Lighting Cones for Haitian Stoves

by

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1 Background and Introduction

In the developing world, close to 3 billion people cook and heat their homes with biomass fuels such as charcoal [IEA 2004]. Typically charcoal burning stoves have relatively shallow and exposed charcoal beds which ignite slowly due to interference from the wind and a lack of air flow through the stove body and charcoal bed. The combustion rate of charcoal is heavily dependent on the extent to which oxygen can reach its surface [Shelton 1983]. In the shallow charcoal beds, it is difficult to achieve the draft required to create a self-sustaining flow of oxygen through the charcoal, so the combustion processes are stifled due to a lack of oxygen. 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 with low incomes 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.

The goal of this research was to examine the lighting cone and its basic usage to identify important design parameters as well as to provide a basic model for field researchers to use when developing lighting cones.

2 Lighting Cone

A lighting cone (Fig. 1) is a conical tube of sheet metal that is used to increase the draft through the charcoal bed and therefore decrease the amount of time needed for ignition.

Figure 1 – Lighting cone on a traditional Haitian stove.

Figure 2 – Traditional Haitian charcoal stove used for testing.

It is placed on the charcoal bed after the kindling, such as fatwood or newspaper, has been lit, and is removed once the charcoal is considered lit enough to place a pot on the fire.

The device can easily be made from scrap metal and although not optimal, almost any dimension will reduce ignition time. A conical shape is preferred to avoid the potential down drafts that could occur with a cylindrical shape, but both are used in the field.

Little scientific exploration of this technology has been conducted with most design being trial-and-error based. This project conducted baseline testing of a lighting cone in a scientific manner, measuring and modeling the flow rate through the cone caused by the temperature difference between the air inside and outside of the cone and its effect on the time needed for charcoal ignition.

3 Traditional Haitian Stove

Testing of the cone was performed using a traditional Haitian stove (Fig. 2). The Haitian stove was chosen because most of the 10 million Haitian people cook with charcoal and wood, which totals 75% of Haiti's energy consumption [USAID 2010, IEA 2004]. This research will help determine the benefits of adding a simple lighting cone to the largely charcoal-burning cooking in Haitian society.

Traditionally, Haitians use simple stoves made locally out of scrap sheet metal. They are widely available in Haiti and have 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.

Dimensions of the traditional Haitian stove used for these tests:

Height: 27 cm	Length/Width: 11 cm	Weight: 2.8 kg

4 Proof of Concept

To evaluate if the lighting cone could reduce lighting time at all, trials using three sizes of cones were performed as a proof of concept.

4.1 Cone Prototypes tested:

The three lighting cone prototypes were made from 0.012 inch thick, stainless steel sheet metal. The sheet metal was cut into the correct 2D shape, and then rolled into a cone and fastened with screws every 4 inches. The seam was tight, so little-to-no air would escape through the seam or bolt holes of the cone.

The dimensions of the three cones were:

	Bottom Diameter (in)	Top Diameter (in)	Slant Height (ft)
Cone 1	10	4.5	1
Cone 2	9	4.5	1.5
Cone 3	8	4	2

4.2 Experimental Setup

The test system consisted of a stove platform under an exhaust hood which drew gases upward through an aluminum duct (15 cm diameter) using two blowers.

Figure 3 – The stove testing system at LBNL. The exhaust hood and ductwork are seen on the right-hand portion of the photo; the instrumentation is on the left.

All testing was performed in a well-monitored indoor space at Lawrence Berkeley National Laboratory.

The fuel for the tests was Grillmark© all-natural lump charcoal. The all-natural lump charcoal is produced in a fashion similar to Haitian charcoal, unlike charcoal briquettes which have additives such as sand. The rectangular lump charcoal was broken into pieces similar in size to Haitian charcoal (no larger than 8 cm by 5 cm by 2.5 cm). Charcoal samples, analyzed using standard oven-dry procedures, were found to have a moisture content of 5.9%.

4.3 Protocol

Each test was performed by filling the traditional stove with 475 g of charcoal. The charcoal was arranged in a circular pile of approximately 15 cm in diameter. A piece of fatwood, a sappy pine, weighing approximately 10 g was used to light the fire by inserting the lit fatwood into the center of the charcoal pile. Time was recorded from when the fatwood was lit until the charcoal bed was considered well-lit. The bed was considered well-lit when at least 70% of the coals were red. Because this was a visually-observed estimate, some of the times may be overestimates.

Statistical significance and standard error 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 ($n < 30$). For more information on the Student's t-test, please see Taylor and Spiegel, et al. [Taylor 1997, Spiegel, et al. 2008]. As these tests only have sample sizes of 3 or 4, the Student's t-test is used for this analysis. All error bars on the graphs represent a 95% confidence interval.

4.4 Results and Questions

The results for each of the three cones as well as the baseline are presented in Fig. 4.

