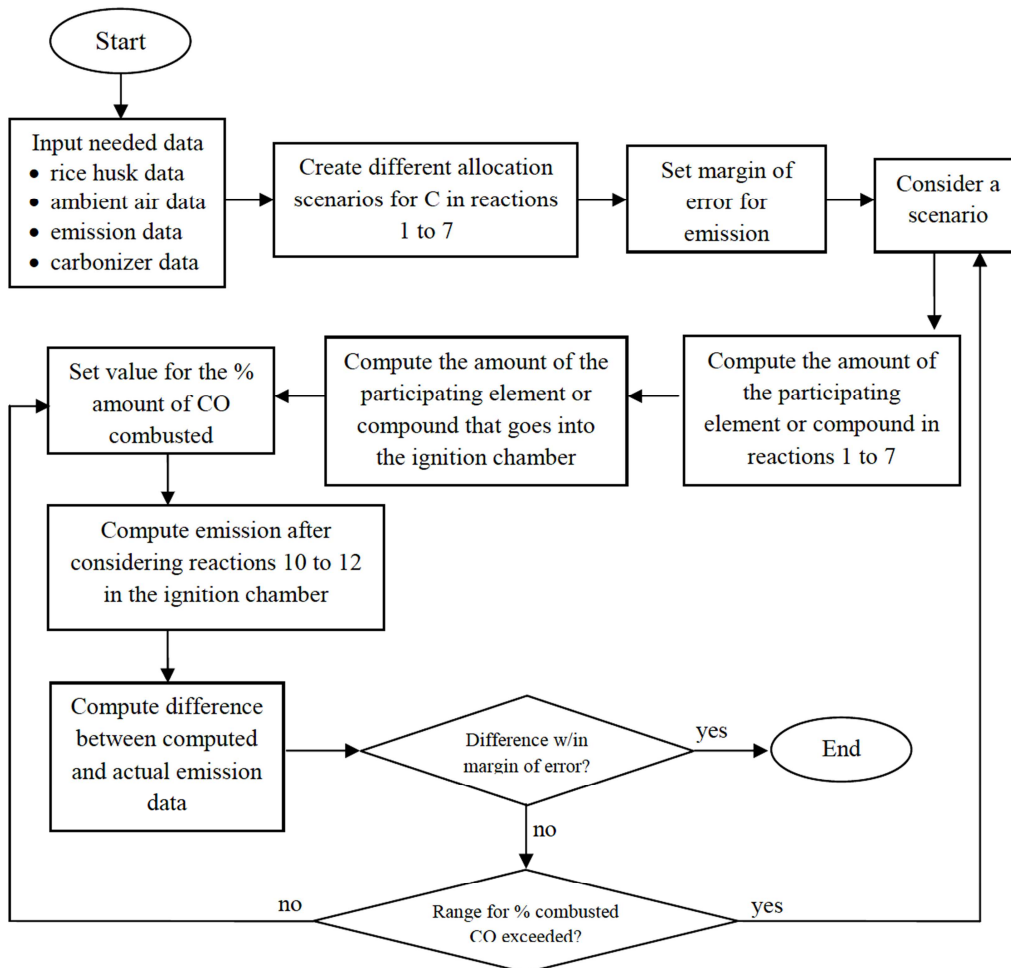


Fig. 4. Algorithm for the computer model for the carbonization process.

## Model output

Table 3 shows output from the MATLAB® program for the carbonization process. With the accounting time of one hour, the gasified C from an input 40 kg RH was 8.4 kg. This was allocated to the six C-consuming reactions in the proportions shown in Table 3. This was the only solution out of the 90,000 C allocation cases considered within the set margin of error of 7.51879%. The Table shows that 37% of the total gasified C was utilized in reaction one, which demonstrates that the reduction zone reactions are mostly partial combustion of RH. Conversely, each of the reactions six and seven consumed 19% of the total available C while reactions two, four and five consumed 9%, 15% and 1%, respectively. The results also show that 99.2% of the total amount (by weight) of CO was burned at the ignition chamber, meaning the remaining 0.8 % escaped as an emission at the chimney.

Table 3. Output of the computer program for material balance.

