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Research paper

Carbon and nitrogen emissions rates and heat transfer of an indirect pyrolysis biomass cookstove

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ABSTRACT

Cookstoves, where fuel is pyrolyzed or gasified, have received much attention due to their potential to reduce environmental and household air pollution (HAP). In this study, an indirect pyrolysis cookstove was investigated to determine how operating conditions influence carbon and nitrogen emission rates and heat input to the cooking water. Multiple linear regression models were developed based on time-resolved measurements. The rate of pyrolysis fuel consumption emerged as the primary driver for the production of CO and NO emissions and heating of water. This parameter alone explained over 70% of the variation in the models for CO, NO and the water heating rate. The CO emission rate had a non-linear dependency on the rate of pyrolysis fuel consumption ($R^2 = 0.70$, $p < 0.0001$), likely because high pyrolysis fuel consumption produced conditions with insufficient air flow for the conversion of C to CO₂. NO emission rates were mainly affected by the rate of N release from the pyrolysis fuel ($R^2 = 0.74$, $p < 0.0001$). However, the pyrolysis temperature also affected the rate of production of NO, accounting for 4% of its variation. The water heating rate has a linear relationship to the rate of pyrolysis fuel consumption ($R^2 = 0.69$, $p < 0.0001$). CO and NO emission rates depend on the speed of cooking and the choice of fuel, as well as on the amount of pyrolysis fuel used. Reduction of CO emissions and increase in efficiency are possible through stove design changes while choosing low-nitrogen pyrolysis fuel can lower NO emissions.

1. Introduction

Nearly forty percent of global households use traditional biomass cookstoves to meet their household energy needs [1,2]. However, these cookstoves experience conditions of incomplete combustion, producing undesirable gaseous and solid particle emissions [3–5]. Of particular importance are CO and NO, toxic air pollutants, which play a significant role in atmospheric chemistry, climate change [6–8] and public health [9,10]. Recent estimates indicate that biomass burning can contribute between 30 and 50% of global CO emissions [11,12] and 20% of NO_x [12], an unknown percentage of which is due to biomass cookstoves. The development and use of more efficient biomass cookstoves could reduce the effects of biomass burning on the climate by reducing CO and NO and directly impacting human health [13].

CO and NO emissions have different formation mechanisms and can

vary significantly by cookstove design, fuel type, operating conditions and combustion environment [14]. In previous studies, fuel properties such as moisture content [15], ash content [3], fuel type and N content [16,17] were found to correlate with the formation of CO and NO. More importantly, other factors such as combustion temperatures, air to fuel ratio, and burn rate [18–22], are also associated with CO and NO formation. Transients in the cookstove can occur at different time scales, affecting the formation of CO and NO. Some of these transients are associated with the feed rate of the fuel while others are associated with the batch nature of the cookstove [18–20,23]. Transients in combustion conditions are important because they affect the formation of CO and NO, in turn causing major fluctuations in emissions rates [3,18–20]. The transient nature of emissions rates due to varying operating conditions can lead to challenges in the control of CO and NO emissions from cookstoves.

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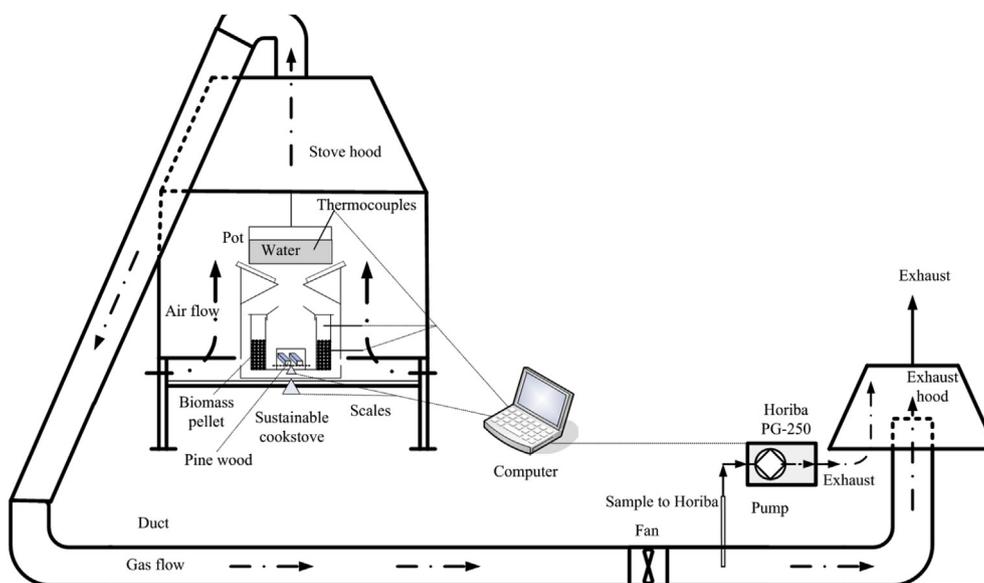


Fig. 1. Schematic of cookstove setup and gaseous sampling system.

