MCGILL UNIVERSITY

Final Report

Improved cooking stoves for the combustion of rice husks

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Executive Summary

The biggest share in the supply of energy in rural areas of developing countries is normally from biomass, fuelwood often accounting for a major proportion of it. Nowadays, several villages in sub Saharan Africa are using the 'three-stone fire' stove in which wood logs are used as fuel. Not only are these stoves inefficient (≈8% efficiency), but the process proves to be harmful to the environment as forests are being cleared off resulting in deforestation, atmospheric pollution and adverse health effects. To address the current issues, an improved cooking stove called the 'insulating three-brick' stove has been designed. The 'insulating three-brick' stove not only proved to be more efficient (≈14.06%) but the emissions of carbon monoxide and nitrous oxides were ≈81% less than the 'three-stone fire' stove. Although the social costs related to the implementation of the stove in the West African villages could not be evaluated, several design parameters were modified to take the criterion into consideration. The stove was constructed with clay (which is abundant in supply in West Africa) and the increase in the cost of construction between the 'three-stone fire' stove and the 'insulating three-brick' stove was kept at a minimum level ($4).

Key words: improved cooking stove (ICS); social costs; efficiency; emissions.

1. Introduction

1.1 Problem Definition

Deforestation has become a major problem in West Africa, necessitating the replacement of the present stove design for the conservation of wooden biomass. According to the UN Food and Agricultural Organization (FAO), nearly half of the world's present population lives in areas suffering from acute fuelwood scarcity or deficit (Manibog 1984). These numbers are only expected to grow in the future because unlike the energy crisis, the fuelwood crisis has shown no signs of easing during recent years.

Figure 1: A typical 'three-stone fire' stove. (Photo credit: Dr. Robert Kok).

In West Africa, the present 'three-stone fire' stove is not only inefficient in its combustion process (≈8% efficiency), but it also causes environmental degradation and indoor air pollution (due to high levels of pollutant emissions) leading to various respiratory diseases amongst the villagers (Ballard-Tremeer and Jawurek 1996). The 'three-stone fire' stove emits 200mg/L of carbon monoxide. Carbon monoxide is the only gas that is considered for emissions calculations because it is produced in the largest amount during wood combustion. Even though there are drawbacks to the

usage of the 'three-stone fire' stove, it is the most popular stove in West Africa simply because of its low cost (<$1) (MacCarty, Ogle et al. 2008).

Many governments and other aid sources are desperately looking for solutions to replace the current stove design. Improved cooking stoves are believed to be one of the many alternatives that are being employed to address this issue. Programs for implementing improved cooking stoves are present all around the world today. Efforts have been made to design and disseminate improved cooking stoves in countries such as Guatemala, India, Kenya, Nepal, Sri Lanka and West Africa. The improved cooking stoves are a major upgrade from the traditional 'three-stone fire' stove in West Africa (Smith, Dutta et al. 2007), as it drastically reduces fuel wood consumption (greater energy conservation) and improves the health of the rural population (reduced emissions). Several improved cooking stoves have already been distributed in Africa over the past. The most notable of these stoves are the jiko (Barnes 1994) and the Zambian charcoal stove (Kammen 1995). However, the widespread adoption of these stove designs for everyday use was hindered due to the fact that the distribution agencies were more concerned about the total number of stoves that were being disseminated rather than the determination of the effects and impacts of the stove on the rural population (Gill 1987). There was no mention of any kind about the felt needs of the end users.

1.2 Design Parameters

The level of indoor air pollution and the efficiency being respectively high and low for the 'three-stone fire' stove, a stove design which enhances these two parameters is targeted. The critical parameter is the efficiency of the combustion process because it has two main effects. It allows the stove to give off less harmful gases that are the product of an incomplete combustion and it also allows cooking or boiling the same quantity of food or water with a lower fuel input. In order to implement a stove which improves these two factors, a third and equally important criterion known as "social costs" needs to be taken into account. In fact, a smooth and eased implementation of the stove is desired within the community. Hence, the proposed stove design has to be similar to the present stove, in both the physical aspect as well as in its inherent features. The objective is to avoid designing a stove which would prove to be a 'quantum leap' comparatively. For instance, not only does the designed stove need to provide lighting to the community, it also needs to provide heating and it has to repel insects. In other words, the stove has to act as a gathering agent for the community. Using materials that are used to construct the 'three-stone fire' stove is also a measure of the ease of implementation. It has been shown that not taking this criterion into consideration in the design of an improved cooking stove leads to a failure in its implementation (Manibog 1984). Thus the three parameters that should be considered to design an improved cooking stove for West Africa are:

- Efficiency.
- Emissions.
- Social costs.