<b>Possible allocation of C</b>
Reaction 1: 3.11 kg (37%)
Reaction 2: 0.76 kg (9 %)
Reaction 4: 1.26 kg (15%)
Reaction 5: 0.08 kg (1 %)
Reaction 6: 1.60 kg (19%)
Reaction 7: 1.60 kg (19%)
TOTAL: 8.40 kg (100%)
<b>Amount of gases entering the combustion chamber</b>
H <sub>2</sub> : 0.00 kg
O <sub>2</sub> : 46.95 kg
CO: 14.18 kg
CO <sub>2</sub> : 1.23 kg
H <sub>2</sub> O: 15.47 kg
CH <sub>4</sub> : 3.55 kg
N <sub>2</sub> : 167.15 kg
<b>CO burned: 99.20% of total</b>
<b>Emitted gases</b>
H <sub>2</sub> : 0.00 kg (0.00%wt) (0.00%vol)
O <sub>2</sub> : 24.74 kg (10.05%wt) (8.84%vol)
CO: 0.11 kg (0.05%wt) (0.05%vol)
CO <sub>2</sub> : 30.61 kg (12.44%wt) (7.96%vol)
H <sub>2</sub> O: 23.44 kg (9.53%wt) (14.89%vol)
N <sub>2</sub> : 167.15 kg (67.93%wt) (68.26%vol)
<b>Difference between calculated and actual data</b>
for O <sub>2</sub> : 0.68%
for CO: 7.46%
for CO <sub>2</sub> : 7.52%
=====
<b>Number of possible solution(s) found: 1</b>
>>

All reactions are associated with either by an absorption or evolution of energy, which usually manifest themselves as heat [23]. The operation of the rice husk carbonizer generates a net heat output, as shown by the sum of reactions one to twelve. Since the generated heat is planned to be utilized for productive rice farming purposes, it is necessary to analyze the heat loss during operation to evaluate the potential of heat recovery unit retrofits. The heat balance model was calculated using the material balance conditions described in Table 3. Fig. 5 shows the temperatures at different zones in the

carbonizer based on data taken during performance testing. These heat balance equations are expressed as the enthalpies (H) of the materials entering and leaving the carbonizer:

$$H_{air} + H_{rh} = H_{crh} + H_{fg} + \text{Heat loss}, \quad (17)$$

where:  $H_{air}$  = enthalpy of the air;  $H_{rh}$  = enthalpy of the RH;  $H_{crh}$  = enthalpy of the CRH, and;  $H_{fg}$  = enthalpy of the flue gas. Since the total enthalpy of a material consists of three thermodynamic properties, heating value (HV), sensible heat (SH), and latent heat (LH).

Equation 17 can also be rewritten to calculate heat loss:

$$\text{Heat loss} = (HV, SH, LH)_{rh} + (HV, SH, LH)_{air} - (HV, SH, LH)_{crh} - (HV, SH, LH)_{fg} \quad (18)$$

