Cook stove Efficiency, Health and Environmental Impacts

Biomass Lab Report

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CONTENT

1. Introduction

The purpose of this experiment was to compare the performance of a traditional charcoal-burning cookstove with an improved version of the same stove. The stoves we tested were the traditional, Kenyan Jiko, and improved Jiko that was equipped with a ceramic liner. The Jiko is portable, weighing under five kilos, and is popular in rural and urban households in Kenya. The study was carried out under standard laboratory conditions, but it must be emphasized that the findings are anecdotal in nature, as we had the opportunity to test each stove only once. This being said, all efforts were made to gain a meaningful data set, and we observed distinct differences in the way the two stoves performed. Performance was was judged on these criteria: boiling time, fuel efficiency during high and low-power phases, carbon monoxide emissions, and more subjectively, the ease of use. These are factors that are likely to affect the both health and quality of life of the user. Such potential benefits, however, must be examined within the context of the likelihood that users will adopt the improved stove.

Both of the experiments were conducted under a ventilated fume hood, using the following standardized procedure.

1) Record the empty stove weight
2) Fill the stove to capacity with mesquite charcoal, and reweigh it.
3) Weigh a cookpot before and after filling it with water(the same pot was used twice)
4) Allow the water to equilibrate with the room, and record the temperature.
5) Calibrate the carbon monoxide detector.
6) Apply an electric charcoal lighter for two minutes, until the charcoal begins to glow.
7) Stir the coals, and wait an additional two minutes until the fire is burning evenly throughout the cooking region.
8) Place the uncovered cookpot on the stove, and begin testing.
9) Situate the CO detector one inch away from the pot, and two inches above its base. (Be sure to match this placement exactly for both tests.)
10) Record CO readings every minute for the duration of the test.
11) Record the water temperature every three minutes.
12) When the water begins to boil, note the time, and reweigh both the pot and the stove.
13) Return the pot to the stove to test on low-power, or simmering mode. To do this, use the airflow control door at the base of the stove to maintain a constant temperature.(+/- 2 degrees) for 30 minutes, or until temperature cannot be maintained.

The first half of the experiment proceeded nearly identically for both stoves, but during the low-power phase it diverged dramatically. The metal stove had already consumed so much of its fuel during the high-power phase, that we had difficulty in maintaining water temperature, even with the airflow door partially open. We ceased testing when the temperature began dropping below the simmering level. The improved stove was markedly easier to use. We were able to maintain the low-power phase for a full half-hour at the desired temperature, and even at that point, it showed no signs of going out. Our results suggest that overall, the ceramic-lined Jiko is superior in some ways. It must be restated that this did not constitute a rigorous, scientific study of the two stoves. It is impossible to perform two tests with complete accuracy, and other factors, such as our increasing familiarity with the stove design, could have skewed our results in favor of the stove we tested second(the improved one).

2. Cookstove Efficiency

Calculate the firepower and efficiency of each of cook stoves

Firepower is energy released by the burning fuel at unit time. So for any phase of combustion, firepower can be calculated as follows:

$$\text{Fire power (W)} = \frac{(M_{ci} - M_{cf}) \times H_c}{\text{time}}$$

Where: P = power (W)

M_{ci} = initial mass of charcoal in the cook stove (g)

M_{cf} = final mass of charcoal in the cook stove (g)

H_c = energy content of charcoal (29000J/g)

time = time of combustion phase (s)

Efficiency is the ratio of energy absorbed by water in the cooking pot to energy released by the burning fuel. In the hi-power and low-power phases, the water has different properties and energy absorbed by water and is calculated using a different equation. They can be divided into the energy required to raise the temperature of water and energy required to evaporate the water. So the efficiency can be expressed as follows:

during hi-power phase: $$\text{Efficiency (\%)} = \frac{M_w \times C_w \times (T_f - T_i)}{(M_{ci} - M_{cf}) \times H_c}$$

during low-power phase: $$\text{Efficiency (\%)} = \frac{H_w \times (M_{wi} - M_{Wf})}{(M_{ci} - M_{cf}) \times H_c}$$

Where: M_w = average water mass in the cook pot from pre-start to first boiling

C_w = heat capacity of water (4.184J/g ^oC)