Raising an open fire to a grate would lead to reduced heat losses to the ground and, by supplying primary air from beneath the fuel bed, would lead to increased completeness of the combustion by preheating the air. This would not only favour both efficiency and emissions, but at the same time it would minimise the social costs for the implementation of the improved cooking stove in the villages (due to the similarity in construction to the present 'three-stone fire' stove). Efficiency can be further improved by sealing the sides with a clay shroud (for insulation) and by introducing a forced air intake mechanism to aid the burning process. This is a proposed design for an improved cooking stove called the 'insulating three brick' stove. This study will evaluate whether or not this improved cooking stove is suitable for the replacement of the 'three-stone fire' stove in the West African villages.

2. Analysis and specification

As mentioned, the clay shroud in the stove is designed to minimize heat losses. In order to find the optimal thickness which would ensure this, heat transfer calculations are carried out. The stove is assumed to be an 'insulated circular cylinder' with the insulated part being the clay shroud. Note that in order to perform the following calculations, it is assumed that heat transfer is unidirectional and occurs at steady state. A hypothetical top view of the stove is presented:

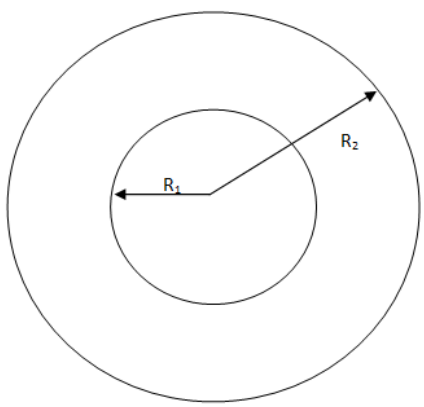

Figure 2: Hypothetical top view of designed stove.

As it can be seen from the figure above, the thickness of the clay shroud can be found by subtracting R_1 from R_2. The value of the resistances of conductive and convective heat transfer depends upon the value of the outer radius (R_2). Increasing R_2 decreases the resistance to convective heat transfer while it increases the resistance to conductive heat transfer. Therefore, it is necessary to find the critical value of R_2 which would match the objective of reducing heat transfer to the surroundings. In situations where one desires to prevent heat transfer, the designed radius has to be equal or greater than the critical radius.

The critical value, R_2 can be found using the following equation:

$$R_2 \geq \frac{k}{h} \quad (1)$$

Where,

R_2= critical radius (m)

k= Thermal conductivity of clay ($\frac{W}{m*K}$)

h= Convective heat transfer coefficient of air ($\frac{W}{m^2*K}$).

The k value can be found in the literature (Shainberg, Rhoades et al.). The convective heat transfer coefficient, however, needs more work. The nature of the flow is first determined by computing the Reynolds number along with the Prandtl number. Since the flow is of a turbulent nature (due to the use of the hand powered bellow which increases the velocity of the air coming in the combustion chamber), an empirical relation for turbulent flows is used to find the Nusselt number which in turn allows to find the convective heat transfer coefficient.

The R_2 value is found to be 9.4''. Therefore, the outer radius of the stove is chosen to be 10'' and its outer diameter 20 '', providing a safety factor of 1.06. Note that a large safety factor is not aimed for as one of the 'social costs' of the stove is to be able to provide heating.

However, the thickness of the stove cannot yet be determined since a spacing is required between the edge of the combustion chamber and the inner wall of the shroud. This spacing can be found using the air to fuel ratio equation:

$$AFR = \frac{\varepsilon * FCR * SA}{\rho_a} \quad (2)$$

Where,

AFR= air flow rate (m^3/hr)

ε= equivalence ratio (unitless)

FCR= rate of consumption of rice husks (kg/hr)

SA= stoichiometric air of rice husk, (kg air/ kg rice husk)

ρ_a= air density (kg/m^3)

Values for ρ_a, SA and ε can be found in the literature whereas the rate of consumption of rice husk (FCR) needs to be computed. To find the value which matches the stove design, several

assumptions are made: It is assumed that the stove will mainly be used to cook rice, as it is the staple food in the region, according to the Food and Agriculture Organization (FAO). From 1995 to 1998, the average rice consumption per capita was 43kg/year and it is assumed to grow by 2% every year (Balasubramanian, Sie et al. 2007). Therefore, the rice consumption per capita in 2012 is expected to be 56 kg/year which translates to 155.46 g/day. Assuming an average household to be composed of five members, the total rice which needs to be cooked per day is 773g. It is assumed that this quantity will be cooked in an hour. The water content of rice is around 66% (Dibba, Weaver et al. 1991), which means 510 g of water needs to be cooked in the rice.

