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Influence of chimneys on combustion characteristics of buoyantly driven biomass stoves

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ABSTRACT

This work examines whether a chimney has influence over the combustion characteristics of biomass within a stove. Experimental work as well as a simplified chemical kinetic model suggests that a chimney plays an active role in the performance of a stove by influencing the overall air-to-fuel ratio and subsequently the production of carbon monoxide. Two different stoves, operated at multiple wood consumption rates, were shown to run with steady state excess air of 300 % — 1250 %. The wood consumption rate was found to be independent of the chimney draft for both stoves. Increasing draft was shown to increase excess air. Draft served to cool combustion gases through dilution with makeup air. Increasing excess air decreased modified combustion efficiency in experiments and kinetic modeling. Increasing the frictional loss coefficient of a chimney by decreasing the diameter was shown to reduce CO production through a reduction of excess air.

Introduction

Global problem

It is estimated that more than three billion people currently rely on biomass as their primary cooking fuel (Martin et al., 2011; Anenberg, 2012). The majority of these people burn biomass in traditional, inefficient cooking structures that produce dangerous indoor air environments, resulting in several million deaths per year (Bruce et al., 2013). For several decades, much effort has gone toward the design and dissemination of improved cookstoves (Smith et al., 1993). Still, only a small fraction of those in need have benefited from these international efforts. While a singular solution does not exist to solve the energy crisis in the developing world, the use of chimneys, flues, or hearths could be an important component in achieving substantial improvements in indoor air quality.

A seemingly simple solution

Within developed regions, nearly every solid fuel combustion system that operates within an indoor environment includes a ventilation system to transport combustion products outside of the user envelope (Smith, 1989). In underdeveloped regions this feature has been met with resistance. Many end-users prioritize stove cost and fuel savings over indoor air quality, and chimneys are sometimes perceived to add cost to a stove without saving fuel (Smith, 1989). Additionally, many poorly executed chimney stoves have led experts to hypothesize that chimney stoves introduce as many problems as they solve (Smith, 1989; Bruce et al.,). However, several stove intervention studies have linked the introduction of chimneys with reduced levels of carbon monoxide and/or particulate matter (Boy et al., 2002; Hartinger et al., 2013; McCracken et al., 2007) in some cases by up to 2/3 (Romieu et al., 2009).

The results presented herein suggest that the chimney of a natural convection driven stove has the ability to change several important operating parameters including the air-to-fuel ratio, the average gas temperature, and the rate of carbon monoxide production; a chimney is indeed capable of being advantageous or deleterious to a stove system depending on design, implementation, and maintenance. Work has been performed by others in regard to numerical modeling of cookstoves (Baldwin, 1987; Urban et al., 2002; Agenbroad, 2010; Zube, 2010), but to the authors' knowledge, this is the first investigation of the implications to combustion characteristics presented by the draft of chimney cookstoves.

Objectives of current work

Multiple parameters that promote complete combustion (residence time, temperature, and turbulence) could theoretically be affected by a chimney (Cheremisinoff, 1993). Added draft (differential pressure between the stove and the environment) increases mass flow rate and Reynolds number, and alters gas temperatures. Also, chimneys keep

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flue gas separated from ambient conditions, providing a longer residence time of gas within a heated environment. The objective of the current work is to better understand the role that a chimney plays in several of the characteristics of combustion within a stove system. More specifically, the goal of the present study was to understand how a chimney affects:

- the wood consumption rate/firepower of a stove,
- the ratio of air to fuel within a stove, and
- the carbon monoxide production of a stove.

Methods and calculation

Background physics

The flow that results from a chimney is due to a physical phenomenon commonly referred to as the chimney effect or stack effect. This flow is induced by the density difference between the ambient air and the column of hotter gas that occupies the chimney. An approximate value for this density-driven pressure difference, based on Bernoulli's equation, is described in Eq. (1):

$$\Delta P_{stack,nonideal} = \left(\rho_{amb} - \rho_{flue}\right) g \cdot Z - \frac{k \cdot \rho_{flue} \cdot V^2}{2} \quad (1)$$

where ρ_{amb} is the density of ambient air, ρ_{flue} the density of flue gas at the average gas temperature in the chimney, g the acceleration due to gravity, Z the height of the chimney, k the overall resistance coefficient of the control volume, and V the average velocity of flue gas in the control volume (ASHRAE, 2012).

Eq. (1) suggests that the taller the chimney the greater the driving pressure difference, or draft. Draft will also increase with increasing flue gas temperature, as the density of a gas is highly dependent on temperature. From the standpoint of a stove, draft can be thought of as the vacuum pressure that draws air into a stove and eventually out of the chimney. The overall mass flow rate can be related to the difference in density of the ambient air and flue gas:

$$\dot{m}_{total} = A_{cs} \left(\frac{2 \cdot g \cdot Z}{k}\right)^{0.5} \left(\rho_{flue}\left(\rho_{amb} - \rho_{flue}\right)\right)^{0.5} \quad (2)$$

where A_{cs} is the cross sectional area of the chimney. Eq. (2) is referred to as the gravity-flow capacity equation (ASHRAE, 2012).