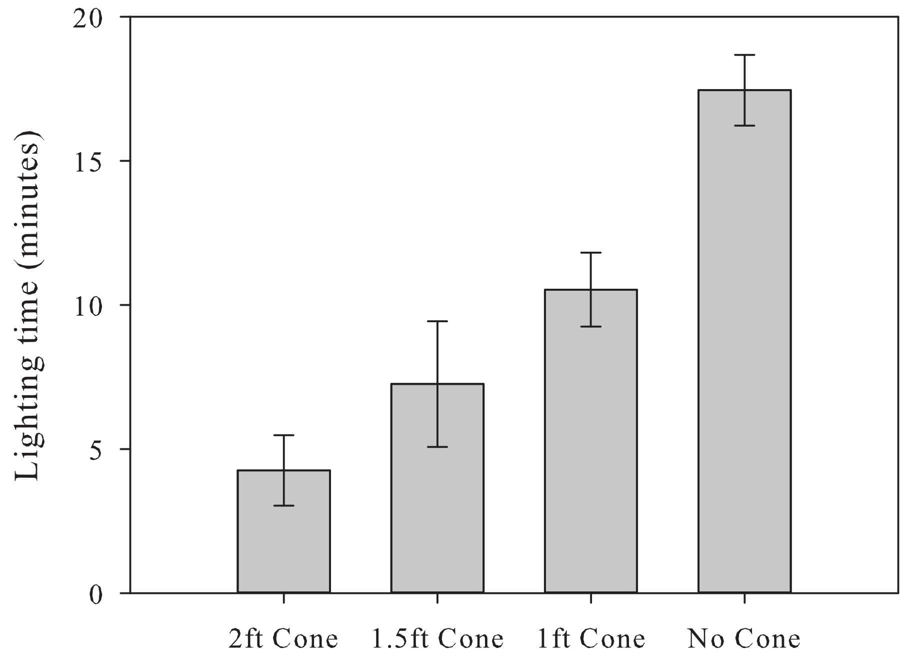


Figure 4 – Results of three preliminary cone prototypes. The 2 ft tall cone performed the best. Error bars are 95% confidence intervals.

The trend showed that the narrower and taller the cone, the quicker the charcoal bed was lit. This was expected as a taller cone created a larger temperature difference between the top and bottom of the cone, creating a larger negative pressure difference between the bottom of the cone and the outside ambient air which increased the flow rate. The tallest cone (2 ft) saved a significant amount of time over the 1 ft cone and the baseline experiment using no cone. Although all cones saved a statistically significant amount of time over using no cone, the best performing prototype (the 2 ft cone) was used for the remainder of the trials and calculations.

The protocol for this experiment was developed in absence of any published or informal documentation on how Haitians light charcoal for cooking. Therefore, several unknowns arose while testing, such as the correct setup for the charcoal bed and when the charcoal bed should be considered well-lit. These unknowns needed to be found prior to the next round of testing. One important question that arose from these trials was if the Haitian cooks would recognize the time savings and appreciate those savings enough to make this a viable product for this region.

5 Haitian Field Observations

An exploratory field visit was carried out to gain user opinion of the cone from Haitian cooks and help develop a more realistic protocol. Although other cultures have been receptive of such cones, it was crucial to ensure the cone would be suitable to the Haitian culture.

With the aid of International Lifeline Fund (ILF), cone demonstrations occurred in the refugee camps and trials were conducted at ILF headquarters. While accompanied by ILF staff and translators, the cone was demonstrated on the traditional Haitian charcoal stoves in the refugee camps. We timed the duration of when the fatwood was first lit to when a cook indicated they would put a pot on. During these demonstrations, Haitian cooks commented on how long it typically took to light a fire, which they estimated to be 8 – 10 minutes.

We conducted side-by-side tests of the cone vs. no cone at the ILF headquarters with the help of Haitian staff members who use charcoal stoves regularly, acting as the stove users. Fires were lit both the traditional way and with the cone by the same user. The time was recorded from when the fatwood was lit through when the user would put a pot on.

5.1 Results

Fig. 5 compares the lighting times for the field trials in Haiti with the lab trials, as well as showing the user estimates of traditional lighting time.