T_f = temperature of first boiling (^oC)

T_i = initial temperature of the water in the pot (^oC)

H_w = heat of vaporization of water (2260J/g)

Analyzing the data, we can get the following results:

KCJ (Kenya Ceramic Jiko):

Hi-power phase:

$$\text{Fire power (W)} = \frac{(M_{ci} - M_{cf}) \times H_c}{\text{time}} = \frac{148g \times 29000J/g}{14\,\text{min} \times 60s/\text{min}} = 5110\text{ W}$$

$$\text{Efficiency(\%)} = \frac{M_w \times C_w \times (T_f - T_i)}{(M_{ci} - M_{cf}) \times H_c} = \frac{2043g \times 4.184J/g^oC \times (93.0 - 20.1)^oC}{148g \times 29000J/g} = 14.5\%$$

Low-power phase:

$$\text{Fire power (W)} = \frac{(M_{ci} - M_{cf}) \times H_c}{\text{time}} = \frac{115g \times 29000J/g}{31\,\text{min} \times 60s/\text{min}} = 1793\text{ W}$$

$$\text{Efficiency (\%)} = \frac{H_w \times (M_{wi} - M_{Wf})}{(M_{ci} - M_{cf}) \times H_c} = \frac{2260J/g \times 509g}{115g \times 29000J/g} = 34.5\%$$

Metal Stove:

Hi-power phase:

$$\text{Fire power (W)} = \frac{(M_{ci} - M_{cf}) \times H_c}{\text{time}} = \frac{138g \times 29000J/g}{17\,\text{min} \times 60s/\text{min}} = 2924\text{ W}$$

$$\text{Efficiency(\%)} = \frac{M_w \times C_w \times (T_f - T_i)}{(M_{ci} - M_{cf}) \times H_c} = \frac{2652g \times 4.184J/g^oC \times (93.5 - 23.2)^oC}{138g \times 29000J/g} = 19.5\%$$

Low-power phase:

$$\text{Fire power (W)} = \frac{(M_{ci} - M_{cf}) \times H_c}{\text{time}} = \frac{19g \times 29000J/g}{14\,\text{min} \times 60s/\text{min}} = 656\text{ W}$$

$$\text{Efficiency (\%)} = \frac{H_w \times (M_{wi} - M_{Wf})}{(M_{ci} - M_{cf}) \times H_c} = \frac{2260J/g \times 139g}{19g \times 29000J/g} = 57\%$$

From the results, we can see that the metal stove has higher efficiency than the KCJ. From the data of metal stove we can see that in the low-power phase, the boiling temperature didn't remain constant, and dropped from 93.5^{o}C to 85.0^{o}C. For water evaporating lower than 90^{o}C, the H_v (heat of vaporization) is less than 2260 J/g, at the same time the water releases energy as it's temperature dropped, so the calculation exaggerates it's efficiency. The lower-power phase of Metal Stove needs some adjustment, because we used only about 300 grams of charcoal in the metal stovewhich was almost used up during the hi-power phase. We couldn't maintain the temperature even with the door open. The low-power phase is from the 18th to 24th minute, that is as the temperature dropped from 93.5^{o}C to 89^{o}C. The H_v still remains constant 2260J/g and the water evaporates linearly to time. During the 7 minutes' low-power phase, the charcoal was used up. During the remaining minutes, the temperature dropped naturally without absorbing energy from the stove.

After the adjustment, the evaporated water with H_v is 139 × 7 ÷ 19 = 51g and the consumption of charcoal is still 19g.

Low-power phase: (Metal Stove)

$$\text{Efficiency (\%)} = \frac{H_w \times (M_{wi} - M_{Wf})}{(M_{ci} - M_{cf}) \times H_c} = \frac{2260J/g \times 51g}{19g \times 29000J/g} = 21\%$$

So we obtain the following results:

Table1

		Metal	KCJ
Hi-power phase	Fire Power (W)	2924	5110
	Efficiency (%)	19.5%	14.5%
Low-power phase	Fire Power (W)	656	1793
	Efficiency (%)	21.0%	34.5%

From the final result we can see that both stoves have higher Fire Power in hi-power phase than the low-fire phase, and higher efficiency in the low-power phase than in the hi-power phase.

