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Abstract

Some types of biomass stoves, such as charcoal stoves, tend to be difficult to light due to poor initial draft and sensitivity to ambient wind. Decreasing the time necessary to light such stoves could increase user acceptance and convenience and decrease the user's exposure to harmful emissions, as ignition is one of the smokiest portions of a cooking fire and may require close tending attention. A device known as a lighting cone has proven to aid ignition in such stoves, while also being inexpensive and easy to build in the field.

This paper provides a basic model for estimating flow velocities produced from lighting cones in relation to the lighting cone dimensions and thermal power. Flow rates through a lighting cone measured empirically are compared with the model to evaluate the validity of using a simplified equation. The average percent error between theoretical and empirical thermal powers was found to be less than 15%. Thus the proposed model could be a useful starting point for sizing prototypes in the laboratory and in the field.

Keywords: Haitian Cookstove; Lighting Cone; Chimney Effect; Ignition Time

1 Introduction

In the developing world, close to 3 billion people cook with biomass fuels [1]. Often, these stoves are slow to ignite due to interference from the wind and a lack of airflow through the stove body and fuel bed. This is especially the case in charcoal stoves which often have shallow and exposed charcoal beds. As the combustion rate of charcoal is heavily dependent on the extent to which oxygen can reach its surface, a shallow charcoal bed with small draft often stifles the early ignition phase due to lack of oxygen [2]. Therefore, devices that increase the amount of oxygen reaching the surface of the charcoal can greatly speed its ignition, reducing the amount of time needed to begin cooking.

Many inventions exist to decrease the amount of time needed for a charcoal bed to be well lit, such as charcoal chimneys and lighter fluid. These products, however, can be expensive and toxic and are not well suited for developing economies where cooking with charcoal is a daily necessity. In many countries, such as China, Zaire, and Mozambique, a device, referred to in this paper as a lighting cone, is used to decrease the ignition time of the charcoal.

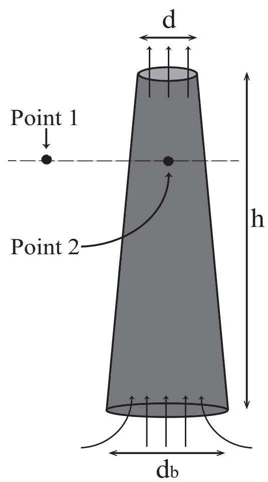
A lighting cone (Fig. 1) is a conical tube of sheet metal that increases draft through the charcoal bed and therefore decreases the amount of time needed for ignition. It is placed on the charcoal bed after the kindling has been lit and is removed once the charcoal is considered lit enough to place a pot on the fire. Lighting cones are easy to build and can even be manufactured from scrap metal in the field, so are well aligned to be used in developing economies.

Figure 1 – Example of a lighting cone on a traditional Haitian sheet metal stove. A lighting cone is used to decrease the ignition time of a charcoal bed.

The goal of this research is to provide designers in the field with a basic model for the flow velocities produced from a lighting cone so cones may be sized for the desired drafts.

2 Theory

A model based on a vertical conical cylinder was used for theoretical approximation of the lighting cone. A diagram of this model is shown in Fig. 2.



Point 1	Point 2
$\vec{v} = \vec{v}_\infty = 0$	$\vec{v} = \vec{v}_{avg} > 0$
$P = P_\infty$	$P = P_{avg}$
$\rho = \rho_\infty$	$\rho = \rho(T_2) = \rho_{avg}$
$T = T_\infty$	$T = T_{in} - T_{out} = T_{avg}$

Figure 2 – Conical Cylinder Model diagram for flow calculations, where $\vec{v}$ is velocity, P is pressure, ρ is density, and T is temperature. Point 1 is resting in ambient air and Point 2 is inside the flow stream.

For simplicity, the flow was assumed to be air acting as an ideal gas at a steady-state velocity and temperature. Heat loss through the wall was assumed to be negligible and basic duct and chimney friction factors were used to estimate wall interactions.

The flow through the cylinder is created by a difference in air densities between the hotter internal air and cooler ambient air. As it is relatively low velocity flow, we assume the air to be incompressible in regards to pressure. Therefore, we use the Boussinesq approximation to describe the buoyancy term due to the difference in air densities.