Experimental setup

Chimneys are closely coupled with the combustion chamber during operation. Combustion heat release induces a draft, which pulls makeup air into the fire, changing the gas temperature and oxidizer concentration, which then alters the draft, etc. In order to gain insight on these interdependencies, experimental work included varying the firepower of the stove (by varying the surface area of wood fuel) and draft (by altering the chimney height, Z). The following subsections describe the equipment and methods used to collect this experimental data. All samples were taken at 1 Hz frequency.

Advanced research chimney

An instrumented modular stainless steel research chimney was designed and fabricated for the purposes of this work. The Advanced Research Chimney (ARC) contains sensors for gas and wall temperatures, gas velocity, differential pressure, and volumetric concentrations of CO, CO_2 and O_2 within the stack. Gas concentrations were measured directly in the chimney using the Testo © Model 350 flue gas analyzer and at the outlet of the laminar flow hood in which the stove was tested using NDIR gas samplers as described in 1. This redundancy was used for validation of direct and diluted gas measurements. This equipment is summarized in Table 1.

Laminar flow hood

All experiments were conducted in a laminar flow hood specifically designed for the testing of biomass stoves (L'Orange et al., 2012). Virtually all of a stove's emissions are captured and pumped, using a precisely-controlled positive displacement pump, through a heated line before a series of sampling equipment. The hood has been tested extensively and shown to have negligible impact on the natural behavior of a stove. The laminar flow hood can be seen in Fig. 1.

Through knowledge of the volumetric flow rate of the laminar flow hood, gas concentrations, as well as the temperature and pressure of the gas (to arrive at an approximate gas density), mass flow rates can be calculated with a high degree of confidence (typically <5% error). An understanding of the carbon composition of the wood being burned allows for estimates of wood consumption rate from continuous gas sampling of carbon monoxide and carbon dioxide. Actual wood fuel is weighed before and after each test to validate gas-based mass flow calculations. Using an estimate for the overall reaction of wood combustion, in conjunction with oxygen concentration in the chimney, the mass flow rate of air can also be calculated.

Stove types

In order to determine whether results could be applied to multiple stoves, two different stoves were used in this work, hereto referred to as Stove A and Stove B. Stove A is a modern improved stove; it is constructed of metal alloys and cast iron and is insulated with composite ceramic materials. Stove B is a traditional improved stove and is constructed of cement, refractory brick tiles, sheet metal, and is insulated with wood ash. Both stoves have a rectangular cavity that serves as the fuel loading and combustion air inlet. Internally, these two stoves have significant design differences. The channel for gas flow, associated loss coefficients, and heat transfer characteristics vary widely. These stoves can be seen in Fig. 2.

Both stoves can be categorized as griddle-style stoves, called “planchas”. These stoves are popular in Latin America, where they are used for making tortillas as well as preparing food in pots. These particular stoves were selected based on prior and ongoing work related to plancha stoves at the Engines and Energy Conversion Laboratory.

Testing

Varying draft and wood consumption rate

A range of transient and steady state behavior was evaluated by operating Stoves A and B with 61 cm, 109 cm, and 227 cm tall sections of chimney attached. As shown in Eq. (1), taller chimneys induce larger magnitude draft.

Tests were also conducted at several wood burn rates. As shown in Table 2, surface area of wood present in the combustion chamber is strongly correlated to wood consumption rate. Thus, wood consumption rate was regulated through the use of precisely spaced wooden shim stacks comprised of four, six, and nine shims. A nine-shim stack, used for high power burns, is shown in Fig. 3.

To minimize variables, shim stacks were made long enough such that very little user intervention was required to keep either stove running during testing. As char formed on the ends of the wood stacks, the stack was pushed into the chamber gently to engage fresh fuel and minimize charcoal accumulation.

Simulated cooking cycle

In addition to the variable draft and firepower testing described in the Experimental setup section, the performance of Stoves A and B was measured through simulated cooking cycles in accordance with the standard water boil test (Bailis et al., 2007). In this procedure, 5 l of water is heated from 15 °C to 90 °C; the fuel required to complete this task is measured and translated into a thermal efficiency value. This testing allows for the comparison of emissions and thermal efficiency over a standard operating cycle. The stoves were operated at a

Table 1
Major equipment utilized in this work.

Description	Model	Geometry	Function
Positive displacement hood pump	Sutorbilt Legend 4LVP	Top of hood, 450 cm up from ground	Pumps const. vol. flow through hood, 0.10 m^3s^{-1} at 1250 rpm
High temperature hot-wire anemometer	Kanomax 0205	Rad. centered in the chimney, 85 cm up from chimney base	Bulk gas velocity measurements
Diff. pressure transducer	Omega PX653	8 cm from chimney base	Measures draft (diff. press.) of chimney system
Laminar flow hood	Custom built	1 m wide × 1 m deep × 4 m tall	Captures and directs flue gas
Thermocouple array	Omega K-type thermocouples	Rad. centered, 1.5 cm, 64 cm, 164.5 cm, and 219.5 cm up chimney	Flue gas temperatures
Flue gas analyzer	Testo 350XL	109 cm up from chimney base	Real-time CO, CO_2, and O_2 measurements
NDIR CO_2	Siemens Ultramat 6 with CO_2 module	At end of 10 m heated line from top of hood	Real-time CO_2 concentration measurement
NDIR CO	Siemens Ultramat 6 with CO module	See above	Real-time CO concentration measurement

medium firepower, regulated by the amount of wood present in the combustion chamber at a given time, by the same user to minimize variability.