The energy required to cook the rice is given by the following equation:

$$Q = (m * c_p * \Delta t) + m * L \quad (3)$$

Where,

$\dot{m}$ = mass of rice to be cooked (kg/hr)

c_p= heat capacity of water at 4°C (KJ/kg)

Δt= temperature difference (^{o}C)

m= mass of water (kg)

L= latent heat of water (KJ/kg)

Assuming that rice is brought from 20°C to 100°C during the cooking process, Q is found to be 1323 kJ/hr. Provided that rice husks have an energy density of 11 MJ/ kg, the amount of rice husks needed (FCR) to cook 0.773 kg in an hour is found to be 0.113 kg. Linking it back to equation (2), the air to fuel ratio (AFR) equals 0.0000396 m^3/s. This translates to a volume of 0.0000396 m^3 that needs to be available in the stove for air to escape, assuming that the amount of air going in the stove is equal to amount leaving it. Modeling the spacing needed as a cylinder, the radius that is needed is at least 0.6’’. Applying a standard safety factor of 1.5 yields a radius of ≈0.9’’ but a radius of 1’’ is used to ease the construction process. The importance of this spacing creates an additional draft of air which is vital because it avoids the fire from being choked.

Knowing the spacing for the air to flow out, the critical radius (R_2=10’’ which translates to 20’’ in diameter) and the pot size (10’’ in diameter), it is possible to determine the thickness of the clay shroud.

$$Thickness = critical\ radius - spacing - pot\ radius \quad (4)$$

Thus, the thickness of the clay shroud which would minimize heat transfer to the surrounding is found to be 4’’.

3. Prototyping

3.1 Computer aided modelling

Keeping the three criteria for an effective stove design in mind, the idea of the ‘insulating three-brick’ stove was conceived. The construction of the stove is rather simple to ease its implementation into the West African community. An insulating clay shroud encompasses a combustion chamber constructed from three stacks of bricks. The bricks are arranged in a triangular fashion to enclose the fuel held on the grate and to balance the pot that’s sits on top of the chamber. The clay shroud has two doors cut into it in a hyperbolic fashion. The larger of the two doors (6’’ wide and 4’’ high) is used for the removal of ash, whereas the smaller door (3’’ wide and 4’’ high) is used to hold the hand-powered bellow (required for forced air intake). The clay shroud also has holes punched on its surface for the introduction of air into the combustion chamber by natural convection. The holes have a diameter of 1.5’’ and are placed in a triangular fashion (in sets of three) around the clay shroud to direct air into the combustion chamber.

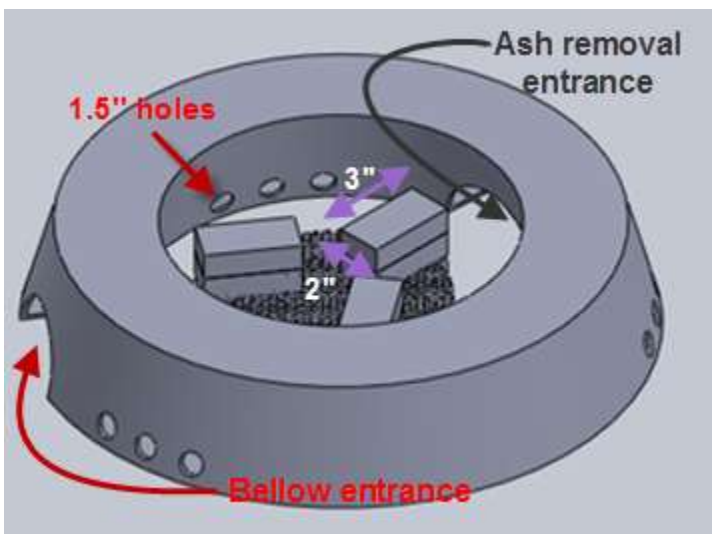

Figure 3: Isometric view of the SolidWorks model for the 'insulating three brick' stove.