Compare the performance of the two kinds of stoves:

During the hi-power phase, the metal stove has a higher efficiency than the KCJ. Because we used about 300 grams of charcoal in the metal stove and the pieces of charcoal were relatively small, all of them were almost lit when we began our lab and they all had completed combustion before and around the boiling degree. So after boiling, we couldn't keep the up temperature anymore even after opening the door, as the charcoal was almost used up. It can be seen that fire power dropped from 2924W to 656W, as the efficiency rose from 19.5% to 21.0%, partly because when water temperature drops, it releases energy and it's vaporization heat is lower than 2260J/g.

In the KCJ, we used about 530 gram charcoal and most of them were quite big (we tried to split them, but couldn't find suitable tools). When we began our lab, they were only partly lit. Even when we reached the boiling point, some of the charcoal hadn't lit. So after boiling, the temperature kept going up even when we closed the door. The amount of charcoal combusting during the hi-power phase was different, even though the ceramic stove has better insulation than the metal stove, the efficiency of metal is higher than the ceramic stove. After boiling, when we closed the door, the CO concentration went up, and this indicates that more incomplete combustion occurred, so the fire power dropped from 5110W to 1793W. But as the charcoal became more fully lit during the low-power phase, the efficiency improved from 14.5% to 34.5%.

In the low-power phase, the ceramic stove's efficiency was 34.5%, higher than the metal stove at 21.0%. This is the result of the great heat conduction property difference between ceramic and metal. Metal conducts heat faster and ceramic can store and conduct heat slowly. So ceramic lining prevents more energy from being released into the environment and absorbs energy to keep the temperature of stove at a constant.

We can also compare the performance of the two stoves through the following table:

Table 2

	hi-power time (min)	*low-power time (min)*	*water (g)*	*charcoal in stove (g)*	*the charcoal used (g)*
KCJ	14	31	2079	530.0	344.0
Metal	17	7	2723	303.5	225.0

Suggestions: we should use the same amount of charcoal and water in the two stoves to compare their performance more easily.

3. Health and environmental impacts of cook stoves

Charcoal cook stoves are often used in indoors, with inadequate ventilation this can result in negative health impacts for its user, and their family. Different stoves emit different levels of pollutants. Therefore the choice of stove a family decides to use could have a significant impact on their health. In this experiment the level on carbon monoxide released from two stoves over the course of a cooking cycle were observed and compared. Carbon monoxide is important to study not only because of its direct negative impact on health, but also because it is an indicator of other harmful pollutants such as particulate matter (PM).
The two stoves were compared in two phases; high power in which water was being brought to boil and the coals were given a maximum amount of air; and low power in which water was simmering and the airflow to the coals was restricted. For each of these phases the average and peak readings were recorded, and the ratio between the peak and average was also recorded.

Ratio = Peak / Average

The results displayed in the appendices and are summarized in the following table.

Table 3

	Metal	KCJ
Average-high phase	1176 ppm	769 ppm
Average-low phase	621 ppm	851 ppm
Peak-high phase	1870 ppm	1597 ppm
Peak-low phase	1000 ppm	934 ppm
Ratio-high phase	1.59	1.63
Ratio-low phase	1.61	1.47

Before the results of the trial are compared, it is important to point out some differences in the operation of the stoves. The metal stove burned its fuel much faster then the KCJ. This, combined with it having less initial fuel, resulted in discrepancies between the different phases of the test. The initial high power phase results, when the water was being brought to boil, are reliable for both stoves. During the metal stove's low power phase the temperature dropped slightly, so the door was opened to maintain temperature. However, by that point there were not enough coals to keep the water hot even with the full amount of air flowing through. Therefore for the Metal stove only the numbers from the first high power phased have been used (min1-17).
In the high phase he Metal stove appeared to have higher emissions than the KCJ. This is due to several reasons. First it burned through charcoal faster, which would obviously result in increased amounts of pollutants. The KCJ appeared to maintain a more even heat through out the chamber resulting in more complete combustion. The Metal stove operated more like an open fire with a center of red coals, with darker bits on the sides. The unevenness of the coals, which resulted from the quickness of this stove, and lack of insulation, resulted in an increase in CO.