A wide variety of improved cookstoves have been developed [3,24–26], including indirect pyrolysis cookstoves, also known as two chamber cookstove [16,27]. Indirect pyrolysis cookstoves are designed to produce combustion gases and heat for cooking in two separate chambers. Heat produced from wood burning in the combustion chamber is transferred to a separate batch of fuel in a pyrolysis chamber. As the fuel pyrolyzes, combustible gases evolve and flow into the combustion chamber, where they are further oxidized to produce cooking heat. The stove also produces a solid carbonaceous material in the pyrolysis chamber; this material can be used as fuel for other combustion devices, or as a soil amendment known as biochar [28].

The operating conditions in an indirect pyrolysis cookstove change over time, with the heating up of the stove and water, the progress of the pyrolysis, and other factors [16]. Little is known about how these changing operating conditions affect the production of CO and NO. It is worthwhile to investigate the variation of stove outputs with time and the relationship of stove outputs to time-dependent operating parameters. Therefore time-resolved measurements also referred to as short-term averages are essential to capture the dependence of stove performance on operating parameters. The variation of these conditions is highly significant in a stove operating with a batch or semi-batch fuel feeding. Also, short-term average measurements are important for assessing human exposure to pollutants [29].

The purpose of this study was to quantify C and N emissions rates and the rate of heat transfer to water under varying operating parameters and to identify the key parameters influencing stove output through multivariate regression analysis. We hypothesized that emissions rate and water heating rate should be proportional to fuel consumption rate. We then sought to identify additional factors of importance, expecting the following to be significant: (a) fuel bound N content will result in a higher NO emissions rate; (b) fuel to air ratio and combustion quenching will be the primary drivers for the production of CO; and (c) the rate of heat transfer to water will depend on the water and gas temperatures.

2. Materials and methods

2.1. Cookstove and fuel description

The cookstove used in the study is a modification of the anila type pyrolysis cookstove first developed by U.N. Ravikumar from the Center for Appropriate Rural Technologies (CART) in India. Our earlier work

[16], gives a brief description of the indirect pyrolysis cookstove used in this study. Additional images (Supplementary Figs. S1–2) and description of the operation of the cookstove is given in Supplementary Section 2.1.

The instantaneous performance data set includes results for three different types of fuel; two brands of wood pellets (Instant Heat, Instantheat Wood Pellets Inc., Addison, NY) and (Dry Creek, Biomaxx Inc., Pittsford, NY), corn stover pellets and switchgrass pellets [16]. The pyrolysis fuels provided a range of N and ash content representative of potential solid fuels available to users of the cookstove. All pyrolysis fuels were in the form of pellets (15.8 mm L x 6.4 mm D) to improve experimental repeatability and exclude fuel size as a variable affecting cookstove performance. Pinewood dowels, which have low N content, were used as the combustion fuel (120 mm L x 15 mm W). After each test, the remaining carbonaceous residue from combustion (referred as charcoal) and pyrolysis (referred as biochar) was collected, subsampled and stored for further analysis.

Solid fuel, charcoal, and biochar heating values were measured by bomb calorimetry using ASTM Standard Method D5865-13 [30] and ASTM E711 – 87 (2004) [31] on a Parr model 6200 (Parr Instrument Company, USA) calorimeter. Calculations were done using the lower heating value of fuel, biochar, and charcoal. Elemental composition of all materials was performed by dry combustion (NC2500, Carlo Erba, Italy) coupled to a Thermo Scientific Delta V IRMS, Germany). Supplementary Table S1, lists the moisture content of the fuels used in this study. Supplementary Table S2 and Supplementary Material in Deng et al. [16] list the heating value and elemental composition of all fuels, charcoal, and biochar.