Chemical kinetic modeling approach

This section describes the chemical kinetic modeling approach that was undertaken for this study. Attempts were made to represent the combustion of wood as accurately as possible within reasonable computation times. It was decided, therefore, to focus on the detailed chemistry in this process and use a simplified-physics approach as it was too computationally intensive to try and capture both effects.

Overall chemical reaction

Often, the combustion of wood has been described by a generalized, one-step overall reaction process similar to that in Eq. (3):

$$\text{woodgas} + a(O_2 + 3.76N_2) \rightarrow n_1CO_2 + n_2H_2O + n_3N_2 + n_4O_2 + n_5CO + n_6H_2 \qquad (3)$$

where the wood gas is described by some overall elemental composition, $CH_yO_zN_f$. The overall carbon content of wood can vary based on wood type and harvest environment, i.e. hardwood, softwood, local climate where the wood is harvested, nutrient availability, etc. This carbon content ultimately affects the quantity of air that is required for combustion. A more accurate estimation of wood combustion can be obtained by considering the actual chemical structure of wood and the subsequent evolution of wood pyrolysis gas.

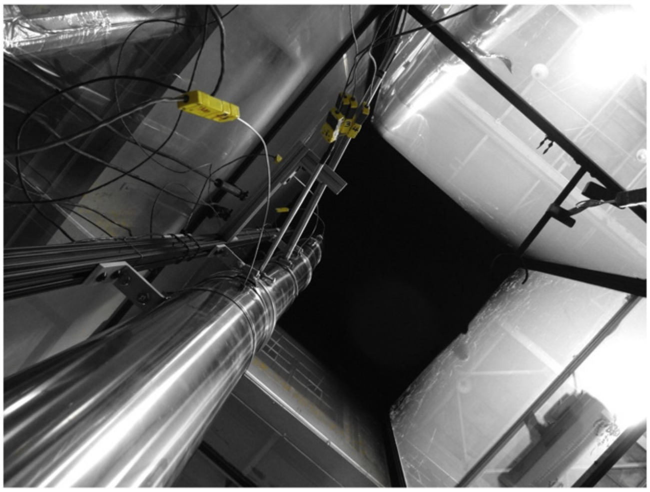

Fig. 1. Modular stainless steel chimney outfitted with an array of sampling hardware inside of a laminar flow hood.

In order to determine a representative composition of pyrolysis gas, the chemical structure of wood must first be considered. Wood is primarily comprised of chains of cellulose ($C_6H_{10}O_5$), hemi-cellulose, and lignin connected together in a complex molecular structure (Browne, 1963). The combustion of wood occurs in several steps. First, the wood must be heated to the point where trapped water vapor is expelled and the molecular chains between wood molecules, such as cellulose and lignin, break down. These molecules are subsequently vaporized. Next, due to the complex nature of the evolved wood molecules and the trapped oxygen within them, pyrolysis begins. The pyrolysis gases quickly transition into a semi-stable, thin, flame region where the gas mixes with the surrounding air. Due to the radiation losses to the wood below the flame and the surrounding air, as well as convection losses to the air, flame temperatures have been calculated to be between 1100 K and 1700 K (Kausley and Pandit, 2010; Ragland et al., 1991). Wood-gas flame temperatures have been measured in our own laboratory to be between approximately 1300 and 1500 K (Miller-Lionberg, 2011) for natural convection cookstoves. After the flame front, excess air is mixed with the combustion products and allows for some additional oxidation of CO and other products. However, the gas quickly cools to the point where significant oxidation of CO is quenched. These steps are summarized in Fig. 4.

Pyrolysis gas mechanism

Recent interest in the applications of pyrolysis stoves as well as improvements in experimental techniques and analysis has increased the depth of knowledge of the components of wood gas (Kausley and Pandit, 2010; Ranzi et al., 2008; Ragland et al., 1991). Several studies have analyzed pyrolysis gases for several different solid fuels using thermogravimetric (TG) mass spectrometry and fourier transform infrared (FTIR) analysis of the evolved and reacted gases (Manya et al., 2003; Hosoya et al., 2007; Radmanesh et al., 2006). Ranzi et al. summarized this research and developed a chemical reaction mechanism with 327 species and 10,934 reactions detailing not only the oxidation of evolved wood gases but also the interactions between these species in the pyrolysis zone prior to the flame (Ranzi et al., 2008). In the present study, the Ranzi et al. mechanism was used to model the gas phase chemical kinetics in the chimney stoves tested herein. Only the major vaporized wood species from the softwood Ranzi et al. model were taken to represent the evolved wood gas; the fuel mass fractions can be found in Table 3. Using the species distribution in Table 3, the stoichiometric amount of air was found to be 6.1 kg for 1 kg of fuel, which is consistent with previous studies (Jenkins et al., 1998; Demirbas, 2004). Charcoal was excluded from the chemical modeling for simplification. This was believed to be reasonable given that charcoal accumulation is relatively minor in both stoves that were tested.

