Supplementary Material

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

Dorisel Torres-Rojas[a], Lei Deng[b], Lauren Shannon[c], Elizabeth M. Fisher[c,e*], Stephen Joseph[d], Johannes Lehmann[a,e]

[a] Soil and Crop Sciences, Cornell University, Ithaca, New York 14853

[b] State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

[c] Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA

[c] University of New South Wales, NSW 2052, Australia

[e] Atkinson Center for a Sustainable Future, Cornell University, Ithaca, New York 14853

1. Fuel properties of solid biomass fuels, biochar, and charcoal

The moisture content of solid biomass fuels and elemental composition and heating value of solid biomass fuels, biochar (the charred residue in the pyrolysis chamber) and wood charcoal (the charred residue in the combustion chamber) are listed in Table S1 and Table S2. Biochar samples from pellets of hardwood (Instant Heat and Dry Creek brand) and switchgrass are denoted as BIHWP, BDCWP, and BSGP. The analyses of elemental composition were performed on an NC2500 (Carlo Erba, Italy) elemental analyzer coupled to a Thermo Scientific Delta V IRMS (Germany), and the analyses of higher heating value are performed on a Parr Model 6200 (Parr Instrument Company, USA) calorimeter.

Table S1. Moisture content of pyrolysis and combustion biomass fuels at the time of individual stove tests. See Deng et al., [1] for moisture data from additional tests.

Sample name	Note	Moisture (%, as received basis)
Instant Heat Wood Pellet		
IHWP1	Pyrolysis fuel	4.80
Pine Wood	Combustion fuel	9.57
IHWP2	Pyrolysis fuel	4.90
Pine Wood	Combustion fuel	9.62
IHWP3	Pyrolysis fuel	5.09
Pine Wood	Combustion fuel	9.85
Dry Creek Wood Pellet		
DCWP1	Pyrolysis fuel	6.24
Pine Wood	Combustion fuel	10.29
DCWP2	Pyrolysis fuel	6.24
Pine Wood	Combustion fuel	11.11
DCWP3	Pyrolysis fuel	6.22
Pine Wood	Combustion fuel	9.83
DCWP4	Pyrolysis fuel	6.27
Pine Wood	Combustion fuel	10.55
Switchgrass Pellet		
SGP1	Pyrolysis fuel	7.60
Pine Wood	Combustion fuel	9.29
SGP2	Pyrolysis fuel	7.47
Pine Wood	Combustion fuel	10.98
SPG3	Pyrolysis fuel	8.17

Pine Wood	Combustion fuel	10.94
SPG4	Pyrolysis fuel	8.21
Pine Wood	Combustion fuel	9.98
SGP5	Pyrolysis fuel	9.16
Pine Wood	Combustion fuel	9.98

Table S2. Elemental composition and higher and lower heating values (HHV, LHV) of triplicate samples of biomass fuel, biochar and wood charcoal (n=3) Each row of biochar properties represents a separate stove test. Each row of wood properties represents a different batch of wood, used in several stove tests. Fuel, wood charcoal and biochar properties for additional stove tests appear in Deng et al., [1].

Sample name	**Elemental composition (%, dry basis)**				**Heating values (kJ kg^{-1}, dry basis)**	
	C (%)	**N (%)**	**H (%)**	**O (%)**	**HHV**	**LHV**
Pyrolysis fuel						
IHWP	54.57	0.11	6.48	44.61	18865	17491
st dev	0.93	0.00	0.16	1.30	N/A	
Combustion fuel						
Wood	57.64	0.07	6.19	42.13	19550	18237
st dev	1.13	0.00	0.19	1.30	241	
Wood1	56.15	0.04	6.19	45.27	19036	17722
st dev	0.74	0.00	0.06	0.47	174	
Wood2	56.57	0.04	6.09	44.44	19366	18074
st dev	0.59	0.00	0.07	0.64	368	
Wood3	55.60	0.04	6.09	44.44	19270	17979
st dev	0.53	0.00	0.11	0.84	224	
Biochar for Instant heat wood pellet						
IHWP1	77.93	0.27	3.86	20.18	28317	27498
st dev	1.23	0.00	0.40	0.79	22	
IHWP2	79.26	0.25	3.56	18.49	28416	27660
st dev	0.55	0.00	0.16	0.97	234	
IHWP3	79.21	0.24	3.61	19.51	28233	27468
st dev	0.37	0.00	0.12	2.19	71	
Biochar for Dry Creek wood pellet						
BDCWP1	82.57	0.34	3.31	15.94	29339	28636
st dev	1.66	0.00	0.08	1.03	99	
BDCWP2	83.16	0.32	3.38	16.19	29170	28453
st de	0.95	0.01	0.17	2.01	64	
BDCWP3	83.95	0.34	3.33	16.12	29460	28754