2.2. Sampling system and gaseous emissions monitoring

The sampling and gaseous emissions monitoring system details are described in Deng et al. [16]. Briefly, the gaseous emissions were captured using the “hood method” [3,32]. The sampling system shown in Fig. 1, consists of a hood attached to air ducts which draw room air through the hood and duct system, using an induced draft fan. Adjusting the speed of the fan controlled the extraction rate of the system. In order to determine the air mass flow rate through the extraction system, we injected a known flow rate of CO₂ into the duct and measured the final well-mixed CO₂ concentration. We used a probe to sample gases in the fully-developed flow region downstream of the duct inlet.

2.3. Test protocol

Various testing protocols have been developed to evaluate and compare cookstove performance under controlled conditions. Among them, the water boiling test (WBT) [33] has been the most widely accepted as the standard. The WBT is a simplified version of the cooking process. The purpose of the test is to measure the efficiency with which a cookstove can deliver heat to a pot of water and measure the gaseous and particulate emissions produced during the test. The WBT consists of three phases that aim to simulate the various stages of cooking. Each stage affects the production of emission and heat differently. The WBT and other tests such as the Stove Manufacturers Emissions and Performance Test Protocol (EPTP) [34] are well suited to test cookstoves used for continuous combustion conditions [35–37]. However, difficulties arise when using the WBT or EPTP for batch and mixed feed stoves, including pyrolysis stoves [38]. Therefore, for this study, the WBT was modified based on the observed burn cycle for pyrolysis cookstoves, to capture all emissions during stove operation. The complete details of the cookstove test protocol and the modifications to the WBT are described by Deng et al. [16].

2.4. Calculations and data analysis

2.4.1. Time-resolved stove outputs and models describing them

Table 1 lists quantities measured at 1-s intervals during the modified water boiling test. The raw data for combustion and pyrolysis fuel masses (Supplementary Fig. S3) and other measured variables (Table 1) was processed, as described below and in Supplementary Section 2.2.1 to obtain short-term averages of stove outputs, operating parameters (Table 2), and to develop multivariate linear models for the key stove outputs.

Three key stove outputs were selected as dependent variables: emission rates for CO and NO (undesired stove outputs), and the rate of heat flow to the water, \dot{Q}_w (desired stove output) (Table 2). CO, and NO emission rates represent the source terms for gaseous household air pollution or for greenhouse gas emissions. \dot{Q}_w is the rate of heat flow to the water (kW), also known as the useful firepower of the stove [34] and calculated as:

$$\dot{Q}_w = C_{pw} * m_w * \dot{T}_w$$

where C_{pw} is the specific heat of water ($\text{kJ kg}^{-1} \text{K}^{-1}$), m_w is the mass of the water (kg) and \dot{T}_w is the rate of water temperature increase (K s^{-1}). This calculation neglects heat loss from the water and water evaporation, thus assuming that all heat entering the water goes into raising its temperature.

These key stove outputs are influenced by stove operating conditions, which can be described using the independent variables given in Table 2, such as rate of pyrolysis fuel consumption, rate of combustion fuel consumption, pyrolysis temperature, the temperature of the water in the pot, and mass fraction of N in fuel. Plots (Supplementary Fig. S5) showing the behavior of each of the independent variables considered are presented in the Supplementary Material Section 2.2.1.

Table 1

Quantities measured directly, at 1-s intervals during the burn cycle.

Variable measured	Description	Units
m_w	combined mass of the combustion wood, its char, and grate that they rest on	g s^{-1}
m_s	mass of the stove and its contents, including m_w , but not including the pot suspended above	kg s^{-1}
T_w	temperature of water in pot	$^{\circ}\text{C}$
T_1	temperature of the pyrolysis fuel bed	$^{\circ}\text{C}$ dimensionless
X_{CO}	mole fraction CO measured in a well-mixed portion of the exhaust duct	dimensionless
X_{CO_2}	mole fraction CO_2 measured in a well-mixed portion of the exhaust duct	dimensionless
X_{NO}	mole fraction NO measured in a well-mixed portion of the exhaust duct.	

Table 2

Independent variables (representing stove operating conditions) and dependent variables (representing key stove outputs) in the stepwise regression models.