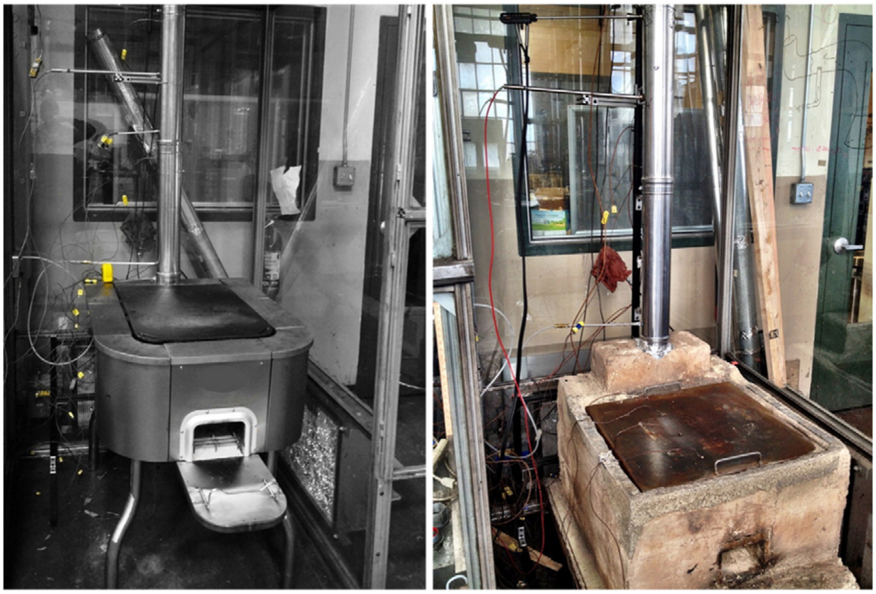

Fig. 2. The two stove models used in this work. Stove A (left) has been recently developed at the EECL for a commercial partner. Stove B (right) was constructed at the EECL based on design drawings for the "Justa" model provided by the Honduran government.

CHEMKIN-PRO© was utilized to explore the interaction between various parameters such as air-to-fuel ratio, reaction zone temperatures, wood combustion rate, and combustion efficiency. Specifically, the chimney stove combustion processes studied herein were modeled as a series of plug flow reactors as follows:

1. The fuel species from Table 3 are reacted through a short pyrolysis section approximated by a plug flow reactor (PFR) beginning at 650 K and ending at the flame. Several models were run, with peak temperatures ranging from 1300 to 1700 K in order to account for variability encountered in experimental work.
2. A stoichiometric amount of air is mixed (non-reactively) with the pyrolysis products.
3. The stoichiometric mixture of fuel and air is reacted through a very short (1–2 mm) reaction zone, which is held at the flame temperature (1300–1700 K).
4. Excess air (also at the flame temperature) is then mixed (non-reactively) with the combustion products.
5. The fuel-lean mixture is allowed to react while being subjected to a decreasing temperature profile for the remainder of the stove gas path (note the temperature profile is taken from experimental measurements).

The entire interconnected model was solved via CHEMKIN-PRO. The non-reactive mixing sections were simulated using the embedded mixer model, while the reacting sections were all simulated using PFRs with the experimental stove dimensions, velocity measurements, and temperature profiles applied where necessary. It was found experimentally that the firepower during a given test fluctuates slightly and thus affects the overall bulk flame temperature. Therefore, the model results are shown as a band ranging in a peak flame temperature from 1300 to 1700 K.

Table 2
Average wood consumption rate (measured) versus shim surface area (calculated).

Number of shims	Approximate surface area of shim array (cm^2)	Average wood consumption rate (g/s)
4	1400	0.18 +/− 0.03
6	2100	0.39 +/− 0.04
9	3150	0.54 +/− 0.09

Results and discussion

The obvious function of a chimney is to vent combustion products outdoors. A chimney also serves as a heated plug flow reactor and a mass flow pump. These roles translate to potential influence over the combustion reactions within a stove.

Chimneys as an extended plug flow reactor

Since chimneys theoretically provide increased residence time within a warm environment, there was interest in determining whether CO is further oxidized to CO_2 within a chimney. Our field and laboratory data indicates that chimney temperatures generally fall within the range of 350–600 K, depending on the power and thermal efficiency of the stove. CHEMKIN-PRO was used to model two hypothetical scenarios to determine whether CO can be oxidized in chimneys under these conditions.

As can be seen in Fig. 5, even a very high temperature chimney is not predicted to provide any oxidation advantage when compared to the exhaust-to-ambient scenario. Appreciable oxidation of CO appears to terminate at temperatures below 1200 K, well above reasonable or safe chimney temperatures for residential stoves. This is an expected result, as kinetic rates in the literature will be extremely slow at the given chimney temperatures (Glassman, 1997).