st dev	0.56	0.01	0.06	1.30	250	
BDCWP4	83.22	0.33	3.27	15.16	29506	28812
st dev	0.79	0.01	0.36	1.51	409	
Biochar for Switchgrass pellet						
BSGP4	73.01	2.04	3.35	17.43	26426	25716
st dev	0.85	0.03	0.19	0.51	6	
BSGP5	72.50	2.04	3.39	17.77	26191	25472
st dev	1.61	0.03	0.14	0.90	139	
Wood Charcoal	89.28	0.08	1.36	6.44	30556	30268
st dev	1.07	0.01	0.05	0.22	163	

[1]Standard deviation.

2. Materials and methods

2.1. Stove description and pictures

The cookstove used in this study is an indirect pyrolysis cookstove. This stove differs from traditional cookstoves because it serves a dual purpose, cooking with biomass energy and producing biochar. It is composed of three main parts (Figure S1); (A) pyrolysis chamber, (B) pyrolysis chamber lid and (C) outer shell (Supplementary Figure S1). The pyrolysis chamber (A) is composed of two concentric cylindrical walls traversed by a wood feed. The region between the walls is the pyrolysis zone, while the central region, inside the inner wall, is the combustion zone. Solid biomass fuel is placed in the pyrolysis zone and heated indirectly by conduction [2] of heat produced in the combustion zone. The pyrolysis chamber lid (B), is placed over the pyrolysis chamber, covering the pyrolysis zone and leaving the combustion zone exposed. The lid creates a low-oxygen environment in the pyrolysis zone. During the initial heating of the solid biomass fuel , dehydration and devolatilization of low-molecular-weight components occur [2–4]. However, at heating temperatures above 250°C, the biomass begins to pyrolyze [2–4], leading to the production of larger quantities of combustible gasses. As biomass is devolatilized, hot gases flow into the combustion chamber through a gap between the pyrolysis lid and the combustion chamber. Hot gases are combusted when they come into contact with heated primary air in the combustion zone. The outer shell of the cookstove serves multiple purposes. The shell creates an air gap between the outer pyrolysis chamber wall and the cookstove users. Secondary air enters the stove through inlets on the bottom of the outer shell (Supplementary Figure S2) and is preheated as it sweeps along the outer wall of the pyrolysis chamber. The preheated secondary air contributes to the complete combustion of the biomass volatiles. Also, the outer shell is used to support cooking pots over the combustion chamber.