Using the hydrostatic equation, $P_\infty - P_{avg} = gh(\rho_\infty - \rho_{avg})$, and Bernoulli's equation for incompressible flow, $P_1 + \frac{1}{2}\rho\vec{v}_1^{\,2} = P_2 + \frac{1}{2}\rho\vec{v}_2^{\,2}$, [3] we find

$$\vec{v}_{avg} = \sqrt{2gh\frac{(\rho_\infty - \rho_{avg})}{\rho_{avg}}} \tag{1}$$

Applying the Boussinesq approximation, $\rho_\infty = \rho(1 - \beta(T_\infty - T))$, we can substitute in temperature for density to find

$$\vec{v}_{avg} = \sqrt{2gh\beta(T_{avg} - T_\infty)} \tag{2}$$

where β is equal to $1/T$ for an ideal gas. The pressure difference due to kinetic losses throughout this simple system can be represented by $\Delta P_{loss} = \alpha\left(\frac{1}{2}\rho\vec{v}_{avg}^{\,2}\right)$. The kinetic correction factor α is the sum of 5 loss components: losses due to acceleration (k_a), losses at the inlet (k_{in}), losses at the outlet (k_{out}), losses due to friction (k_c), and losses due to obstructions in the flow (k_r). From the ASHRAE handbook, k_a, k_{in}, and k_{out} are equal to

1, 0.5, and 0.5, respectively, and as there were no major obstructions in the flow, $k_r = 0$ [4]. Frictional losses (k_c) were found using $k_c = \frac{f_s h}{d_h}$ where h is length of the tube and d_h is the hydraulic diameter [5].

When including the losses, the velocity formula becomes

$$\vec{v}_{avg} = \sqrt{\frac{2gh\beta}{\alpha}\left(T_{avg} - T_\infty\right)} \tag{3}$$

For comparison with experimental data, it is useful to know the relationship between velocity and thermal power. From theory, thermal power is proportional to temperature and volumetric flow rate by

$$P_T = \rho\, c_p\, \Delta T \dot{Q} \tag{4}$$

Converting Eq. 3 to volumetric flow rate, we find:

$$\dot{Q} = A\vec{v}_{avg} = A\sqrt{\frac{2gh\beta}{\alpha}\left(T_{avg} - T_\infty\right)} \tag{5}$$

where $\dot{Q}$ is the volumetric flow rate and A is the outlet area. Note, this is quite similar to the well-known stack effect equation $\left(\dot{Q} = CA\sqrt{2gh\left(\frac{T_{avg}-T_\infty}{T_\infty}\right)}\right)$ where C is the discharge coefficient [6].

We can rewrite Eq. 3 to find ΔT such that

$$T_{avg} - T_\infty = \left(\frac{\alpha}{2gh\beta}\right)\vec{v}_{avg}^{\,2} \tag{6}$$

Substituting Eq. 5 and Eq. 6 into Eq. 4, we find that thermal power is proportional to velocity cubed.

$$P_T = \left(\frac{\alpha A \rho c_p}{2gh\beta}\right)\vec{v}_{avg}^{\,3} \tag{7}$$

It is important to note the model is constrained by extreme dimensions, which should be further explored in future work. For example, if a lighting cone is quite tall or otherwise has a large wall area, heat losses through the walls and friction will no longer be negligible due to the large surface area and the velocities will be slowed. Conversely, if the cone is quite short, there is not enough height in the cone for the temperature to be well distributed, causing the basic assumptions of the model to be inapplicable. Also, if the top and bottom diameters of the cone are severely different, constricting effects such as overlapping boundary layers will occur and could greatly reduce the flow.

3 Experimental Setup

To validate the simplified conical cylinder model, empirical tests were conducted to measure velocity through a lighting cone at different temperatures and thermal powers.

3.1 Lighting cone

The lighting cone used for these experiments is shown in Fig. 1. It was made from 0.3 mm thick stainless steel sheet metal. The sheet metal was cut into the correct 2D shape then rolled and bolted into a conical shape. The seam was tight, so little-to-no air would escape through the seam or bolt holes of the cone. The cone had a bottom diameter of 0.2 m, a top diameter of 0.1 m, and a slant height of 0.6 m.