In the low phase the stoves were just about even in terms of emissions, with the metal stove slightly lower. Whether this was due to some stove design feature or simply fewer coals is hard to determine without continued testing.

The benefits to a household using an improved stove are substantial. According to the World Health Organization more people die from respiratory aliments then HIV/AIDS, Malaria and all childhood diseases combined. Although smoking undoubtedly plays a large role in that so does air pollution. Almost all of the worlds exposure to air pollution happens indoors, with 90% of that being in the developing world (Smith 1988). Indoor pollution in developing countries is a problem affecting millions of people’s lives, to which there is no easy solution.

Decreasing the pollution produced by cook stoves has real advantages for households. The benefits are greatest for the women in the family (who do most of cooking) and the children, who spend a lot of their time indoors, and are more affected by air pollution. An improved stove that drastically reduces indoor pollution levels would result in drastically reducing incidences of respiratory diseases. Improved stoves also help families economically, by saving on fuel cost, or on the time devoted to gathering fuel.

Designing stoves so that combustion is more complete and pollution is thereby reduced, decreases user’s exposure to indoor air pollution. Adding insulation causes the combustion chamber to have more even heat. Decreasing the gaps that heat is allowed to escape from, saves fuel and decreases the amount of CO released per cooking cycle.

There are ways of reducing indoor air pollution other then direct improvements to cook stoves. Ventilation can greatly reduce the amount of pollutants indoors. Even better—cooking outside. Unfortunately both of theses alternatives are often contrary to local weather of culture. Also using other fuel, though perhaps more expensive, other result improved air quality.

In addition to immediate human health impacts, cook stove efficiency also plays a role in global climate change. The main product of combustion, CO_2, is neutral from biomass burning since grow plants sequester it from the air. However CO and other products of incomplete combustion can have a significant impact on global climate. Although usually released in small quantities PICs can have a detrimental effect on global warming many times, some times hundreds, that of CO_2. In the developing world many countries largest contribution to climate change is from biomass. Improved stove can reduce these gases both buy requiring less fuel to cook at given meal, and also by the more efficient combustion of materials, thereby reducing PICs.

4. Carbon monoxide comparisons

Table 4 Carbon Monoxide Emissions

	Metal Jiko	KCJ
Mean CO Emissions	921ppm	769ppm

Standard Deviation	401ppm	329ppm
High Power Emission	1176ppm	769ppm
Low Power Emission	621ppm	851ppm

The data we collected on carbon monoxide emissions has little to no statistical significance. This is at least partially attributable to the very small sample size. Other tests of CO emissions have been hindered by similar problems (Ezzati 2000). Small inconsistencies in the testing conditions are very likely to have affected results more than any real difference in the performance of the two stoves. These include, but are not limited to: improper calibration of the detector, different airflow currents in the laboratory resulting from the opening and closing of doors, etc., and perhaps most importantly, the precise placement of the detector in relation to the stove. Data were recorded at an approximate distance of two inches above, and one inch away from the base of the cook pot. In contrast, Ezzati et al. carried out their tests at a distance of .5x.5 meters away, which is a more realistic distance of exposure in the home. We were limited by our testing conditions. As a result, our CO concentration readings are much higher for each stove, as would be expected. The purpose of studying CO levels is to determine exposure levels of people who use the stoves in their homes, not to collect laboratory data for its own sake. Future tests should be carried out in the home whenever possible, although as found by Ezzati, meaningful results may still be difficult to obtain with a limited sample size. Furthermore, it appears that there is only a weak correlation between CO emissions, and particulate matter (PM). Acute and chronic health effects from the use of charcoal-burning cook stoves are likely attributable more to exposure to PM's, so they should be measured directly whenever possible. For the reasons stated above, further discussion of CO emissions will refer to the data gathered by Ezzati, as our data is inadequate.

The problem of quantifying exposure to harmful stove emissions is further complicated by the differences in individual behavior within a household. It is not enough to simply take day-long averages of emissions, and assume that each family member is exposed equally. Division of labor often means that cooking and stove-tending responsibilities are taken on by a single individual. Furthermore, short periods of intense exposure may be at least as detrimental to the health as prolonged periods of low-level exposure (Ezzati 2000). The highest average emissions occur during the high-power phase, a time when someone is likely to be standing over the stove preparing food. From the limited available data, it seems that a peak during this phase occurs just after ignition of the charcoal, when the fire is not yet burning evenly. Lower temperature during this initial time period leads to incomplete combustion of the fuel. As this is a time when the stove is not yet producing usable heat, public health may benefit from an advisory not to stand near a stove during this short period.