The clay shroud is built in the shape of a truncated cone to funnel the heat from the combustion chamber to the bottom of the cooking pot. The thickness of the clay shroud is 4'' at the bottom (near the location of the raised grate). This is the thickness required to reduce convective heat losses and aid in insulation.

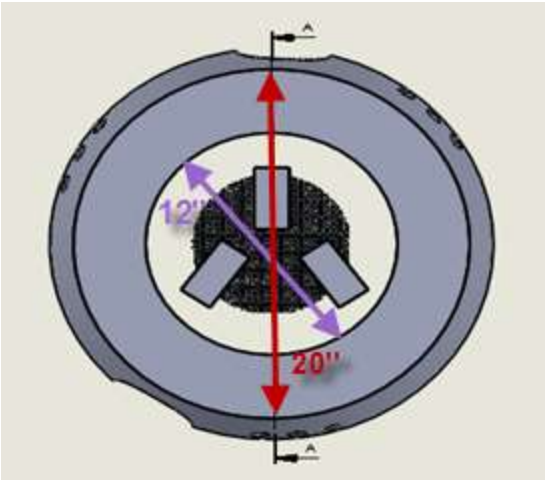

Figure 4: Top view of the 'insulating three brick' stove.

In the villages the stoves used for cooking are used with specific cauldrons. Thus improved cooking stoves are usually designed for a particular pot diameter. The clay shroud of the 'insulating three-brick' stove is designed to hold a 10'' pot. The distance from the edge of the combustion chamber to the edge of the clay shroud is 1'' (as determined by stoichiometric calculations). This is required to allow sufficient air flow, out of the combustion chamber ensuring that the fire does not choke and the emissions of harmful gases are minimal. Thus the overall inner diameter of the clay shroud is 12''and the outer diameter is 20'' (considering the given safety factor).

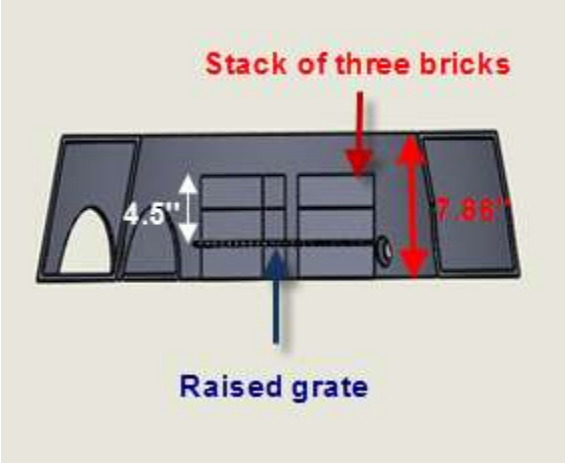

Figure 5: Cross-sectional view of the designed stove.

As it can be seen from the cross-sectional view, each stack of bricks in the combustion chamber is three bricks high. The dimension of each brick in the chamber is 3 x 2 x 2.25 inches. In order for the pot to sit within the clay shroud an additional spacing of 1.13'' is kept on top of the combustion chamber. Thus the shroud is designed to be 7.86'' high. The raised grate is made of a circular piece of expanded metal of diameter 10''. It is held between the first and second layers of bricks in each stack. The primary function of the grate is to hold the fuel (rice husk briquettes) as it burns. Apart from the fact that the grate minimises heat loses to the ground and pre-heats the incoming air, it also separates the ash from the burning briquettes. The ash falls through the expanded metal sheet and collects at the bottom of the combustion chamber where it can be easily removed with the help of the larger door cut into the shroud.

3.2 Construction of a physical model

In order to test the effectiveness of the designed stove, several prototypes were built according to the given specifications. The final prototype was tested to evaluate its performance under each of the specified design criterion.

3.2.1 Clay texture

The clay texture is critical when one moulds. Wet clay is not ideal to work with as it cannot be stacked whereas dry clay is to be avoided because of the difficulty to mould it. The clay that is used to build the stove was provided by Mr.Wayne Fijal from the John Abbot College. Since the texture of that clay was too watery to work with, an agent which absorbs the water from the clay needed to be added. Following Mr. Fijal's advice, clay bricks were crushed and mixed with the moulding clay in order to make it drier and therefore more suitable for the moulding process. In order to achieve this, an initial ratio of 1 clay brick for 5 liters of clay was used.