Variable	Description	Units
Dependent variables		
\dot{m}_{CO}	Carbon monoxide emissions rate	mg s^{-1}
\dot{m}_{NO}	Nitric oxide emissions rate	mg s^{-1}
\dot{Q}_w	Rate of heat input to the water	kJ s^{-1}
Independent variables considered		
\dot{m}_w	Combustion fuel consumption rate	g s^{-1}
\dot{m}_{py}	Rate of pyrolysis fuel consumption	g s^{-1}
\dot{m}_{py}^2	Rate of pyrolysis fuel consumption squared	$\text{g}^2 (\text{s}^2)^{-1}$
f_{py} ^a	Fraction of pyrolysis completed	dimensionless
T_1	Temperature of the pyrolysis fuel	$^{\circ}\text{C}$
T_w	Temperature of the water in the pot	$^{\circ}\text{C}$
X_n	Mass fraction N in the pyrolysis fuel	dimensionless
$\dot{m}_{py} * X_n$	Rate of nitrogen release from pyrolysis fuel	g s^{-1}

^a Equation defined in section 2.1.1 of the Supplementary Material.

2.4.2. Statistical analysis

A multivariate linear regression describing the relationships among each dependent variable and the relevant independent variables was developed as follows. Stepwise regression was performed using JMP version 12.0.1 [39] to select the most significant of the independent variables for inclusion in multivariate linear models. P-value thresholds of 0.1 were used to allow an independent variable to enter the model, while 0.01 was used to remove an independent variable from the model. A mixed stopping rule was applied to allow the alternation of forward and backward steps. This process allows the most significant terms to enter the model and the least significant terms to leave. The variance inflation factor (VIF), is used to detect any collinearity between the predictor variables. If the VIF was less than 10, the variables are considered to be uncorrelated.

3. Results and discussion

3.1. Qualitative description of stove operating conditions

The stove behavior develops over the course of three phases (Fig. 2), each corresponding to the heating of one pot of water from room temperature to 100 $^{\circ}\text{C}$. In Phase I of the test (pre- and early pyrolysis), a cold pot of water is placed on the cookstove, and the wood fire is initiated in the combustion chamber. During this phase, the stove heats up (Supplementary Fig. S5). Significant mass loss of pyrolysis fuel occurs in the second half of the phase. Emissions are relatively low, and they increase at the onset of devolatilization (Fig. 2). During Phase II (main pyrolysis), the cookstove is already hot. Devolatilization of pyrolysis fuel is the dominant process at this stage, accompanied by high

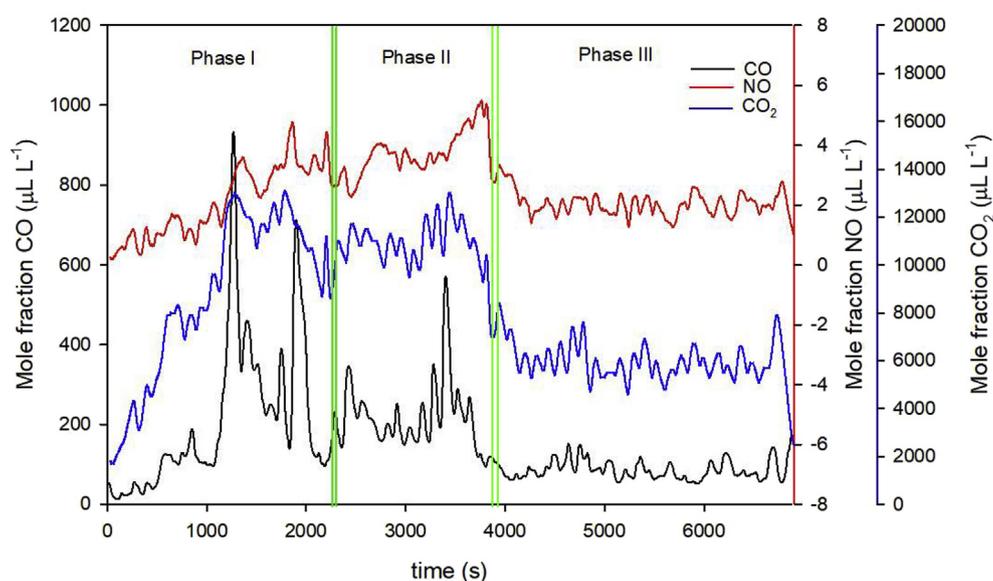


Fig. 2. Real time gas pollutant emissions concentration for CO, NO and CO₂ (µL L⁻¹) for wood pellets pyrolyzed in an indirect pyrolysis cookstove. Green vertical lines represent the times at which new pots of cooking water were placed over the cookstove. These lines can be interpreted as separating the cooking test into three phases of pyrolysis. Phase I is pre and early pyrolysis; Phase II is main pyrolysis; Phase III is late pyrolysis.

exhaust mole fractions for all measured species (Fig. 2). In Phase III (post-pyrolysis), devolatilization of pyrolysis fuel is almost complete (Supplementary Fig. S5). Thus, the combustion fuel is the primary source of heat and emissions. Emissions drop considerably compared to the previous stage but are still somewhat higher than at the beginning of the test. The rate of heat input to the water differs in the different phases of pyrolysis. The rate of change in the water temperature is highest during the peak fuel devolatilization periods (Supplementary Fig. S5). The water heating rate is lowest during phase three, as pyrolysis reactions cease or decrease and wood combustion becomes the main heating source.