Excess air

Results from this study, shown in Fig. 6, as well as previous work at the laboratory (Agenbroad, 2010), indicate that natural convection biomass stoves tend to operate with high excess air.

In Fig. 6, 0 on the Y-axis represents stoichiometric combustion. As can be seen, the excess air from both Stoves A and B fluctuates between ≈350% and 1250% excess air.

The flames of biomass cookstoves are non-premixed diffusion flames. In such flames, insufficient air limits the amount of volatile

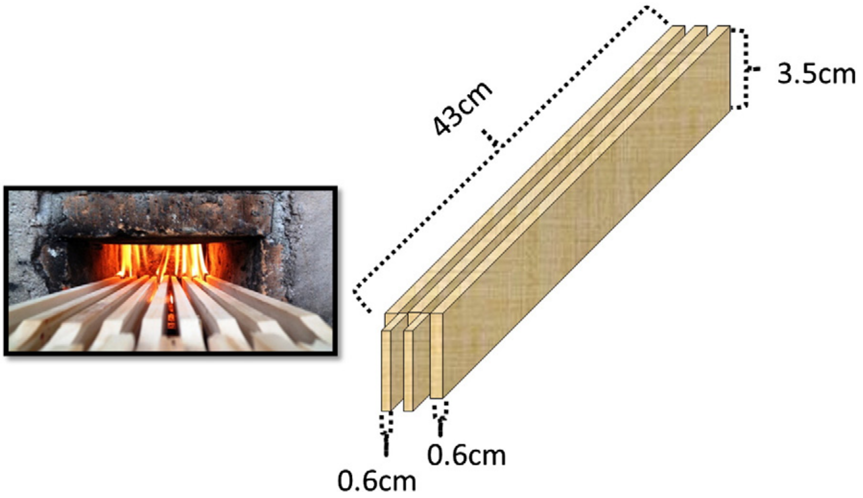

Fig. 3. For better control of firepower, precisely spaced wooden shims were used as fuel. Arrays with four, six, and nine shims were used to hold low, medium, and high firepowers.

gases that can be combusted. Too much air, on the other hand, pulls heat away from the combustion zone, limiting the amount of volatile gases that are released, and thus the heat output of the reaction. Given the high excess air results shown in Fig. 6, obtained by testing with a 2.27 m tall chimney, it was important to determine how combustion in Stoves A and B was impacted by varying chimney height and thus natural draft.

The relationship of draft to wood consumption rate

One of the fundamental objectives of this work was to understand how increased air flow (through increased chimney draft) influences the consumption rate of wood fuel. Drafts of different magnitude were produced through addition of chimney height, as described in the Experimental setup section. As can be seen in Fig. 7, at steady state operations for two different stove types at two different power modes, fuel burn rate was found to be relatively unaffected by draft. In all of the tests, fuel burn rate was almost entirely dependent on the surface area of wood present in the combustion chamber, as shown in Fig. 3.

While steady state wood consumption rate was seen to remain relatively constant with different chimney drafts, total mass flow was shown to increase substantially, in accordance with Eq. (2).

The relationship of draft to the fuel equivalence ratio

As described in the Varying draft and wood consumption rate section, increasing chimney draft (through the addition of chimney sections) did not affect the consumption rate of wood. The increasing draft did, however, result in significant increases to the flow rate of air. The ratio of fuel to air can be described by the fuel equivalence ratio, Φ shown in the following equation:

$$\Phi = \frac{\left(\frac{A}{F}\right)_{stoich}}{\left(\frac{A}{F}\right)_{actual}}. \tag{4}$$

The overall fuel equivalence ratio, Φ, is a measure of how lean or rich the combustion reaction of fuel with air is in a given combustion system. As discussed in the Excess air section and shown in Fig. 6, natural convection stoves tend to operate far from stoichiometric, corresponding to $\Phi << 1.0$. As chimney sections are removed, the air pulling capacity of the chimney is reduced. Thus, excess air is reduced, wood consumption rate remains fixed, and Φ increases. This dependence of Φ on total chimney height can be seen in Fig. 8.

With two different stoves, Φ is shown to decrease with increasing chimney height. The shapes of these curves are different between stoves