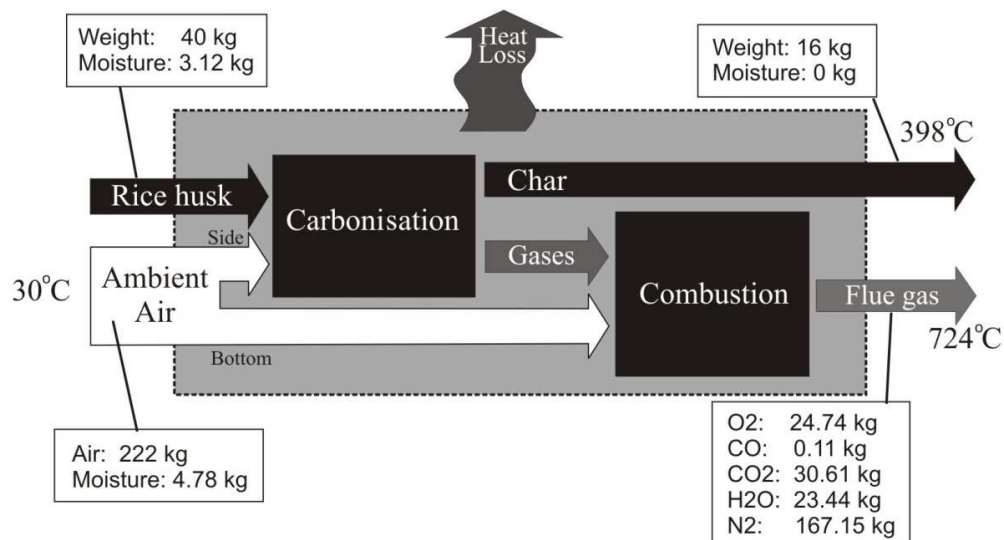


Fig. 5. Parameters used in the heat balance analysis

For materials or substances that are composed of several constituents, the total enthalpy is taken as the sum of the enthalpies of the individual constituents (elements or compounds) of which it is composed of. For sensible heat in particular, the following equation applies:

$$SH = mCp(\Delta T) \quad (19)$$

where:  $m$  = mass of the material or substance,  $Cp$  = specific heat capacity, and  $\Delta T$  = difference between reference and final temperature. For the gases in the ideal state, the specific heat capacity at constant pressure is computed as follows [24]:

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$$C_p = a + b \times T + c \times T^2 + d \times T^3 \quad (20)$$

where:  $C_p$  = in J mole<sup>-1</sup> K<sup>-1</sup>, T = temperature in °K, and where  $a$ ,  $b$ ,  $c$ , and  $d$  = are constants with values for selected gases shown in Table 4.

Table 5 shows the calculated results for HV, SH, and LH, at a reference temperature of 30°C (303°K) using values in Table 6. The analysis results show the calculated heat loss is 150,047 kJ, equivalent to 25.8% of the total enthalpy of the system.

Table 4. Constants for computing the specific heat capacity of selected gases.

Constant	H <sub>2</sub>	O <sub>2</sub>	CO	CO <sub>2</sub>	H <sub>2</sub> O	CH <sub>4</sub>	N <sub>2</sub>
a	27.143	28.106	30.869	19.795	32.243	19.251	31.15
b	0.0092738	-3.68E-06	-1.29E-02	7.34E-02	1.92E-03	5.21E-02	-1.36E-02
c	-1.38E-05	1.75E-05	2.79E-05	-5.60E-05	1.06E-05	1.20E-05	2.68E-05
d	7.65E-09	-1.07E-08	-1.27E-08	1.72E-08	-3.60E-09	-1.13E-08	-1.17E-08

Source: Towler and Sinnott [24].

Table 5. Summary of heat balance computations.

Material	Amount, kg	HV, kJ	SH, kJ	LH, kJ	Total
IN					
Rice husk	40	571,080	0	0	571,080
Moisture in	3.12	0	0	0	0
Air	222	0	0	0	0
Moisture in air	4.78	0	0	10,786	10,786
Sub-total		571,080	0	10,786	581,866
OUT					
Char	16	200,960	5,888	0	206,848
Flue gas:					
O <sub>2</sub>	24.74	0	17,255	0	17,255
CO	0.11	1,115	85	0	1,200
CO <sub>2</sub>	30.61	0	22135	0	22,135
N <sub>2</sub>	167.15	0	128071	0	128,071
H <sub>2</sub> O	23.44	0	3406	52904	56,310
Sub-total		202,075	176,840	52,904	431,819
Heat loss					150,047

Table 6. Rice husk data used in the material and heat balance analysis.

Parameter	Value
Proximate Analysis	
Moisture, %	7.8
Ash, %	18.1
Volatile, %	55.5
Fixed Carbon, %	18.6
Ultimate Analysis	
Carbon, %	38.2
Hydrogen, %	5.5
Oxygen, %	35.2
Nitrogen, %	0.9
Ash, %	20.2

## Conclusion

This work describes the use of modeling to optimize carbonizer performance and to obtain a greater understanding of the operational processes of converting RH into CRH. The material balance analyzed the flow and fate of the elements and compounds constituting the RH and the ambient air. A low (0.8%) level (weight basis) of CO emissions out of the chimney was achieved.

Likewise, the energy balance model determined there is a good potential for the carbonizer to be retrofitted with heat capture technology to utilize the continuously generated heat on-site from RH conversion into CRH. The constructed PhilRice continuous carbonizer prototype was able to process 40 kg of RH in one hour at 40.3% CRH yield with a purity of 99.1%, and unlike current batch RH carbonizers in use, it produces much cleaner emission, and produces useful heat.

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