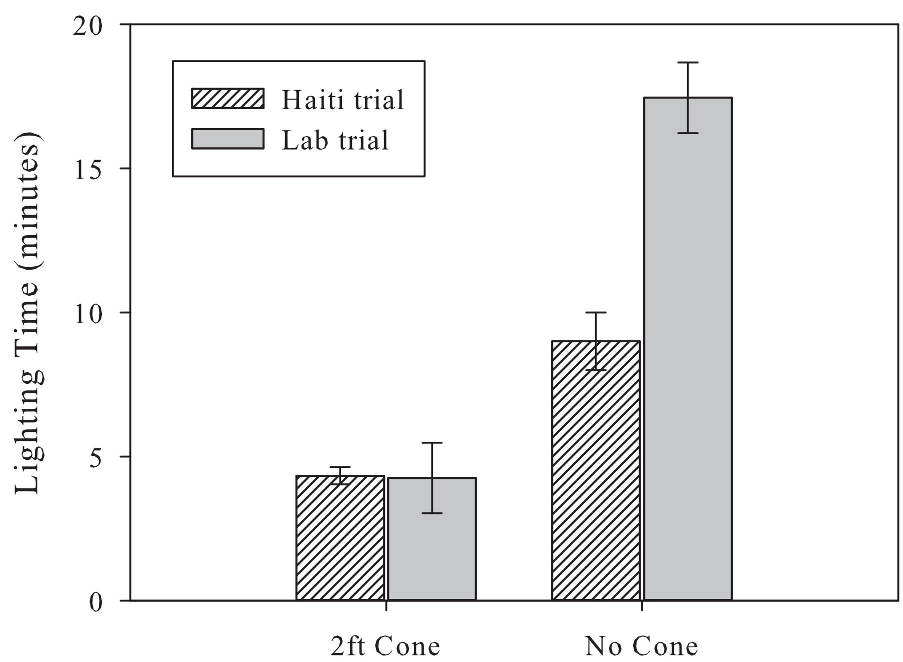


Figure 5 – Results from cone demonstrations in Haiti and trials in the lab at LBNL. Both in the lab and in the field the 2 ft lighting cone reduced the lighting time by at least 50%. Error bars represent 95% confidence intervals.

On average, the cone performed similarly in the lab and field and produced at least a 50% reduction in the ignition time.

It is interesting to note the large difference between starting the fire without a cone in the lab and in the field. Haitian cooks have far more experience lighting fires than lab personnel and therefore take far less time to get the fire started in tests without cones. However, in both the field and the lab, the lighting time with the cone was comparable, averaging slightly over 4 minutes.

5.2 Observations and Conclusions

By informally observing the Haitian lighting practices, it became apparent the charcoal bed was set up similarly to the one in the prototyping experiments. The user would arrange the charcoal in a circle in the shallow bed of the stove, and make a small teepee of three fatwood pieces in the center of that circle, lighting the fatwood pieces prior to inserting them into the charcoal bed (Fig. 6). Some pieces of charcoal were then carefully stacked on top of the lit fatwood teepee and allowed to ignite (Fig. 7). Approximately 1000 g of charcoal and 15 g of fatwood was used for each test.

Users considered the fire to be well-lit when approximately 60% – 70% of the charcoal bed was lit.

Figure 6 – Lighting the fatwood.

Figure 7 – Fully stacked charcoal bed.

It can be seen that the lighting cone did achieve its purpose of reducing the ignition time. In fact, it reduced the amount of time by about 50%. However, only one of the five Haitian user groups noticed any reduction in time, so although the cone technically saves time, a user likely would not buy or use it for that purpose.

User comments revealed other unexpected but very desirable benefits though – mainly smoke direction. Lighting a fire is one of the smokier parts of cooking. Often, users will light the fire outside and then bring the stove inside once the charcoal is well-lit. Every user commented that the greatest benefit of the cone was as a chimney. The cone stopped the smoke from blowing into the faces of children and adults kneeling by the stove. The other main benefit noted by the users was that the cone offered the fire protection from the wind, which can often extinguish the fire as it is starting.

6 Temperature Experiments

Now that the lighting cone appeared both feasible in the field and viable in the lab, lab experiments were conducted to gain temperature distribution data for the 2 ft cone.

6.1 Experimental Setup

Inconel K-type thermocouples were used to measure temperature at 3 locations: T_1 was approximately 1.5 cm below the top edge of the cone; T_2 was approximately 5 cm up from the bottom of the cone; and T_3 was 5 cm under the charcoal bed in the ash pan. All thermocouples were placed inline with the center axis of the cone. The same equipment and facilities from the prototype experiments were used with the addition of an Omega HH374 4-channel thermocouple reader used to continuously measure and record temperatures in real time (1 Hz).

6.2 Protocol

The charcoal bed was built similar to the Haitian charcoal bed, using 475 g of charcoal and 10 – 15 g of fatwood split into 3 pieces and built into a pyramid. Once the fatwood was lit, the cone was placed on the charcoal bed. The cone was left on for 5 minutes to ensure the charcoal bed was well-lit.

6.3 Results

Several temperature tests were run; a typical temperature curve may be seen in Fig. 8.

The temperatures begin to rise as soon as the cone is added to the charcoal bed; this event occurs at line A. Temperatures increase slowly at first and then much more rapidly as the fatwood and then charcoal ignites. Note the drop in temperature for T_1 and T_2 at line B. It is estimated that at this point, the fatwood had completely combusted so the thermal output momentarily drops until more of the charcoal begins to combust. The behavior of T_3 supports the conclusion that the cone is increasing the draft through the stove; when the cone is removed at line C, it substantially reduces the updraft through the charcoal bed and the heat transfers down into the stove body, radiating to the ash pan where T_3 is located.

Due to the inability to directly observe and control the placement of T_2, its temperature profile differed greatly from test to test and also during a given test depending on if it touched a lit charcoal piece or not. The temperature profile created from the thermocouple touching a lit charcoal piece was helpful to see the progress of the combustion and temperature rise in the overall charcoal bed. However, T_2 would overestimate the average air temperature at the cone bottom if T_2 was resting on a lit charcoal piece. Therefore the average air temperature in the cone was taken as the temperature of air at the top of the cone (T_1).

