Energy for Sustainable Development 23 (2014) 286–293

Contents lists available at ScienceDirect

Energy for Sustainable Development

Influence of chimneys on combustion characteristics of buoyantly driven biomass stoves

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ARTICLE INFO

Article history:
Received 17 March 2014
Revised 1 August 2014
Accepted 29 August 2014
Available online xxxx

Keywords:
Stove
Biomass
Chimney
Emissions
Carbon monoxide
Efficiency

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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http://dx.doi.org/10.1016/j.esd.2014.08.007
0973-0826/© 2014 Published by Elsevier Inc.

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