3.2 CO_2 tracer gas system

A CO_2 tracer gas system was utilized to measure the flow rates at different temperatures and thermal powers. Such a system is capable of measuring the volumetric flow rate by injecting a very small amount of CO_2 as a tracer gas into the flow stream. A real charcoal fire therefore could not be used for testing because the CO_2 produced in charcoal combustion would obscure the CO_2 tracer gas.

Thus an electric "charcoal" bed, or e-bed, was designed to mimic a charcoal fire. This e-bed consisted of a hot plate covered in mesh designed to mimic the porosity of a charcoal bed and controlled by a variac, so the power input could be controlled. The wattage was measured using a Kill-A-Watt electricity load meter. A Sensidyne Gilibrator-2 recorded the flow rate of the injected CO_2 using the standard size cell (20 cc/min to 6 Lpm). CO_2 measurements were taken every 30 seconds over a period of at least 10 minutes. The exiting CO_2 concentration (typically 1095 $\pm$ 92 ppm CO_2) was measured in real time (1 Hz) using a PP Systems EGM-4 Environmental Gas Monitor for CO_2 (range 0-2000 ppm).

CO_2 was injected into the bottom of the cone using a circular manifold; this manifold consisted of quarter-inch copper tubing which ringed the inside of the bottom edge of the cone. Injection came from 18 holes (1 mm diameter) angled at 45º from the upward flow stream through the cone. CO_2 was collected by a straight quarter-inch copper tube with 10 holes (1 mm diameter) spaced 9.5 mm apart facing straight down into the flow.

3.3 Validation of E-bed with Charcoal cookstove

As temperature differences are the driving force in the velocity of the lighting cone, temperature measurements were compared between the e-bed and a charcoal stove to validate the e-bed system is a suitable proxy in these measurements.

The cookstove chosen for this validation was a traditional Haitian charcoal stove (Fig. 3). The Haitian stove was chosen as it is widely used among the Haitian population and it suffers from the problems posed in the introduction, namely a shallow and exposed charcoal bed. Traditionally, Haitian stoves are made locally out of scrap sheet metal with either a square or circular charcoal chamber. The stove used for testing has evenly-distributed holes along the sides and the bottom of a square charcoal chamber.

The fuel used for the Haitian stove trials was Grillmark© all-natural lump charcoal, which is produced similarly to Haitian charcoal and was broken into similar sizes (no larger than 80 mm by 50 mm by 25 mm). Charcoal samples, analyzed using standard oven-dry procedures, were found to have a moisture content of 5.9%.

Inconel K-type thermocouples were used to measure the temperatures in each system. The thermocouple was located 15 mm below the top edge of the cone inline with the center axis. An Omega HH374 4-channel thermocouple reader was used to continuously record the temperatures in real time (1 Hz).

Figure 3 – Traditional Haitian charcoal stove used for testing. Stove dimensions: height = 270 mm, length/width = 110 mm, weight = 2.8 kg

On average, the temperatures produced in the real charcoal bed were found to be comparable with the temperatures produced by the e-bed at 100% input power (968W). The charcoal stove temperature was approximately 424 K and the e-bed was 430 K, so the e-bed is a good proxy for the charcoal bed to generate the temperature-based driving force.

4 Methods

Velocity was determined using a CO_2 tracer gas system in the following way. The rate of CO_2 flowing into the cone [cc/min] was measured by the Gilibrator-2. The CO_2 concentration exiting the cone was measured by the EGM-4 as a voltage which was then converted to ppm by an experimentally-determined calibration equation. Dividing the CO_2 flow rate into the cone by the concentration out and using the appropriate conversion factors, the volumetric flow rate was calculated. The velocity through the cone was then calculated by dividing the volumetric flow rate by the area of the cone.

Standard error and confidence intervals for all tests were found using the Student's t-test. The Student's t-test is used when measurements are assumed to be normally distributed but the sample size is small ($n < 30$). Because these tests have sample sizes of 3 or 4, the Student's t-test is used for this analysis. For more information on the Student's t-test, please see Taylor and Spiegel, et al. [7, 8].