Overall, the primary benefit of the CKJ seems to be in its increased fuel efficiency, which is what it was designed for. It appears that moderate reductions in CO and PM may also be gained, but these need to be studied in further detail. Future studies need to carefully monitor the behavior of the people who face the highest level of exposure. Amount of exposure may, in fact, be more the result of individual behavior than stove design. For instance, any benefits gained during the high-power phase could easily be offset if the KCJ is left to smolder in the house after use, as its higher fuel efficiency may prolong this period. The main concern of researchers should be to improve the quality of life of the stove user. To do this, a careful monitoring of emissions must be coupled with an intimate understanding of how the stove is used within the household.

5. Cookstove Efficiency

Typically when cooking, we use the boiling water to cook with; that is the low-power phase, as it use less fuel but higher efficiency. So we can use the efficiency 34.5% and 21.0% to compare the performance efficiencies of the two stoves.

From Samuel F. Baldwin (1986) *Biomass Stoves: Engineering Design, Development, and Dissemination*, Chapter II, page 11, we can get the following table:

Table 5 Energy Consumption in Kenya Percent of National Total * by End-use

	Non-traditional fuel (%)	Biomass (%)		
		wood	charcoal	other
Urban Household				
Cooking/Heating	0.8	1	3.3	-
Lighting	0.6	-		-
Other	0.2	-	0.5	-
Rural Household				
Cooking/Heating	0.2	45.3	2.8	2.7
Lighting	1.1	-	-	-
Industry				
Large	8.6	5.3	0.3	-
Informal Urban	-	0.1	0.6	-
Informal Rural	-	9.1	0.1	-
Commerce	0.6	0.5	0.1	-
Transportation	13.7	-	-	-
Agriculture	2.5	-	-	-
Total	28.3	61.3	7.7	2.7

- Total National Energy Consumption = 332 million GJ
- Per Capita Power Consumption = 658 W

We assume that urban and rural households all use stoves (Metal or Ceramic) to cook/heat. The fuel of stoves are biomass and the stoves have the same efficiency whatever the fuel is wood or charcoal. To simplify the compare, we assume the category of other biomass belongs wood. So

energy from wood will be 49% $\times$332 million GJ = 169×10^{15} J

energy from charcoal will be 6.1%$\times$332 million GJ = 20×10^{15} J

Assume energy content of wood is 16000J/g and charcoal is 29000J/g. So we can get the amount of wood and charcoal consumed by dividing the energy with the energy content and efficiency. The result is shown in the table:

Table6

	wood (Mt)	charcoal (Mt)
Metal (21.0%)	47.6	3.3
Ceramic (34.5%)	29.0	2.0
saving amount	18.6	1.3
Saving percent %	39.1%	39.4%

We can assume that the cost of charcoal and wood remains constant although the production may decrease or increase, that is there is no scaling up for the fuel market. According to *Biomass Stoves*, in page 15 Table 12, we estimate the cost for wood at \$3.70/tonne, and cost of charcoal at \$114/tonne (from the Earth Mound in Thailand). So we can deduce that the improved ceramic stove will save \$69 million for wood and \$148 million for charcoal, and the total is \$217 million.

From table 5, we can also deduce the population in Kenya is 16 million and we assume there are 4 people in an average family, so there will be 4 million households.

Suppose the cost of ceramic stove is \$5 and the number of households in Kenya is, we can get the simple pay back time is:

$$T= \frac{\$5 \times 4 \textit{million}}{\$217 \textit{million}/\textit{yr}} \times 12 \textit{ month/yr} = 1.1 \text{ month}$$

From the result above, we can see that the ceramic stove can bring great benefits to households.

From table 6, we get that 56.1% of energy consumed is for cooking and heating. 6.1% of households use charcoal and could save \$148 million if they use the improved stove. More practically, we assume that only these households use stoves, that is 6.1/56.1* 4 million = 0.4 million household use stoves. So the new pay back time is almost 5 days.