3.2.2 First attempt

The first attempt was a rather straight forward approach. In order to construct the clay shroud (with the described clay mixture), chicken wire was cut and shaped in the form of the required geometry and dimensions.

Figure 6: Photo displaying the chicken wire frame along with two layers of bricks for the combustion chamber.

Clay was then moulded on both sides of the frame to create a shroud thickness of 4'' at the base. It was found that the clay mix was still inconsistent and difficult to mould. However, the moulding process was continued. Since the openings for the doors and the holes were already cut in the chicken wire frame, the clay was simply moulded around the cuts to produce these entrances.

Figure 7: Clay moulding in progress around the chicken wire frame.

The clay shroud took five days to construct after which it was left to dry. To aid the drying process, the shroud was left under heating lights over a period of two days. However, since clay

contracts as it dries and the metal frame does not, large cracks formed on the surface of the clay shroud. These cracks compromised the structural integrity of the shroud and it soon started to fall apart. Thus the stove was broken down, the metal frame was discarded and a new approach for building the clay shroud needed to be found.

Figure 8: Large cracks on the surface of the clay shroud after two days of drying.

3.3 Revision

3.3.1 Clay texture

Using a ratio of 1 crushed brick and 5 liters of clay yielded a clay texture which was still difficult to work with due to its poor consistency. Therefore, the amount of crushed bricks, mixed per 5 liters of clay, was doubled. Furthermore, in order to minimize the amount of water within the clay, the mixture was left to dry in an open area thus ensuring natural convection to occur. These two measures allowed coming up with a texture of clay that was much easier to work with due to its thicker consistency.

3.3.2 Second attempt

Due to the failure of the first prototype, a second attempt was made at constructing a functioning stove. However, in order to observe the drying behaviour of the clay under standard room conditions, a scaled down version of the clay shroud was first built (≈10 times smaller). This model did not have the doors or holes cut on its surface. The scaled down model was dried over a period of three days in an enclosed room and no cracks were observed during that period.

Figure 9: Scaled down model of the clay shroud.

3.3.3 Re-designing

It took approximately an hour and a half in order to create the smaller version of the clay shroud. This is a large amount of time considering the size of the model. Thus, to reduce the construction time and to ease the moulding process, a turn table was built.

Figure 10: Turn table being used to clay moulding.

The rotating surface of the turn table was 23" in diameter, which allowed moulding the clay according to the specified dimensions quite easy. The turn table was powered with a 12V car wiper motor connected to a car battery jumper. The turn table provided two distinct advantages:

- It was easier to produce the shape of a truncated cone for the clay shroud, by pressing inwards on the wet clay as it turned.
- It reduced construction time to half of what it used to be previously.

3.4 Final Product

The turn table aided in constructing a clay shroud that was ideal for the stove design. The thickness of the shroud was 4'' at the bottom and it reduced to 1'' at the top. This created the funnel like appearance of a truncated cone. The doors and the holes were cut in the shroud after two days of drying in standard room conditions (when the clay had a leathery texture). The bricks were arranged according to the described manner in order to support the cooking pot. This concluded the construction phase of the 'insulating three-brick' stove.

Figure 11: Photo of the finished improved cooking stoves.

3.5 Preliminary test runs

After the completion of the improved cooking stove, it was fired up to observe its performance. Since rice husk briquettes were not available, combustion was carried out using sawdust briquettes as the primary fuel source. Sawdust logs were purchased from Eco-Logic. The logs were 9.5'' in length and 2.5'' in diameter with 1'' holes drilled in them.

Figure 12: Sawdust logs used to as the fuel source for combustion.

The first preliminary test run was carried out with the sawdust logs being cut in the shape of small donuts, to serve as the primary fuel source. The donut shaped briquettes had a thickness of 1'' and outer and inner diameters of 2.5'' and 1'', respectively. Four donut shaped briquettes were loaded on the grate through the top of the clay shroud.

Figure 13: Combustion chamber loaded with sawdust briquettes.

Lighter fluid was then poured on top of the briquettes to ignite the fuel. A metal pot (of 10'' diameter) containing 2.5L of water was placed on top of the combustion chamber and a timer was started to record the amount of time that it took for the water to boil. The hand powered bellow was placed in the smaller door of the clay shroud. It was used intermittently throughout the cooking process to increase the intensity of the flame and to reduce the production of smoke by introducing oxygen into the combustion chamber.