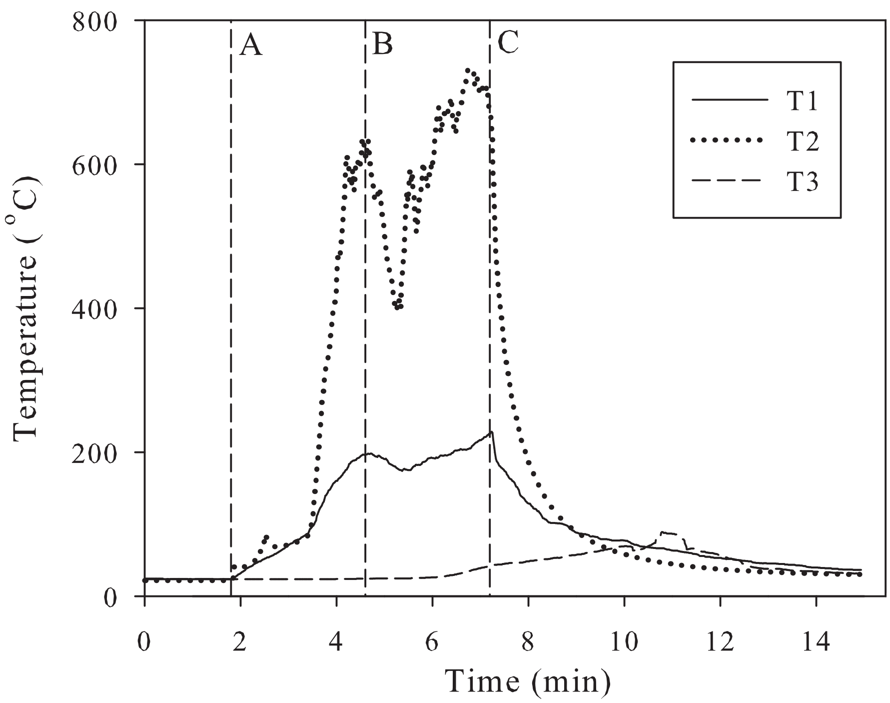
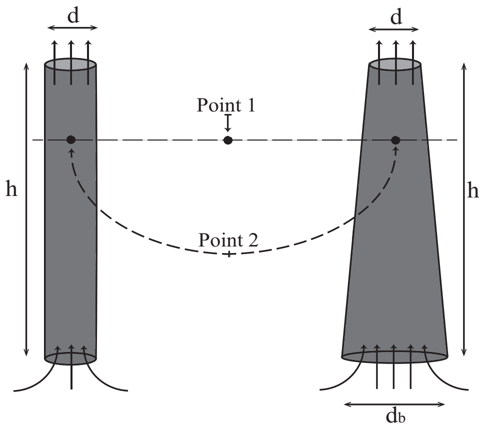


Figure 8 – Example temperature curve from the lighting cone on a charcoal fire. T_1 is at the top of the cone, T_2 is near the charcoal bed, and T_3 is below the charcoal bed. The three vertical lines mark when the cone was put on (A), when the fatwood is estimated to be fully consumed (B), and when the cone was removed from the charcoal bed (C). Note that there is only a slight lag time between the temperature fluctuations observed in T_2 with those seen in T_1(at the bottom and top of the cone). This is reflected when looking at the advective time scale for this system, which is faster even than the sampling rate at approximately 0.5 seconds.

7 Theory

Using these experimental observations, two models were used for theoretical approximation of the lighting cone: a cylindrical tube and a conical tube. The models were simplified as they are meant to be used in the field for approximating the necessary cone size for a given stove. The model is compared to the experimental data to find the percent error of using such a simplified model.

A diagram of these models is shown in Fig. 9, where $\vec{v}$ is the 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.



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 9 – Cylindrical and Conical Tube Model diagrams for flow calculations

7.1 Cylindrical Tube Model

The original model was based on a vertical cylinder with adiabatic walls. For simplicity, the flow was assumed to be steady-state both in velocity and temperature and to be air acting as an ideal gas. Changes in flow due to boundary layers were ignored.

7.1.1 Buoyancy-driven flow: Application of Boussinesq Approximation

The flow through the cylinder is created by a difference in air densities between the hotter internal air and cooler ambient air. We assume the air to be incompressible in regards to pressure, meaning the density (ρ) is not dependent on pressure.

We know that if $M < 0.3$, where M is the Mach number, the flow can be assumed to be incompressible [Anderson 2001]. As $M = \vec{v}/c$, where $\vec{v}$ is velocity and c is the speed of sound, this means if $\vec{v} < 0.3c$, then ΔP is small enough that the flow is incompressible with respect to pressure.

Using the data from the temperature tests, the average interior temperature of the tube is 150 ºC. At that temperature, $c = 412.4$ m/s, so the above condition translates to:

$$\vec{v} < 0.3\,(412.4\ \mathrm{m/s}) = 123.7\ \mathrm{m/s}$$

The velocity through the cylinder is much slower than 124 m/s, so we can safely assume density is not dependent on pressure in this model.