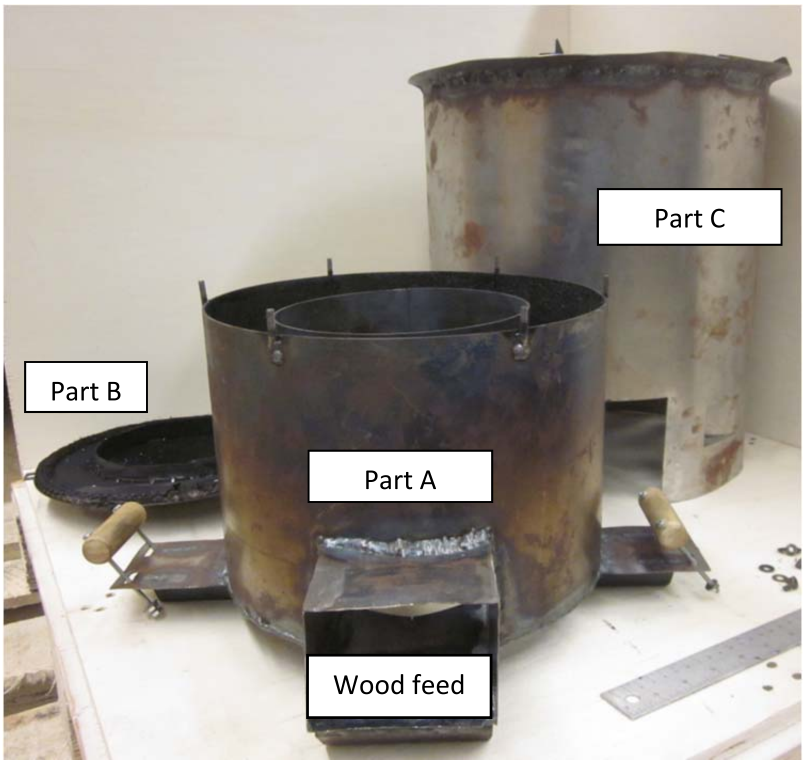


Figure S1. Main components of the pyrolysis cookstove

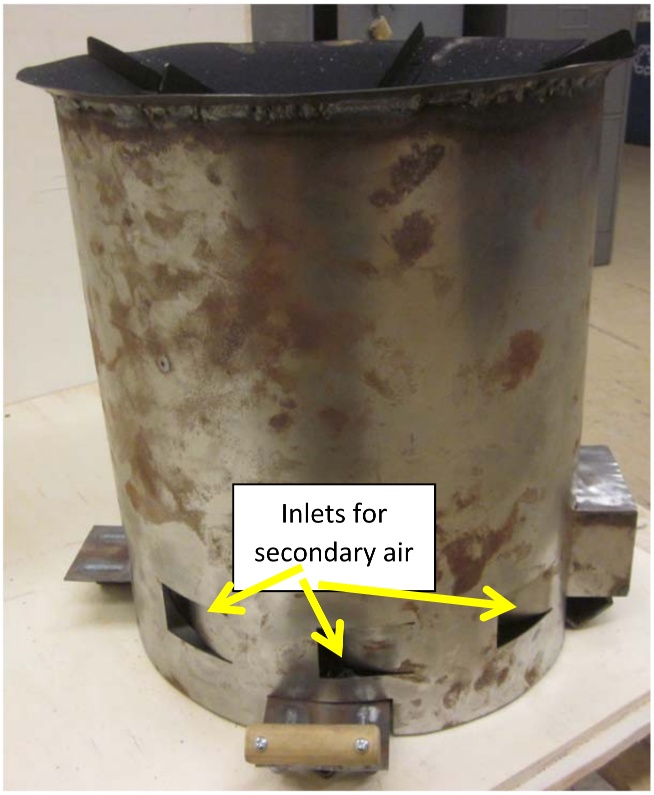
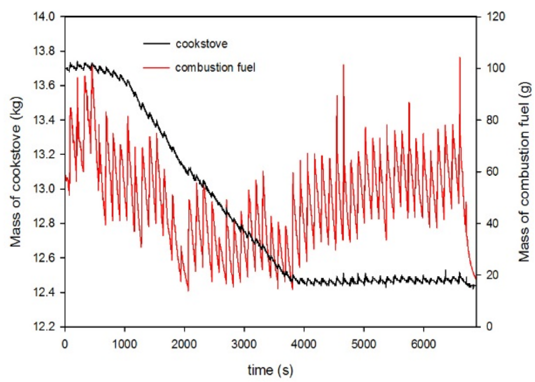


Figure S2. Secondary air inlets are bent in to induce swirl.

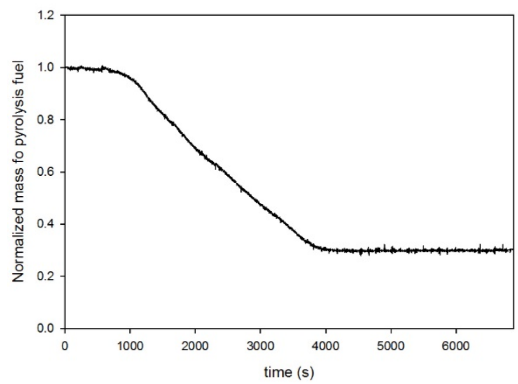
2.2. Calculations and data analysis

2.2.1. Data processing for instantaneous measurements and derived variables used in models

Raw measurements of masses vs. time appear in Figure S3a. The mass of combustion wood, biochar, and grate (m_w) vs time shows a sawtooth pattern, with (1) a rapid rise in mass, corresponding to the insertion of a new batch of wood, followed by (2) a slower decline in mass, corresponding to the combustion of the current batch of wood. The sawtooth width is 2-3 minutes, which is the time between wood feedings. The mass of the stove (m_s) shows random fluctuations comparable in magnitude to the sawtooth pattern (Figure S3a), due to the lower resolution on the scale used for that measurement. The mass of the contents of the pyrolysis chamber, m_{py}, was obtained from the combined mass of the wood, biochar and grate (m_w) and the mass of the stove (m_s) through the following steps. The limited resolution of the large scale used for mass of the wood, biochar and grate (m_w) dictated some aspects of the data processing. Specifically, as described below, it necessitated that time averaging be performed over the wood feed interval.