Figure 14: Boiling water using the 'insulated three-brick' stove.

As the test went on, it was observed that the fire was dying down when the water started to simmer. Due to the packing density of the sawdust briquettes in the combustion chamber, the ash started to accumulate on top of the grate since it could not fall through. This was choking the fire. Even though the hand powered bellow was being used continuously to increase the intensity of the flame, all attempts of reviving the fire failed. Thus the water never reached its boiling point and the first preliminary test run was unsuccessful.

3.5.1 Sawdust chips

In order to enhance the combustion process, the donut shaped sawdust briquettes were crushed into chips to increase the surface area exposed to the air and to the starter fluid. This followed the failure of the first preliminary test run. Therefore, crushing briquettes into chips allows for an improvement of the combustion process by minimising the accumulation of ash while keeping the fire burning for a longer time.

4. Testing

With preliminary test runs completed to observe the behaviour of the combustion, it was now time to evaluate the performance of the stove under the efficiency and emissions criteria. The tests were carried out in a large enclosed space, under standard indoor conditions.

4.1 Water boiling test

The efficiency of the stove was determined by carrying out a water boiling test in which 2.5 liters of water was brought to boil. The following equation was used to calculate the efficiency:

$$\eta = \frac{c_p \overline{m} \Delta T + h_{fg} m_{fg}}{m_f h_f - m_c h_c} \quad (5)$$

Where:

η=efficiency (fractional)

c_p= specific thermal capacity of water (KJ kg^{-1} K^{-1})

$\overline{m}$ =average mass of water in the pot during the heating up phase (kg)

ΔT= rise in water temperature for the heating-up phase (K)

h_{fg}=enthalpy of vaporisation of water (KJ kg^{-1})

m_{fg}= mass of evaporated water (kg)

m_f= mass of fuel used during the test (kg)

h_f=enthalpy of combustion (lower calorific value) of the fuel (kJ kg^{-1})

m_c= mass of the remaining char at the end of the test (kg)

h_c=enthalpy of combustion of the char (kJ kg^{-1})

The mass of the remaining ash as well as the mass of fuel used during the test were measured empirically by a balance. The mass of evaporated water was determined using a series of calculations. First, the volume of evaporated water was determined by taking the difference between the water level before and after the water boiling test. Then, the obtained volume was multiplied by the density of water at the average temperature of 60°C.

In order to get a more accurate value for efficiency, the water boiling test was carried out 6 times. The amount of fuel used across the 6 replicates was identical to ensure coherence in the methods.

4.2 Emissions

Emissions were recorded with the help of a Testo 330-LL series flue gas analyzer. Cartridges were loaded for measuring the emissions of CO and NO_x only. The consumption of O_2 was recorded automatically by the analyzer without the requirement of an external cartridge. Emissions testing were carried out simultaneously with the water boiling test. As the water started to simmer, the sensor was held within the clay shroud at distance of ≈5cm from the grate containing the burning sawdust chips. Emissions values were recorded over a period of one minute and the measurement was repeated three times in order to improve the reliability of the results.

5. Results and discussion

5.1 Efficiency

The efficiency of the stove was found to be 14.06% and the boiling time for 2.5 liters of water, using 535 grams of sawdust briquette chips, was on average 15 minutes and 25 seconds. Results for the water boiling test can be found in the appendices at the end of the report.