5 Results and Discussions

5.1 Empirical Results

For comparison with the basic models, the velocity through the cone was determined experimentally. Volumetric flow rates were recorded as the power input into the e-bed was varied from 10% to 100% of the total e-bed power and converted into velocities. All electrical power was assumed to turn into thermal power with mechanical power use and system losses deemed negligible as there are no moving parts in the burner. The results, averaged over all trials, can be seen in Fig. 4.

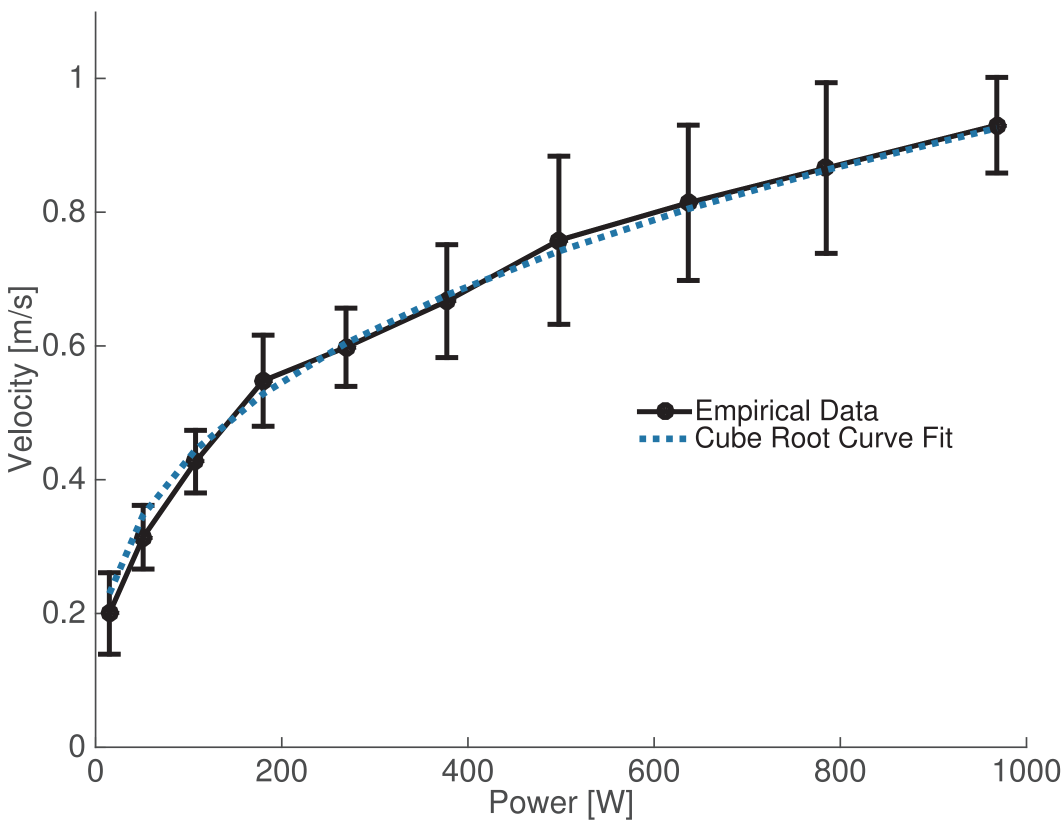


Figure 4 – Thermal power vs. velocity for e-bed tests. A cube-root power curve fit, which would be expected from the cubic dependence of power on velocity in the theoretical model, is shown to be a good fit ($R^2 = 0.994$). Error bars are 95% confidence intervals.

A power curve of order 0.33 is found to be a good fit for the empirical data with an R^2 value of 0.994. This shows the conical cylinder model, in which velocity has a cube-root dependence on thermal power, is generally in good agreement with the experimental data. It is important to note, however, that the cube-root fit has a multiplier of 0.75 compared to the idealized model. We believe this multiplier accounts for all of the simplifying assumptions as real world conditions, such as frictional losses and transitioning temperatures, will predominantly cause the velocity to be slower than estimated by the model.