3.2. Models of key stove outputs as functions of operating parameters

Some qualitative trends of variables such as pyrolysis fuel consumption are shown by the plots of stove outputs (Fig. 3) and operating parameters vs. time (Supplementary Fig. S4). Multivariate linear models relating short-term average stove outputs to operating parameters averaged over the same time periods provide a more quantitative description of the relationship between stove outputs and operating conditions. If stove operating conditions were not relevant, we would expect each of the three key stove outputs to be simply proportional to the rate of consumption of fuel (Tables 3 and 4). In other words, a certain amount CO and NO will be produced, and a certain amount of heat would be transferred into the water, whenever a given mass of fuel is consumed. In this case, the multivariate linear model would identify only \dot{m}_w and \dot{m}_{py} as significant variables. Instead, different or additional operating parameters are identified as important in predicting each of the key stove outputs. These findings are discussed in the sections below.

3.2.1. Effects of operating parameters on CO emissions rate

The measured CO emission rates between 1.0 and 61 mg s⁻¹ (Fig. 3c) with an average of 8.9 mg s⁻¹ were consistent with CO emission rates obtained for various char producing cookstoves (1–300 mg s⁻¹) [19]. Stove operating conditions are expected to affect CO emissions in two ways. Flame quenching in low-temperature zones and insufficient oxygen due to inadequate airflow or poor mixing can hamper the conversion of CO to CO₂, and thus lead to CO emissions to the environment [40]. Thus variables associated with flame quenching or insufficient oxygen are expected to appear as significant independent variables in the multivariate model. If, on the other hand, operating parameters were not relevant, then the CO emissions rate (\dot{m}_{CO}) would

be linearly proportional to the rate of combustion fuel consumption and rate of pyrolysis fuel consumption (\dot{m}_w and \dot{m}_{py}), with no other significant independent variables.

The model indicates that the CO emissions rate (\dot{m}_{CO}) is most closely related to the squared rate of pyrolysis fuel consumption, \dot{m}_{py}^2 (Table 3). This variable explains 70% of the variance in the model for the CO production rate. The sequential inclusion of the rate of combustion fuel consumption (\dot{m}_w) and the rate of N released from the pyrolysis fuel ($\dot{m}_{py} * X_n$) accounted for only an additional 3.0% and 0.5% of the model variance, respectively.

The dependence on the rate of pyrolysis fuel consumption squared, \dot{m}_{py}^2 rather than on the rate of pyrolysis fuel consumption, indicates that the CO production is disproportionately high during high pyrolysis-fuel mass loss periods. This finding is consistent with the oxygen-starvation mechanism for CO emissions. At times of greatest pyrolysis fuel mass loss rate, it appears that the natural draft airflow is insufficient to complete combustion converting CO to CO₂. Thus a large fraction of C remains as CO rather than being converted to CO₂ during those times. Interestingly, the second possible influence of operating conditions on CO production was not borne out by the variables selected in the model. We hypothesized that CO emission production rates would be influenced by thermal quenching of combustion before the CO is converted to CO₂. If this process were important for the pyrolysis cookstove, the model would show the water temperature T_w as an important variable, because quenching would be stronger when the water temperature was low (immediately after the pot had been changed). As T_w was not selected as an influential variable, this possible mechanism of CO production appears to be relatively unimportant for the pyrolysis cookstove.

3.2.2. Effect of operating parameters and fuel characteristics on NO emissions rate

The NO emission rates were lower for fuels with low N content (0.006–0.32 mg s⁻¹) than for fuels high N content (0.008–2.16 mg s⁻¹), i.e., corn and switchgrass (Fig. 3b). This difference is consistent with the finding of previous cookstove studies considering NO [16,17,22,38,41,42].