However, the driving force of natural convective flow is the difference between densities of the fluid, in this case creating buoyant flow. Neglecting all changes in density would neglect the body force creating the flow. Mathematically, the buoyancy term ($g\Delta\rho$) is on the same order as other forces such as inertia and acceleration, so it cannot be neglected. Therefore, we use the Boussinesq approximation which states:

$$\rho_\infty = \rho\,(1 - \beta\,(T_\infty - T)) \tag{1}$$

Typically, the Boussinesq approximation should not be used unless $\beta \Delta T < 0.3$. For our model, $\beta\,(T_{avg} = 150\,^\circ\mathrm{C}) = 2.37\mathrm{x}10^{-3}\ 1/\mathrm{K}$ and $\Delta T = 125$ K, so

$$\beta \Delta T = 0.296 \leq 0.3$$

Although we are quite close to the bounds of the Boussinesq approximation, this bound is typically used for high precision models. Since this is a simplified model, Boussinesq can still apply for our purposes.

7.1.2 Velocity Derivation

Using the hydrostatic equation, the pressure difference can be described by:

$$P_\infty - P_{avg} = g\left(\rho_\infty h - \rho_{avg} h\right) = gh\left(\rho_\infty - \rho_{avg}\right) \tag{2}$$

In general theory, the flow is broken into two regions: a boundary layer along the walls, where viscous and rotational effects are most significant, and an irrotational flow region in the center; as boundary layers are ignored in this model, the flow is therefore assumed to be irrotational [Munson, et al. 2006]. Therefore, Bernoulli's equation for incompressible flow $P_1 + \frac{1}{2}\rho\vec{v}_1{}^2 = P_2 + \frac{1}{2}\rho\vec{v}_2{}^2$ [Anderson 2001] can be adapted to this model, and we find:

$$P_\infty - P_{avg} = \frac{1}{2}\rho_{avg}\vec{v}_{avg}^{\,2} - \frac{1}{2}\rho_\infty\vec{v}_\infty^{\,2}$$

however, $\vec{v}_\infty = 0$ so

$$P_\infty - P_2 = \frac{1}{2}\rho_{avg}\vec{v}_{avg}^{\,2} \tag{3}$$

Combining Eqs. 2 and 3, we find:

$$\vec{v}_{avg} = \sqrt{2gh\frac{\left(\rho_\infty - \rho_{avg}\right)}{\rho_{avg}}} \tag{4}$$

Applying Eq. 1, we can substitute in temperature for density to get:

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

Note, Eqs. 4 and 5 do not depend on the diameter of the tube, only the height. Therefore, these equations are used for both the cylindrical and the conical tubes.

7.1.3 Chimney Effect Equation

It is important to note that Eq. 5 is analogous to the commonly-used chimney effect equation (Eq. 6) [ASHRAE 2008].

$$\dot{Q} = CA\sqrt{2gh\left(\frac{T_{avg} - T_\infty}{T_\infty}\right)} \tag{6}$$

where $\dot{Q}$ is the volumetric flow rate, A is the outlet area, and C is a constant to account for losses, etc.

We know that $\vec{v} = \frac{\dot{Q}}{A}$, and applying to Eq. 5, we find:

$$\dot{Q} = A\sqrt{2gh\beta\left(T_{avg} - T_\infty\right)} \tag{7}$$

For an ideal gas, $\beta = \frac{1}{T}$, and Eq. 7 would likewise need a constant to account for losses, etc. Thus, the two equations are the easily comparable.

7.1.4 Losses

The pressure difference due to kinetic losses throughout this simple system can be represented by:

$$\Delta P_{loss} = \alpha\left(\frac{1}{2}\rho\vec{v}_{avg}^{\,2}\right) \tag{8}$$

with the coefficient of losses, or the kinetic correction factor (α), broken down into 5 components [ASHRAE 2005]:

$$\alpha = k_a + k_{in} + k_{out} + k_c + k_r$$

where

k_a	losses due to acceleration
k_{in}	losses at the inlet
k_{out}	losses at the outlet
k_c	friction losses
k_r	losses due to obstructions in the flow (rods, etc.)

From the ASHRAE handbook for an upright duct, k_a, k_{in}, and k_{out} are equal to 1, 1, and 0, respectively. As we are examining the section of the duct above the charcoal bed, k_r equals 0. From Brinkworth [Brinkworth and Sandberg 2005], we know that frictional losses (k_c) can be found using:

$$k_c = \frac{f_s h}{d_h}$$

where h is the length of the tube and d_h is the hydraulic diameter. For a cylinder, $d_h = {}^{4A}/_{P} = 2r = d$ and $f_s \simeq 0.316\, Re^{-1/4}$ for the turbulent regime. The Reynolds number (Re) is defined as:

$$Re = \frac{\vec{v} d_h}{\upsilon}$$

When including Eq. 8, the velocity formula becomes

$$\vec{v}_{avg} = \sqrt{\frac{2gh\beta}{\alpha}\left(T_{avg} - T_{\infty}\right)} \tag{9}$$

To see if the flow is still developing in the turbulent regime, the entrance length (L_e) of the tubes can be found using the Reynolds number and forced flow equations. Since we are treating the temperature on the interior of the tubes constant, it is as though the air is forced through the tube by the pressure difference and therefore, we can reasonably use forced convection equations. We find:

$$L_e = E_l\, d_h$$

where E_l is the entrance length number calculated for the turbulent regime by:

$$E_l = 4.4\, Re^{1/6}$$

7.1.5 Calculations for Cylindrical Tube Model

We know T_{avg}= 150 ºC = 424 K and ΔT = 125 K, so our defined variables are:

$\rho_{avg} = 0.83$ kg/m³	$c_p = 1.018$ kJ/kg K
$\beta = 2.37\text{x}10^{-3}$ 1/K	$d = d_h = 0.102$ m
$\upsilon = 29.181\text{x}10^{-6}$ m²/s	$h = 0.6$ m

Using these values, we can find the velocity through the cone using Eq. 5 and we get:

$$\vec{v}_{avg} = 1.86 \ \mathrm{m/s}$$

Using this velocity, we calculate the Reynolds number:

$$Re = 6491.8$$

which is in the turbulent regime. The entrance length is calculated to be 1.93 m, therefore the flow is still developing.

To calculate the loss coefficient (α), we first find the losses due to friction: $f_s = 0.035$ which lead to $k_c = 0.208$. Therefore,

$$\alpha = 1 + 1 + 0 + 0.208 + 0 = 2.208$$

Substituting α into Eq. 9, we find that the velocity through a cylinder is

$$\vec{v}_{avg} = 1.25 \ \mathrm{m/s}$$

7.2 Conical Tube Model

As Eqs. 4 and 5 do not rely on the volume of the tube, only the height, the conical tube model is different from the cylindrical tube model through losses. Calculating the hydraulic diameter, $d_h = \frac{4A}{P}$ where A is area and P is the perimeter, we find that $d_h = 0.17$ m.

Calculating the Reynolds number from this, we find that $Re = 10835$, indicating this is turbulent flow. The entrance length is calculated to be 3.5 m, and again the flow is still developing.

For a conical chimney, k_a= 1, k_{in}= 0.5, k_{out}= 0.5, k_r= 0, and k_c= 0.18. Therefore, velocity through a conical chimney is:

$$\vec{v}_{avg} = 1.26 \ \mathrm{m/s}$$

The differences between the cylindrical and conical tube model calculated velocities end up being negligibly different with this model.

8 Power / Flow experiments

For comparison with the basic models, the volumetric flow rate through the cone was determined experimentally.

8.1 Experimental Setup

Different methods for measuring the flow rate were considered. Ideally, laser doppler velocimetry could be used; however, the cost deemed it unfeasible. A hot-wire anemometer was ruled out as the thin wire quickly would become clogged with soot from a fire. An SF_6 tracer gas setup ran the risk of vaporizing SF_6 into toxic byproducts at high temperatures which would be quite dangerous. Because these methods were unacceptable, a CO_2 tracer gas system was used to measure the flow rate even though a real charcoal fire could not be used for the tests as the CO_2 produced in charcoal combustion would obscure the tracer gas.

Therefore an electric "charcoal" bed (e-bed) was designed to mimic the charcoal fire. This e-bed consisted of a hot plate controlled by a variac, so the power input could be held constant, instead of the automatic temperature cycling of most hot plates. The actual wattage was measured using a Kill-A-Watt electricity load meter.

Two K-type, Inconel thermocouples were used to measure the temperatures at the top and bottom of the cone. The top thermocouple (T_1) was located slightly below (1.5 cm) the center of the top of the cone. The bottom thermocouple (T_2) was attached to the heating coil of the hot plate approximately 4 cm from the center of the heating coil. A Sensidyne Gilibrator-2 recorded the flow rate of the injected CO_2 using the standard size cell (20 cc/min to 6 LPM). Measurements were taken every 30 seconds over a period of at least 10 minutes. The exiting CO_2 concentration was measured using a PP Systems EGM-4 Environmental Gas Monitor for CO_2 at 1 Hz, recorded in real time.

Various CO_2 tracer gas injection configurations were tested for suitability. A manifold designed to inject CO_2 into the bottom of the cone at multiple points was found to be the best option. The manifold consisted of quarter inch copper tubing that ringed the inside of the bottom edge of the cone. Injection came from 18 holes (0.1 cm diameter) angled at 45 degrees from the upward flow stream through the cone. CO_2 was collected by a straight quarter-inch copper tube with 10 holes (0.1 cm diameter) spaced 0.95 cm apart facing straight down into the flow. These holes were consistently spaced but offset from the center axis to ensure a good distribution of CO_2 was collected across the top of the cone.

To double check this collection system, ensuring the flow was not over or under sampled, a single line collection device was used to observe the distribution of the CO_2 concentration as it emerged from the cone. The single line collection point was moved across the center line of the top of the cone. Data was collected at 5 locations, each being held for 10 minutes. The results of these 5 points were less than 15% different from each other, so the distribution was considered well sampled.

8.1.1 Experimental Calculations

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 exit velocity from the cone was then calculated by dividing the volumetric flow rate by the exit area of the cone.

8.2 Results

The results of these trials focus on two main aspects: (1) temperature and (2) the relation between the input thermal power and the outlet air velocity.

8.2.1 Temperature curves

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 (968 W), with the real charcoal temperature being 150 ºC and the e-bed being 155.5 ºC.