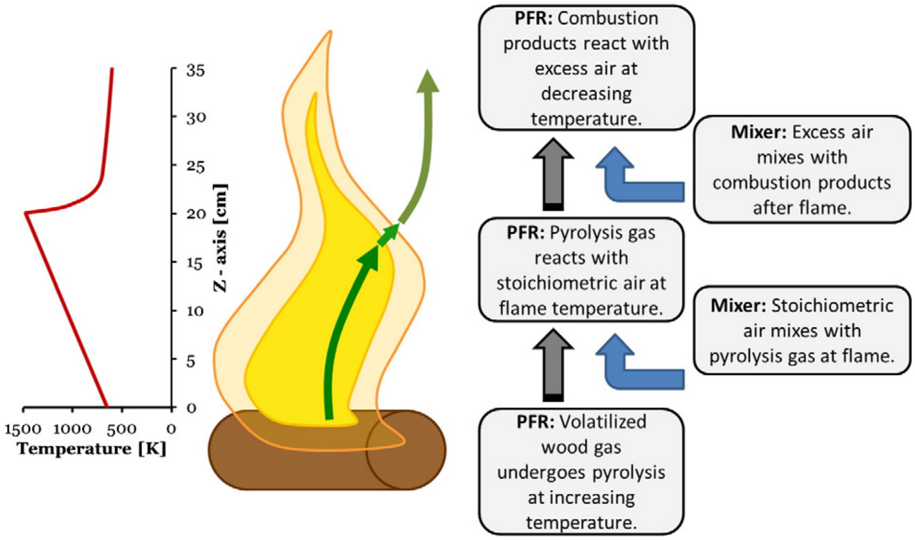

Fig. 4. The temperature profile at left and wood gas composition, listed in Table 3, are input into the CHEMKIN-PRO software and run in the sequence listed shown at right.

Table 3
Evolved wood gas composition based on Ranzi et al.'s Mechanism (Ranzi et al., 2008).

Species	Mass fraction
$C_{11}H_{12}O_4$	0.238
$C_5H_8O_4$	0.029
$C_6H_{10}O_5$	0.338
C_3H_5OH	0.044
$C_2H_4O_2$	0.010
C_2H_5OH	0.008
C_2H_4	0.007
CH_3OH	0.065
CH_2O	0.030
CH_4	0.003
CO_2	0.098
CO	0.058
H_2O	0.062
H_2	0.009
Total	1.000

as they each have different relationships between draft and the resulting mass flow of air. These differences result from the unique flow resistance and heat transfer properties of each stove.

The relationship of Φ to combustion efficiency

As described, chimney stoves have the tendency to operate at highly fuel lean conditions (low Φ). The highest steady state average value for Φ that was observed in either stove at any firepower was just above 0.3, corresponding to an excess air percentage of approximately 200 %. Since these stoves operate exclusively above stoichiometric air, any added draft pulls the reaction further away from stoichiometric conditions. This is especially relevant given the results shown in Figs. 7 and 8, which indicate that draft simply increases air flow, leaving fuel flow fixed.

High excess air/low Φ within wood combustion reactions has been linked to increased carbon monoxide production (Johansson et al., 2004; Agenbroad, 2010). Carbon monoxide production can be expressed in the non-dimensional quantity called the modified combustion efficiency (MCE). The modified combustion efficiency essentially describes the degree to which the carbon in hydrocarbon fuels is converted to CO_2. It is defined by:

$$MCE = \frac{[CO_2]}{[CO] + [CO_2]} \tag{5}$$

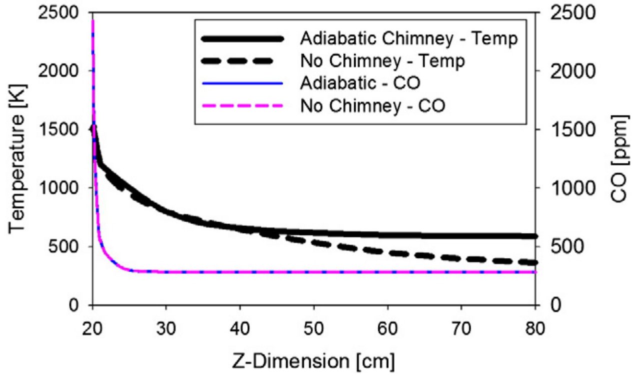

Fig. 5. CHEMKIN-PRO results for hypothetical oxidation of CO in a stove with (a) an adiabatic chimney at 600 K and (b) a direct emission of CO into the ambient air scenario. The z-dimension is a linearized path through the stove, where 20–80 cm is the distance from combustion chamber exit to the chimney. The average gas velocity is set to 1.27 m per second based on measured experiment values.

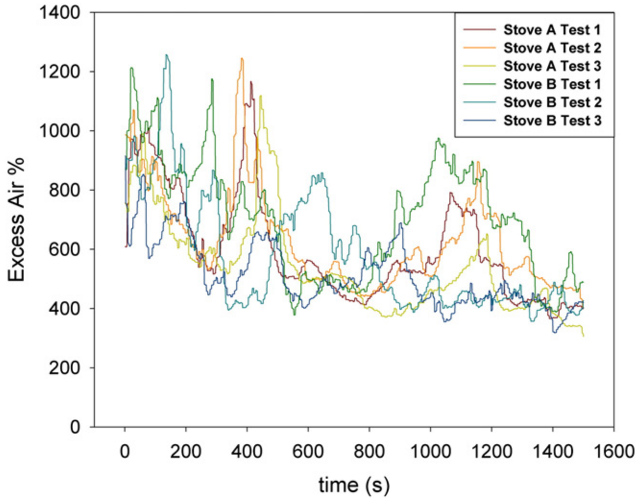

Fig. 6. Excess air % over the first 25 min of simulated cooking cycle for Stoves A and B. Tests 1, 2, and 3 indicate replicates.

where [CO] is the concentration of carbon monoxide and $[CO_2]$ the concentration of carbon dioxide (Shen et al., 2011).