NO is known to be formed by several combustion-related processes, mainly (1) conversion of fuel-bound N compounds, and (2) reactions involving N₂ and O₂ from the air, occurring most rapidly at very high temperatures and fuel-lean conditions. The fuel-bound N mechanism is dominant for most solid fuels but is influenced by temperature and fuel and air mixing [43]. Thus it was anticipated that variables related to

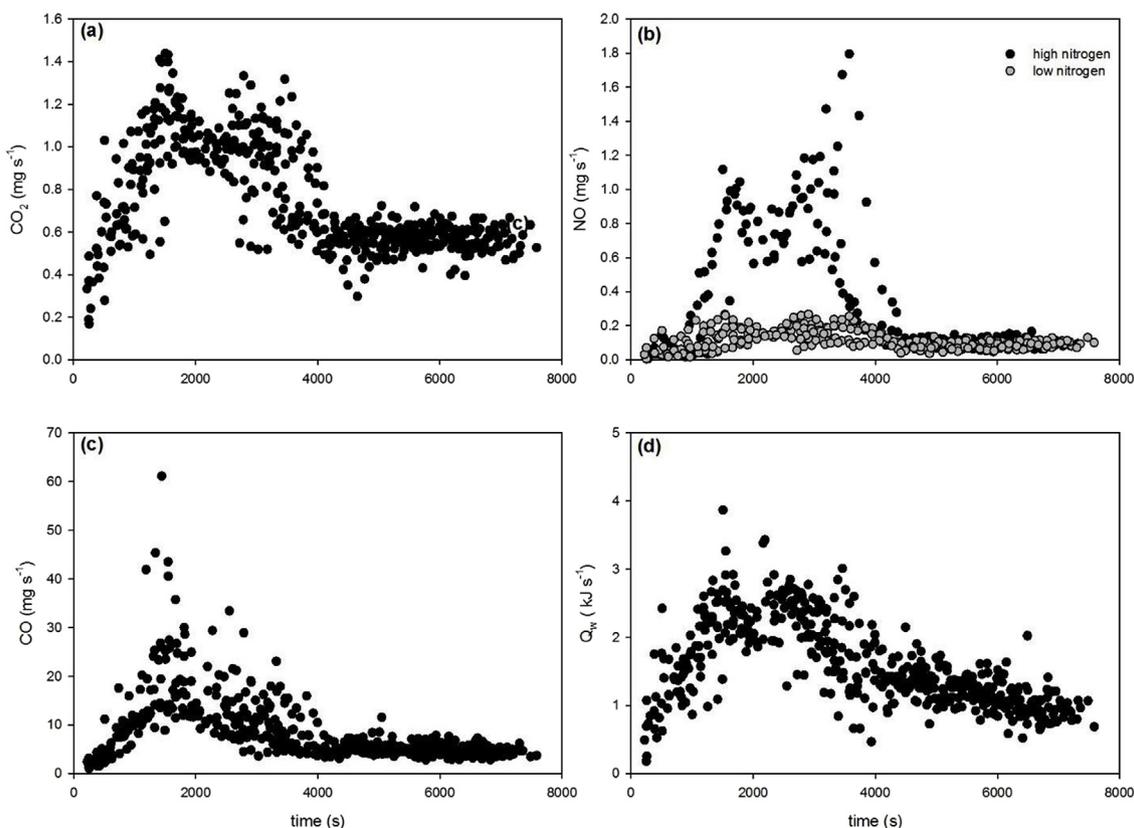


Fig. 3. Short-term average for gaseous emission rates and heat input to water. The quantity of each gaseous emissions as a function of time for (a) CO₂, (b) NO and (c) CO and (d) the heat input to cooking water (\dot{Q}_w). Each point (n = 485) represents a short-term average determined from data from eleven water boiling tests. Grey circles and black circles in (b) represent low N content woody biomass and high N content of the biomass (corn and switchgrass).

fuel N content and fuel-to-air ratio and flame temperature would be identified as significant.

By far the largest portion of the variance of \dot{m}_{NO} (73.96%) is explained by the rate of N release from the pyrolysis fuel ($\dot{m}_{py} * X_n$). Pyrolysis temperature, T_1 accounts for (4.3%) of the variance, and \dot{m}_{py} by itself makes only a small contribution (0.43%) to the model (Table 4) beyond the contribution to ($\dot{m}_{py} * X_n$). The positive dependence of \dot{m}_{NO} on pyrolysis temperature (T_1) also suggests that the N release from the pyrolysis fuel is not uniform, and that it is favored by higher-temperature conditions.

Interestingly the degree to which the pyrolysis is completed (f_{py}) was not important in predicting NO production. Completion of pyrolysis was expected to be important in NO production because different N-containing species are released during different parts of the pyrolysis process [43,44]. If this effect occurs, it appears that pyrolysis temperature (T_1) is a better predictor of it than the degree of completion of

pyrolysis is.