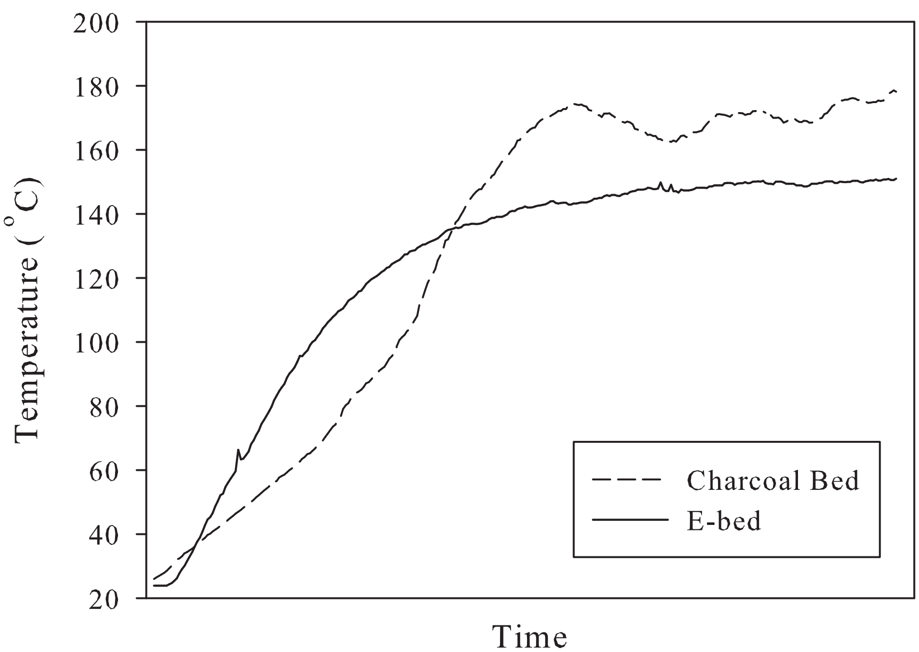


Figure 10 – Comparison of the temperature trends for the e-bed and the real charcoal experiments as measured at the top outlet of the cone.

Fig. 10 shows a comparison curve between the temperatures produced by the real charcoal fire and the e-bed. Although overall the charcoal fire became hotter than the e-bed over the course of the test, the average temperatures of the charcoal fire varied by 35% between tests. Accounting for the error associated with such variations in data, the e-bed and charcoal fires are relatively similar.

8.2.2 Power vs. Velocity

The power input was controlled over the tests, measuring the changes in flow rate and therefore velocity. The results, averaged over all trials, can be seen in Fig. 11.

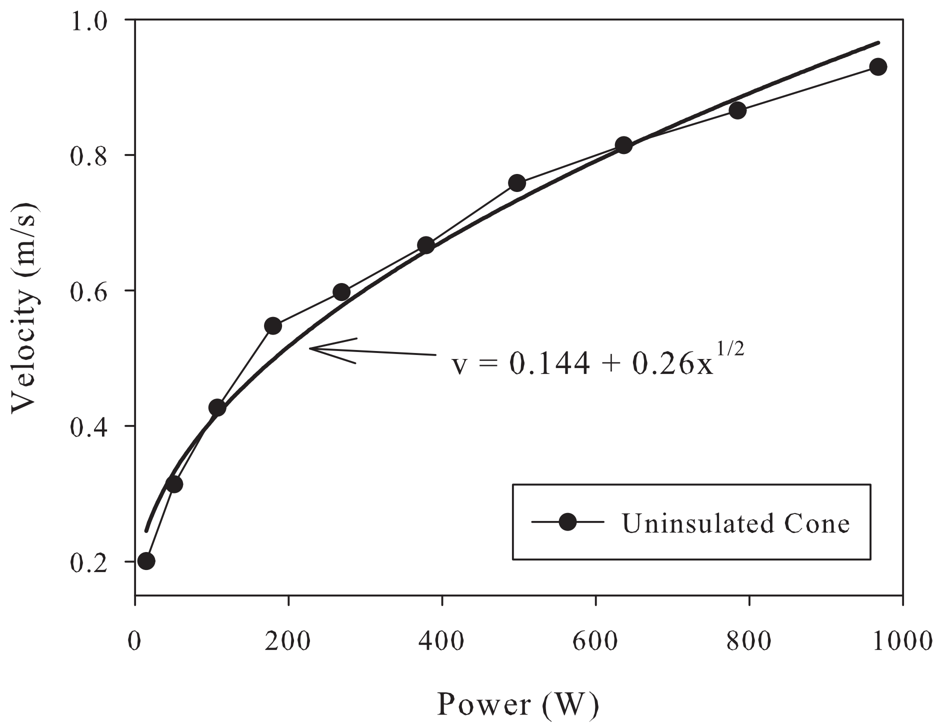


Figure 11 – Power vs. Velocity for E-bed tests.

A best-fit trendline of the curve in Fig. 11 would be a power curve of order 0.4. However, as can be seen in Fig. 11, if a power curve of order 0.5 is forced fit to the curve, it is still a reasonable match. This is in good agreement with the model, in which velocity has a square root dependence on temperature. As temperature is proportional to thermal power (see Section 9.2 for more detail), the model states that velocity is proportional to the square root of power, which is validated by the experimental data.