5.2 Comparison of Theoretical and Empirical Results

At full power, which produced equivalent temperatures to the real charcoal fire, the thermal power of the e-bed is 968 W. Using the same temperature, T = 430 K, the model predicts a velocity of $\vec{v}_{avg} = 1.32$ m/s. Substituting this value into Eq. 4, we find thermal power to equal to 1121 W. Comparing this value from the theory with the experimental power provides only a 14.7% difference for operating temperatures. Even for the full power range, the average percent difference is 14.1%, thus further validating the conical cylinder model as an acceptable rough approximation for lighting cone design.

5.3 Adiabatic Walls

Trials were conducted with an insulated cone to judge the real effects of heat losses through the walls and ensure the assumption that they were negligible was valid. Mineral wool insulation (50 mm thick) was added to the exterior of the cone. The same protocol as the uninsulated cone trials was used and the results are compared in Fig. 5.

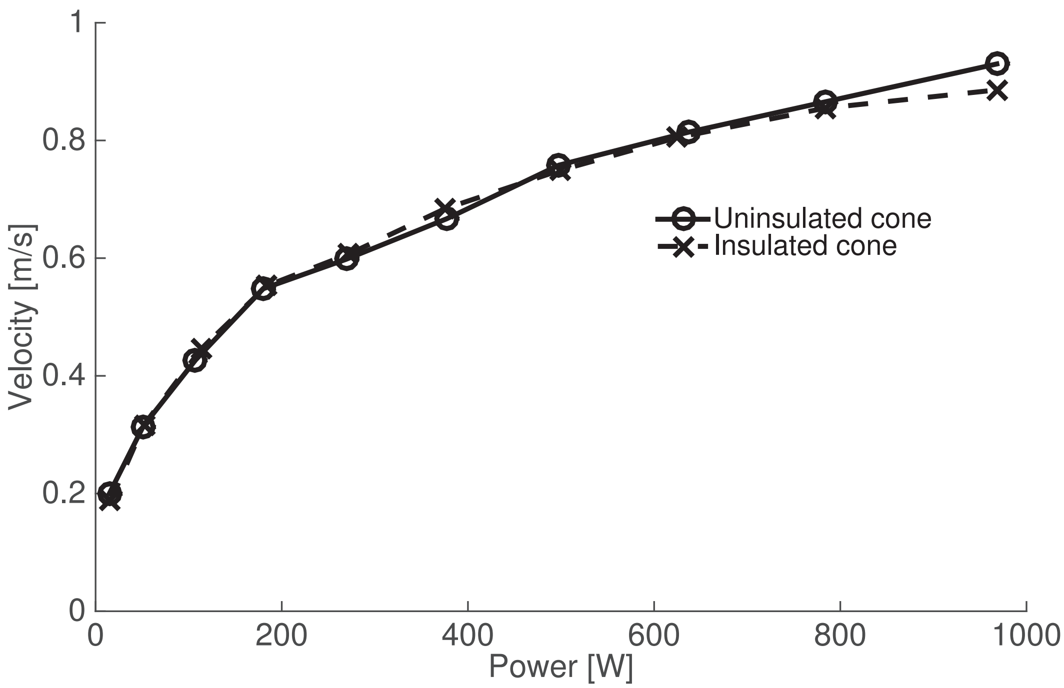


Figure 5 – Insulated vs. uninsulated cone trials. Insulating the walls of the cylinder appears to have little effect on the velocity, indicating heat losses through the walls are negligible.

The insulation made little difference to the flow velocity with an average percent difference between the two of 2.7%, indicating losses through the walls for a cone of this size are negligible as assumed for the model.

6 Conclusions

From comparisons between calculated and empirical results, it can be seen that the model proposed here provides a working approximation for determining lighting cone parameters to achieve a desired draft. For lighting cone design, the model highlights the importance of the height of the lighting cone in controlling the velocity. Other parameters, such as the bottom diameter of the lighting cone, are found to be less critical as long as they are not extreme, so a cone can be easily adjusted for larger or smaller fuel beds. Even a thin sheet metal cone is found to maintain the necessary temperature difference for inducing draft, so insulating materials are not necessary. It is important to note that the model proposed here will likely overestimate the produced velocity due to the simplifying assumptions. In general, however, the simplified model presented here adequately estimates the main components for lighting cone design for first draft prototyping or use in the field.

Acknowledgments

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