(a) Mass of combustion fuel and cookstove



(b) Normalized mass of pyrolysis fuel

Figure S3. Mass histories

The mass of the wood, biochar, and grate (m_w) measurements were used to identify the time periods during which wood feedings occurred, i.e. time periods when m_w increased. These brief time periods were discarded from further analysis because mass changes during these periods represent the indistinguishable effects of mass loss from chemical reaction and mass gain due to wood feeding. The time periods between wood feedings, where the mass of the wood, biochar and, grate (m_w) has a negative slope with respect to time, were selected for further processing. For each of these periods, a linear fit of mass of the wood, biochar and grate (m_w) vs time was used to determine the rate of combustion fuel consumption($\dot{m}_w$). For the same time periods, a linear fit of the total mass of the cookstove (m_s) vs time was performed. The rate of pyrolysis fuel consumption ($\dot{m}_{py}$) was determined for a given time period by subtracting the rate of combustion fuel consumption ($\dot{m}_w$) from the magnitude of the slope of the total mass of the cookstove (m_s) vs time. Temperatures and mass fractions were averaged, and a linear fit of the temperature of the water in the pot (T_w) with respect to time was performed, over the same time periods used in the processing of mass data. Each time period between wood feeds (approximately two minutes) thus made up a single data point, for which values of temperatures, fuel masses, and time derivatives of these quantities, were known.

Certain time periods were discarded from further analysis on the basis of quality measures. Specifically, R^2 for the linear fits was required to be no lower than 0.75. Any time periods in which the temperature of the water in the pot (T_w) had a negative slope were discarded, as these periods corresponded to the swapping of water pots. Any time periods in which the total mass of the cookstove (m_s) had a positive slope were discarded, as were time periods shorter than 50 seconds, as these periods generally corresponded to times when the stove had been bumped accidentally. After all these criteria were applied, 485 data points remained, each representing the average behavior of the system during the time between two successive wood feedings. Eleven separate water boiling tests were represented. The results are considered robust because they were found to be insensitive to slight changes of criteria for selecting and rejecting time periods.

Figure S4 shows the resulting measured quantities and derived variables for the cookstoves. These measurements were used in the models as independent variables to explain variability in selected performance indicators. The following plots include all the data points used to develop the models describing cookstove performance. The plots show the fuel consumption rate for the combustion fuel (a) and pyrolysis fuel (b). The rate of consumption of the combustion fuel shows very little variability when compared to the pyrolysis fuel; this is because the feeding rate of the combustion fuel was kept constant throughout the test. The non-linear variable for the pyrolysis fuel rate consumption is presented by plot (c). Plot (d) presents the rate of release of the N from the pyrolysis fuel. The higher values of $\dot{m}_{py} * X_n$, represent the fuel that had higher initial N content. Plot (e) represents the level of completeness of pyrolysis, f_{py}.This variable is defined as the fraction of the initial amount of pyrolysis fuel converted to biochar at a given time.

$$f_{py} = \frac{mass\ of\ pyrolysis\ fuel\ at\ time\ x - initial\ mass\ of\ pyrolysis\ fuel}{final\ mass\ of\ pyrolysis\ fuel - initial\ mass\ of\ pyrolysis\ fuel} \quad (8)$$

f_{py} approaches 1 when pyrolysis is complete. Plot (f) shows the water temperature for the three pots of water boiled.