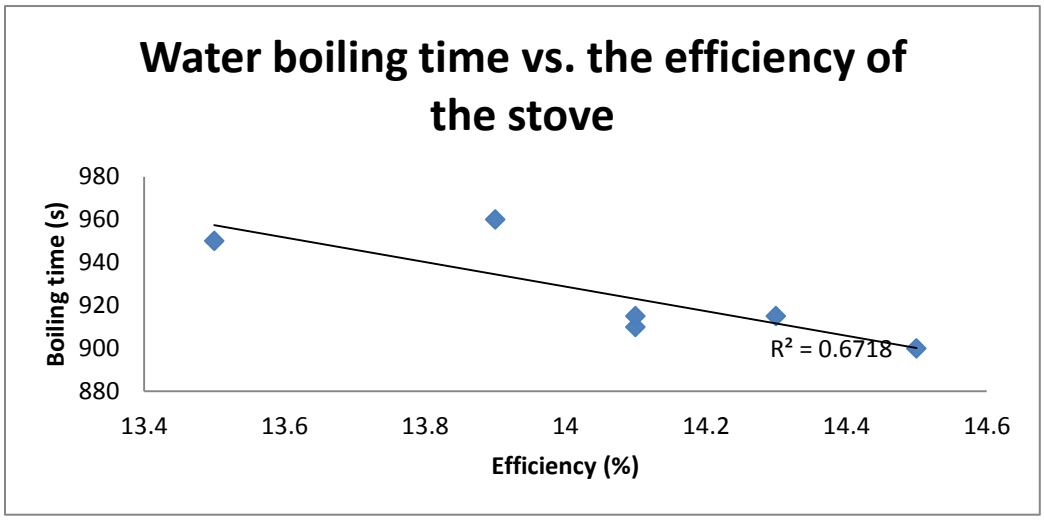

Figure 15: Figure representing the boiling time as a function of the efficiency of the stove.

The above graph shows the boiling time as a function of the efficiency of the stove. It can be seen that as the boiling time decreases the efficiency increases which translates to a correlation factor of -0.819. The strength of the correlation factor indicates that efficiency has a significant impact upon the boiling time. In fact, a higher efficiency means that more energy is being transferred to the top and ultimately to the water within the pot, decreasing its boiling time. This has been shown in the literature as well (Boy, Bruce et al. 2000).In none of the water boiling tests was the efficiency lower than the 'three-stone fire' stove efficiency. In fact, the average efficiency of the 'three-stone fire' stove is around 8% (Balasubramanian, Sie et al. 2007) which is ≈76% lower than the efficiency of the 'insulating three-brick' stove. Looking at the boiling time demonstrates that the 'insulating three-brick' stove is as effective as the high efficiency improved cooking stoves that are currently being implemented in West Africa (for example, the rocket stove which has an efficiency of 26% boils water in 13 minutes).

5.2 Emissions

Average emissions data is tabulated for each of the recorded gases over three test runs:

Table 1: Average emissions of carbon monoxide, nitrogen oxides and the average oxygen consumption

% O_2 present in combustion chamber	CO emissions (mg/L)	NO_x emissions (mg/L)
20.71	38	0.1

Carbon monoxide dosages of over 100mg/L are lethal to human beings. Thus the 'three-stone fire' stove is very harmful to the human health (emissions of carbon monoxide are 200mg/L). In comparison, the 'insulating three-brick' stove performs very well. With carbon monoxide emissions at an average level of 38mg/L, it emits 81% less carbon monoxide than the 'three-stone fire' stove. At the same time, the nitrous oxide emissions are minimal and well below the level that causes atmospheric pollution. Oxygen is always present in ample amounts to aid in the completion of the combustion process. The average oxygen concentration within the combustion chamber is approximately equal to atmospheric oxygen levels. Thus both the natural (air entering through the openings) and forced (hand powered bellow) air intake into the combustion chamber worked efficiently.

The behaviour of the emissions was graphed for the third experiment to determine the effect of the bellow on the combustion process.