As can be seen in Eq. (5), high concentrations of carbon monoxide reduce the magnitude of the MCE, indicating that the combustion reaction is incomplete. Incomplete combustion is generally the result of a combination of the following:

1. Insufficient oxidizer, such as in smoldering reactions.
2. Insufficient mixing of fuel and oxidizer.
3. Excessive cooling of the reaction zone, essentially freezing chemical reactions before carbon in the fuel has been fully converted to CO_2.

As results indicate that chimney stoves tend to run with high excess air, insufficient oxidizer was not believed to be a point for further optimization. Given the high levels of excess air observed in all tests, however, cooling of the reaction zone was believed to be an area for potential optimization. Fig. 9 shows a parametric study of modified combustion efficiency over a range of values for Φ. Experimental data is overlaid on the model results.

The model results bracketing the data in Fig. 9 are a result of running the chemical kinetic model described in Fig. 4 over a range of flame temperatures (1300–1700 K) and Φ values (0.01–0.4). The model data is shown as a band to reflect the inherent fluctuations in temperature

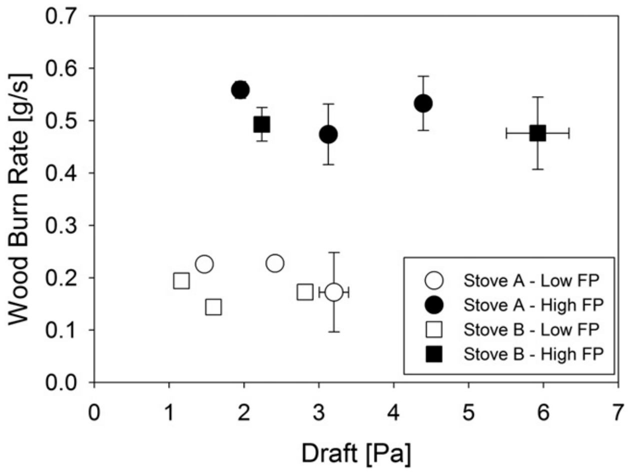

Fig. 7. Steady state burn rate of wood was shown to be relatively insensitive to steady state draft at both high and low firepower (FP) operating levels.

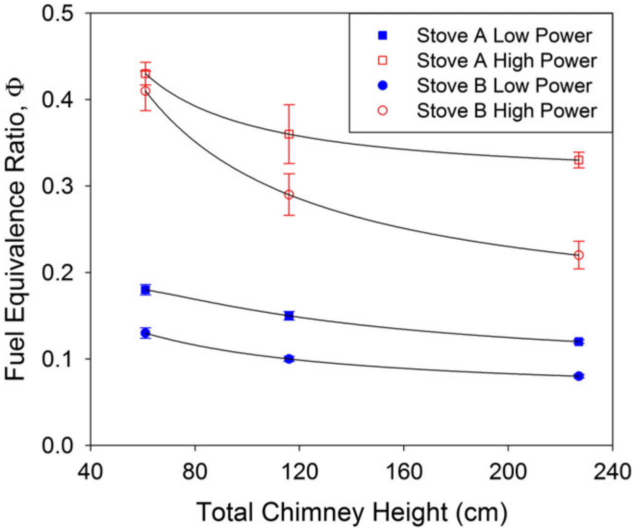

Fig. 8. Φ vs. total chimney height at high and low power for Stoves A and B.

that can occur even for fairly consistent wood burn rates. Note that combustion efficiency is predicted to drop off around a Φ value of approximately 0.1. This decrease is primarily due to the nature of Φ as it approaches zero — specifically, the amount of excess air increases exponentially as Φ decreases. This large increase in excess air serves to significantly decrease the CO concentration at the flame exit, which lowers the conversion driving force. Additionally, at a constant fire power, the flame can only deliver so much heat to the incoming air; thus any excess air serves to cool the local temperature such that CO conversion to CO_2 is effectively frozen immediately downstream of the reaction zone.

Actively altering Φ

Having found that the wood burn rate was relatively insensitive to chimney draft, as shown in Fig. 7, it was hypothesized that Φ could be increased by reducing the total mass flow rate allowed through the stove. It was believed that CO production could be reduced by confining a stove to a high- Φ operating region, based on results shown in Fig. 9. The total mass flow rate could be regulated through a variety of methods, but the simplest and most applicable appeared to be by reducing the diameter of the chimney. Adding a damper to the four inch chimney would add to the part count and cost of a stove. Reducing the size of the fuel mouth may aggravate users of the stove. Swapping out a larger diameter chimney for a smaller diameter chimney, on the other hand, reduces the material cost of a stove system (an essential requirement for improved stoves) without altering the user experience in any obvious way. It was hypothesized that a smaller diameter chimney should act as a mass flow limiter through increased viscous loss terms. Fluid resistance through a pipe increases with inverse radius to the fourth power, as described by Hagen–Poiseuille flow (Moran et al., 2003).

As shown in Fig. 10, Stove A operated at higher Φ with the reduction to the chimney diameter. When comparing the total emissions of two cases, there was a 38 % reduction in CO when the 10 cm ID chimney was replaced with a 7 cm ID chimney.