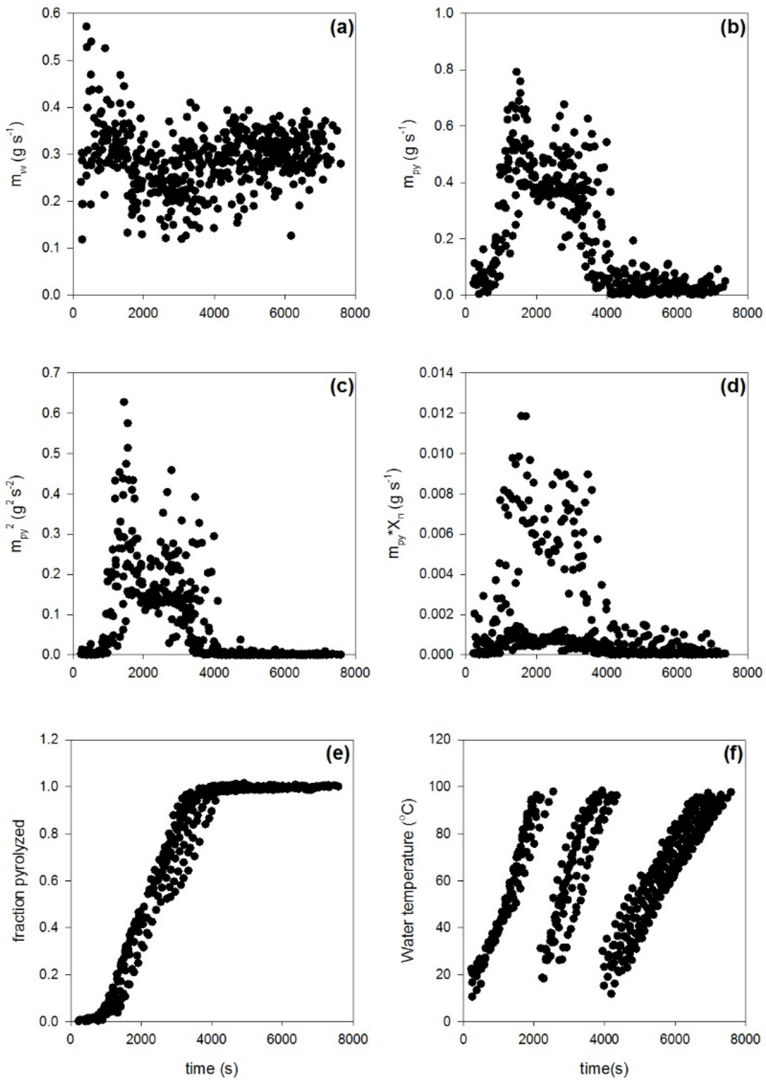


Figure S4**.** Instantaneous measurements of selected independent operating parameters

3. Results

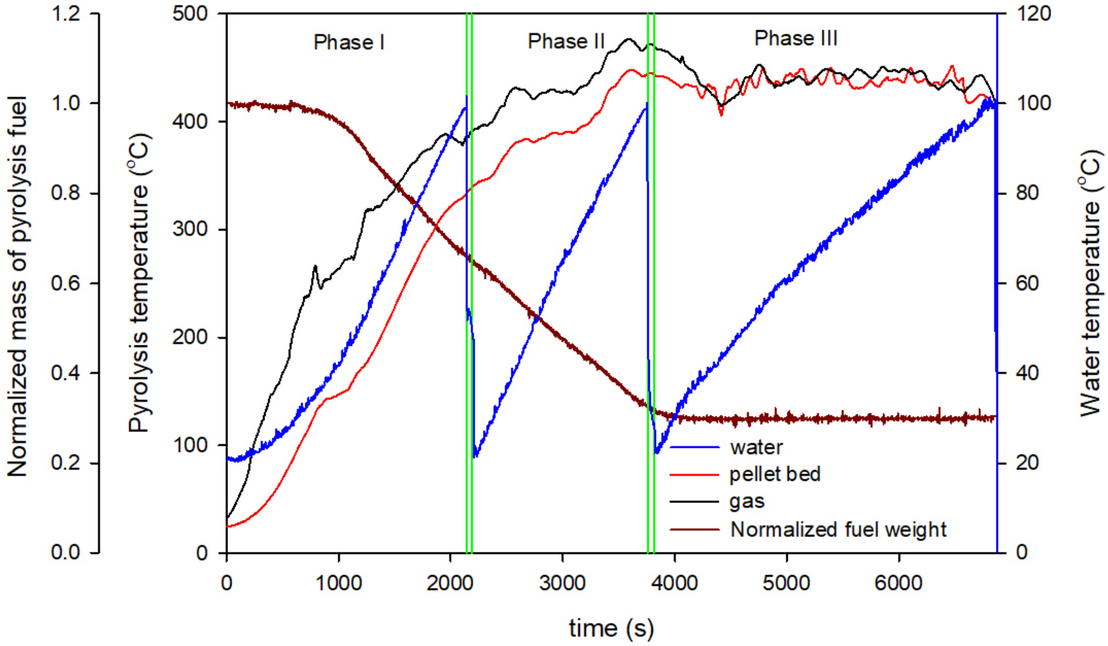


Figure S5**.** Pyrolysis and water temperatures for wood pellet

References

[1] Deng L, Torres-Rojas D, Burford M, Whitlow TH, Lehmann J, Fisher EM. Fuel sensitivity of biomass cookstove performance. Appl Energy 2018;215:13–20. doi:10.1016/j.apenergy.2018.01.091.

[2] Zaror CA, Pyle DL. The pyrolysis of biomass: A general review. Proc Indian Acad Sci Sect C Eng Sci 1982;5:269–85. doi:10.1007/BF02904582.

[3] Demirbas A. Combustion characteristics of different biomass fuels. Prog Energy Combust Sci 2004;30:219–30. doi:10.1016/j.pecs.2003.10.004.

[4] Shafizadeh F. Introduction to pyrolysis of biomass. J Anal Appl Pyrolysis 1982;3:283–305. doi:10.1016/0165-2370(82)80017-X.