8.2.3 Adiabatic Walls

Trials were conducted with an insulated cone to judge the real effects of heat losses through the walls. 2.5 - 5 cm of mineral wool insulation 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. 12.

The insulation made little difference to the flow velocity or temperature, indicating losses through the walls for a cone of this size are negligible as assumed for the model.

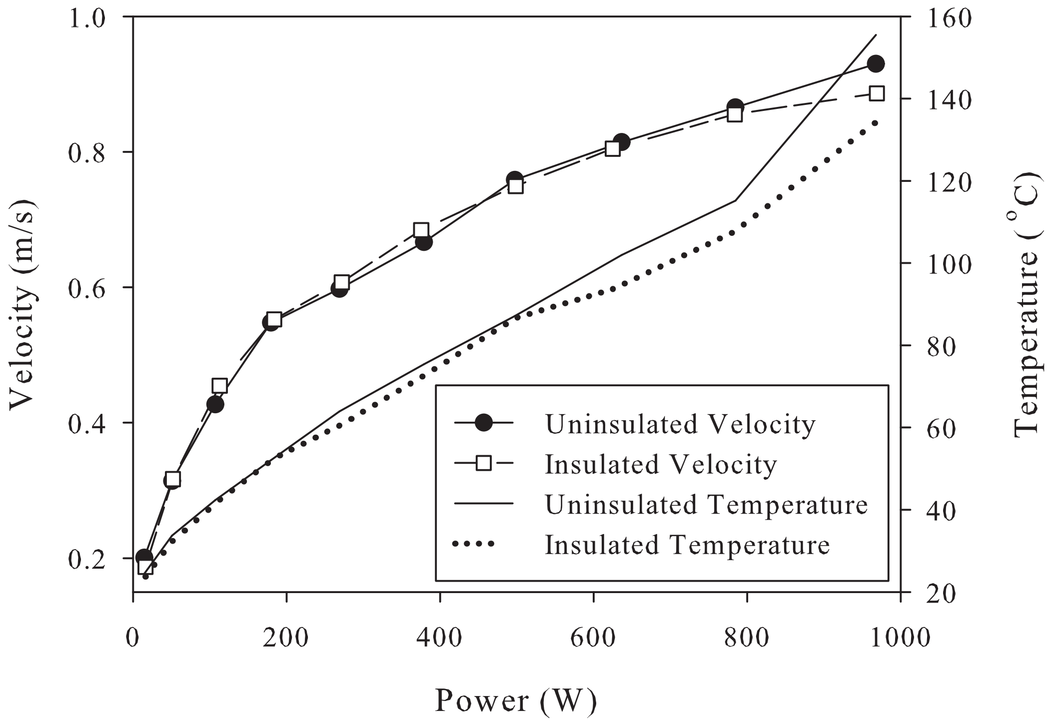


Figure 12 – Insulated vs. Non-insulated cone trials.

9 Comparing Model, Theory, and Experiments

For comparison between the model and experiments and as validation of the experimental data, we found thermal power in 3 ways: the experimental results, general thermal theory, and our model results.

9.1 Thermal power from experimental results

The power input was measured over the course of the test. All electrical power is assumed to turn into thermal power, with mechanical power use and system losses deemed negligible. At full power, which produced equivalent temperatures to the real charcoal fire, the thermal power is 968 W.

9.2 Thermal power theory calculations

In theory, thermal power can be calculated by

$$P_T = \rho \, c_p \, \Delta T \dot{Q} \tag{10}$$

To check the validity of the experimental results, we substituted the results for ΔT and $\dot{Q}$ into the known theoretical equation. At full power, $P_T = 854.5$ W, a percent difference of only 12.5%. Across all power ranges, we found an average percent difference of 19.8%, which indicates reasonable agreement between the theory and experiments.

9.3 Thermal power from model results

Using the temperature of the e-bed at maximum power, the model predicts $\vec{v}_{avg} = 1.3$ m/s.

From there, calculating the volumetric flow rate and substituting into the theoretical equation for thermal power (Eq. 10), we find $P_T = 1.19$ kW. Comparing this value with the experimental results provides only a 20.5% difference, thus further validating the model as an acceptable rough approximation for lighting cone design.

10 Conclusions

The model proposed here can provide a rough working approximation of the parameters required for a lighting cone and a way to test those parameters to achieve the desired flow rate through the cone. The conclusion is bounded, however, by extreme dimensions, which should be further explored in future work.

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.

It is important to note that the ignition time is a small portion of the time spent cooking, easily 15% or less of total cooking time. Therefore, any effects created by using a lighting cone on efficiency, fuel consumption, and emissions are likely negligible in comparison to the effects from the rest of the cooking period; the lighting cone in this study is intended as a convenience for Haitian cooks to save time, protect the fire, and direct the smoke.

The three main conclusions that arise from this work are:

1. Lighting cones perform well both in the lab and in the field to shorten lighting time.
2. Lighting cones appear to be acceptable to the Haitian culture, at least based on exploratory observations.
3. The simplified model presented here adequately estimates the main components for lighting cone design and could be used in the field or for first draft prototyping.

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