It is important to note that the wood consumption rate of the two cases shown in Fig. 10 and Table 4 was very similar, as was the overall draft and thermal efficiency. The major difference between the two cases was the total mass flow rate, and subsequently the excess air, Φ, and carbon monoxide production. While total emissions from the stove were significantly reduced, a reduction in mass flow rate translates to a lower velocity of air into the front of the stove. This is an important trade-off to consider, as insufficient frontal velocity into the combustion chamber can lead to emissions of combustion products from the front of the stove. Furthermore, below a minimum chimney diameter, flow through the stove will be choked and draft will be insufficient to pull any oxidizer into the combustion chamber.

Conclusions

The results of this work confirm that a chimney serves important functions within a buoyantly driven stove system beyond ventilation of combustion products. A chimney can alter the overall air-to-fuel ratio of a stove significantly, leading to large shifts in gas temperatures and combustion efficiency. Draft was not shown to affect wood consumption rates at high or low firepower levels or between Stove A and Stove B, but has a large effect on the mass of air that is pulled through the stove. Combustion efficiency was shown to increase with increasing fuel equivalence ratio, Φ. Theoretically, as Φ approaches the sooting limit, combustion efficiency would drop, but that limit was not encountered with the stoves tested in this work. Introducing a smaller diameter chimney to limit total mass flow was a simple solution to decrease carbon monoxide emissions from Stove A. The chemical kinetic modeling using CHEMKIN-PRO produced results that compared well to experimental data when using the Ranzi et al. pyrolysis gas mechanism and an experimentally measured temperature profile.

Future work includes investigating similar approaches toward understanding and reducing the production of particulate matter

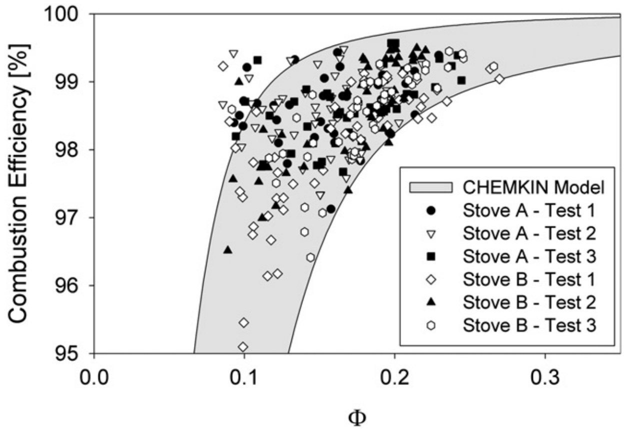

Fig. 9. Modified combustion efficiency vs Φ for steady state data and chemical kinetic model.

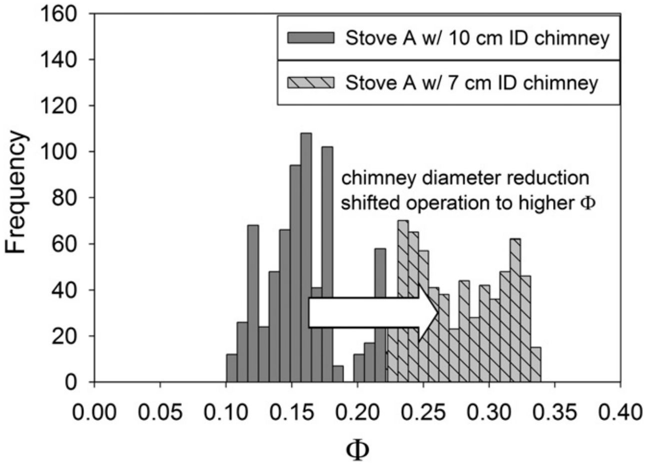

Fig. 10. Histogram showing the amount of time (in seconds) spent at various values of Φ when Stove A was run with a 10 cm ID chimney and a 7 cm ID chimney.

Table 4
Performance comparison of Stove A with two chimney diameters.

Parameter	10 cm chimney	7 cm chimney
Chimney inner diameter [cm]	10.12	7.01
Average steady state wood consumption rate [g/s]	0.334	0.354
Average steady state total mass flow rate [g/s]	13.29	8.33
Excess air [%]	557	273
Average steady state Φ	0.158	0.274
Average steady state chimney draft [Pa]	4.38	3.91
Overall thermal efficiency [%]	26.47	26.05
Average steady state CO production rate [g/s]	0.00757	0.00466
Percent reduction in CO	–	38%

(PM). It is also of interest to see how mixing of oxidizer and fuel can be optimized through utilization of the draft. The current work suggests that many stoves may be over-drafting, thereby cooling the reaction zone in the combustion chamber. A true optimization may involve trading high volume, low velocity inlet air for lower volume, higher velocity inlet air to facilitate mixing without excessive cooling. Lastly, these findings may have important implications for non-chimney stoves and forced draft stoves. All biomass stoves require air to flow through them to operate. Designing any biomass stove with implications to airflow specifically in mind may allow for more significant performance gains.

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