3.2.3. Effects of operating parameters on the rate of heat input to the water

The heat input rate to the water (useful firepower) ranged from 0.18 to 3.86 kW, with an average of 1.58 kW. Other studies [24], have reported similar findings for char producing cookstoves. However, there is a quite a significant variation in the rate of heat input to the water during the entire WBT (Fig. 3d). The highest heat input rate occurs during the end of Phase I and Phase II (main pyrolysis) of the stove operation.

The sources of the heat input to the water are the combustion of wood and pyrolysis gases. Thus, if operating conditions were not relevant, we would find that rate of heating the water (\dot{Q}_w) would be proportional to the rates of consumption of combustion fuel and pyrolysis fuel (\dot{m}_w and \dot{m}_{py}) with no other significant independent variables. This simple relationship is reflected in the definition of cookstove

Table 3

Stepwise regression input variables, resulting predictor variables and coefficient of determination. The predictor variables are listed in decreasing order of importance.

Input variables	\dot{m}_{CO}		\dot{m}_{NO}			\dot{Q}_w		R^2	
	Predictor variables	R^2	Input variables	Predictor variables	R^2	Input variables	Predictor variables		
	\dot{m}_{py}^2	73.48	\dot{m}_w	$\dot{m}_{py} * X_n$	78.69	\dot{m}_w	\dot{m}_{py}	76.68	
	\dot{m}_w		\dot{m}_{py}	T_1		\dot{m}_{py}	T_w		T_1
	$\dot{m}_{py} * X_n$		f_{py}	T_1		f_{py}	\dot{m}_w		T_1
			T_w			T_w			
			X_N			X_N			
			$\dot{m}_{py} * X_N$			$\dot{m}_{py} * X_N$			

Table 4
Stepwise regression coefficients and collinearity statistics of regression models.

Dependent variables	Predictors	Coefficient Estimate	Standard error	t statistic	Standardized coefficients	VIF
\dot{m}_{CO}	Intercept	-6.10E-04	8.24E-04	-0.74	0.00	
	\dot{m}_{py}^2	5.69E-02	1.82E-03	31.30	0.94	1.63
	\dot{m}_w	18.65	2.64	7.13	0.17	1.09
	$\dot{m}_{py} * X_n$	-2.58	0.85	-3.03	-0.09	1.59
\dot{m}_{NO}	Intercept	-1.22E-04	2.13E-05	-5.74	0.00	
	$\dot{m}_{py} * X_n$	1.02	0.03	31.97	0.88	1.71
	T_1	5.44E-07	5.29E-08	10.28	0.23	1.16
	\dot{m}_{py}	0.12	0.04	3.15	0.09	1.74
\dot{Q}_w	Intercept	0.01	2.36E-03	6.21	0.00	
	\dot{m}_{py}	66.59	1.83	36.34	0.98	1.47
	T_w	-1.56E-04	1.51E-05	-10.32	-0.26	1.23
	T_1	3.13E-05	3.27E-06	9.57	0.27	1.57
	\dot{m}_w	29.72	5.51	5.39	0.14	1.27

efficiency. Variation in operating conditions might affect the rate of heat transfer into the pot through competing processes (e.g., heating up of the stove) or through changes in gas flows and temperatures that would affect the heat transfer coefficient. In other studies, gas temperature, mass flow rate and firepower are specific variables that influence the heat input to the water [45].

In our model, the rate of pyrolysis fuel consumption (\dot{m}_{py}) has a strong positive correlation and greatest effect on the heat input rate to the water (Table 4). It accounts for 69% of the variance in the model. The water temperature, T_w has a relatively strong negative relationship (-0.26) with \dot{Q}_w and explains an additional 3% of the variance. Pyrolysis temperature, T_1 and \dot{m}_w also have a positive correlation with the heat input rate to water, however, T_1 has a stronger influence over \dot{Q}_w than \dot{m}_w . The stepwise regression model developed in our study explains 77% of the variation in \dot{Q}_w (Tables 3 and 4). The degree to which the pyrolysis was completed (f_{py}), was also expected to appear in the model for water heating rate, because heat transfer into the pyrolysis chamber competes with heating of water. The presence of the closely related variable T_1 may explain the fact that f_{py} was not selected.

The rate of pyrolysis fuel consumption is the most influential parameter in our model; as the rate of pyrolysis, fuel consumption increases the heat input to the water increases. As mentioned above, this finding makes sense because as pyrolysis fuel consumption is the main source of the heat output. On the other hand, the contribution of heat input to the water from the mass flow rate of combustion fuel is relatively small in comparison to that of the pyrolysis fuel, because combustion fuel is fed at regular time intervals and thus little variation in this variable is present in the dataset.

Pyrolysis fuel temperature and water temperature played a major role in determining the rate of heat output from the stove. The pyrolysis fuel temperature may appear in this model because it is strongly related to the thermal energy stored in the stove. At the start of the test, a significant fraction of the fuel's heat release is used to heat the stove, i.e., to increase the thermal energy stored in the stove. Once the stove is hot, this undesired use of the heat release is no longer active and does not compete with heat transfer to the pot. The positive relationship between \dot{Q}_w and T_1 may represent this transition. In addition, the water temperature (T_w) also affected the heat input rate to the water. As the water temperature increased, the rate of heat input decreased. The heat transfer rate (for pure convection) is expected to be linearly proportional to the difference between gas temperature and pot temperature. Thus, as the water temperature increases the heat transfer rate should get smaller, which is reflected in our observations.

4. Conclusions

Indirect pyrolysis cookstoves represent an alternative to traditional solid fuel open fires. Not only do they offer the versatility of being able to use a wide variety of fuels but also can be used in various modes of

operation. It is important to understand the mechanisms that are responsible for desirable and undesirable stove outputs in order to make useful improvements to stove design and use. In this study, we found empirical associations between thermal, chemical and physical operating parameters of an indirect pyrolysis cookstove and the production of selected gaseous emissions and useful heat.

Keeping only the most important single variable in each model, we obtain a simple description of the stove's operation, one that accounts for over seventy percent of the variation of each output variable. According to this simple description, the water heating rate is proportional to the pyrolysis fuel consumption rate, implying that we must use a certain amount of pyrolysis fuel to perform a given heating task with this stove. The amounts of NO and CO produced depend on how the heating is accomplished when a given amount of pyrolysis fuel is used. NO production is proportional to the product of the mass fraction N in the pyrolysis fuel and the rate of pyrolysis fuel consumption, indicating that the amount of NO produced in a given cooking task depends on the choice of fuel. For CO, the rate of pyrolysis fuel consumption appears in the model multiplied by itself, indicating that the amount of CO produced in a given cooking task depends on the rate of pyrolysis, (i.e., on the speed of cooking).

These simple descriptions imply two important tradeoffs for emissions. First, the NO emissions model indicates clearly that high nitrogen content in fuels, typical of waste biomass, is associated with high NO emissions for a given cooking task. Though indirect pyrolysis cookstoves have the versatility of being able to operate with waste fuels in the pyrolysis chamber, they produce more NO when waste fuels are used. Second, the model for CO emissions indicates that rapid cooking is associated with high CO emissions for a given cooking task. There is a tradeoff between avoiding CO emissions and accomplishing a cooking task quickly. On the other hand, using waste biomass, or cooking rapidly, does not seem to impact the quantity of fuel used for a given cooking task; the tradeoffs are associated only with emissions.

The emissions models have implications for the design and operation of future stoves. Stove design changes that reduce the rate of pyrolysis fuel consumption or increase the airflow rate are likely to reduce CO emission rates. For example, increasing the height of the stove or the internal gas temperature by insulating the stove or its chimney if applicable, can improve airflow by increasing the driving force of natural convection. Reducing the rate of pyrolysis fuel consumption may be achievable through changes in the geometry of the pyrolysis chamber. Fuel choice, rather than stove design, seems to be the main determinant of NO emissions.

As for the stove's heat output, it is essentially proportional to pyrolysis fuel usage for the particular stove tested. A different stove design could achieve a different constant of proportionality between these two quantities by improving heat transfer from the hot gases to the cooking pot. For example, surrounding the pot with a sleeve will increase heat

transfer by directing hot gases along the sides of the cooking pot. Also, optimizing the choice of spacing between the stove and pot can increase the heat transfer to the water by changing the gas flow characteristics and temperatures. Such design changes would improve efficiency.

Most users desire cookstoves that cook quickly and efficiently, with as little fuel expense as possible. On the other hand, the primary goal of the research community is to reduce emissions, improving household indoor air and reducing environmental pollution. Our investigation indicates tradeoffs among the various desired cookstove characteristics. However, it also points to the possibility of addressing some of those tradeoffs through design improvements.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.biombioe.2019.105279>.

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