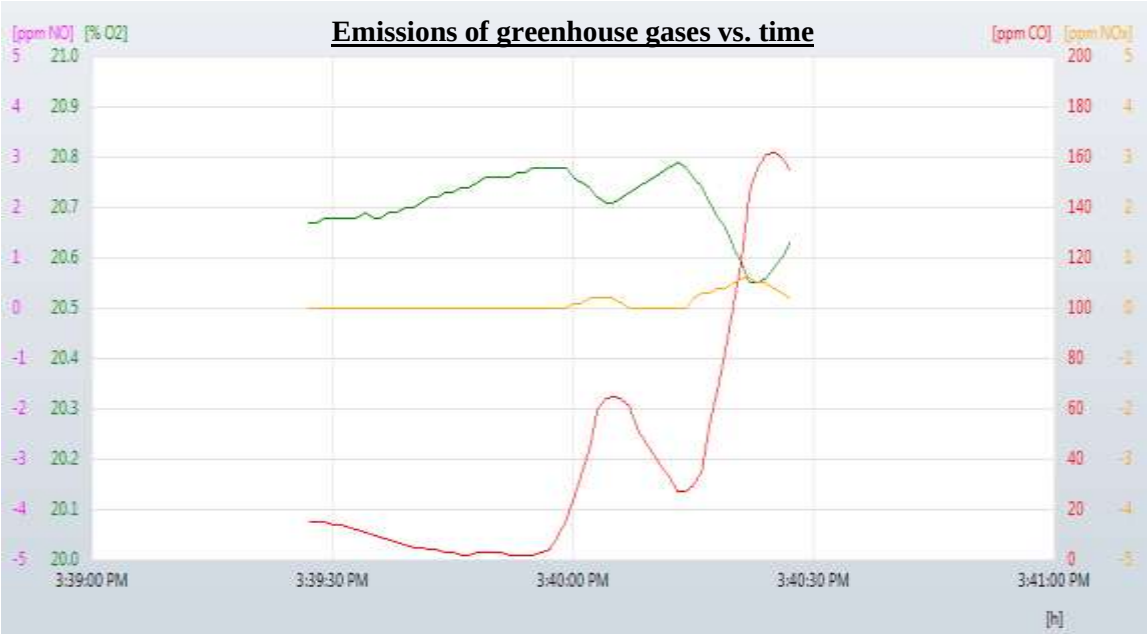

Figure 16: Graph displaying the emissions of CO and NOx during the combustion of sawdust chips.

An increase in oxygen concentration indicates that the hand powered bellow is functioning. Looking closely at the graphs of the concentrations of carbon monoxide and oxygen, it is observed that as oxygen concentrations increase the level of carbon monoxide decreases. Thus, the emission of carbon monoxide is inversely proportional to the amount of oxygen that is present in the combustion chamber. This relationship can also be seen with the nitrous oxide emissions. However, since the NO_x emissions are not very large, the relationship is not very prominent. Nevertheless, we can conclude that the incorporation of the hand powered bellow in

the design of the 'insulating three-brick' stove proved to be effective as it mitigated the emissions of both the greenhouse gases.

5.3 Social costs

Out of the three main criteria kept in mind during the stove design, the 'social costs' criterion is the most intricate one to evaluate. In fact, a social research needs to be carried out to effectively assess the implementation of the stove in the West African region. That way, villagers can test out the stove to see if it fits their criteria which we intended to include in this design process. It can nevertheless be said that some design measures were undertaken in the construction of the stove. For instance, the spacing left for the air to flow out also allows for the flames to escape, thus providing lighting and heating to the community. One of the main challenges in this project was to come up with a fairly simplistic and rudimentary stove while trying to optimize as much as possible the design with the proper scientific calculations which are in this case linked to heat transfer and thermodynamics. By keeping the stove design as simple and similar to the current 'three-stone fire' stove, the implementation of the 'insulating three-brick' stove is optimized. Furthermore, keeping the design simple also allows for reduced costs. The hand powered bellow is an item which can be handmade by the villagers and the metal grate can be found relatively easily as metal is often recycled in the region. One of the issues with using a metal grate would be having the proper tools to cut the piece to fit the stove dimensions. Bricks can be made in the bread making ovens. Moreover, clay was chosen as the primary stove material for two main reasons: For its insulation properties and for its abundant availability in the region (particularly on the river banks)(Jones 1973). Overall, the stove design fulfills the social costs criterion by accounting for the availability of the materials, the design as a whole and the intangible assets such as heating, lighting and the ability of the stove to act as a gathering point.

6. Conclusion and recommendations

The 'insulating three-brick' stove was tested out according to our criteria which are emissions, efficiency and social costs. Compared to the current 'three-stone fire' stove, the 'insulating three-brick' stove is ≈76% more efficient while emitting 81% less carbon monoxide into the atmosphere. The social costs criterion could not be evaluated although some measures in the design process were taken to address this parameter. In fact, a good balance was found to minimize the heat losses and to provide heat to the community simultaneously. Thus, it can be said that the 'insulating three-brick' stove proves to be an improvement compared to the current 'three-stone fire' stove, while keeping the differences in the design minimal. The only notable differences in the design are the introduction of a hand powered bellow and a metal grate. These two items increase the cost of the stove by ≈ $4 compared to the 'three-stone fire' stove.

One major drawback of the design is that the addition of the rice husk briquettes is a batch process, meaning that the fuel can only be added at the beginning of each cooking process.

Therefore the amount of fuel introduced at the beginning of each cooking process needs to last the entire cooking time. Refuelling the stove is a difficult task, since the pot has to be removed from the stove. This could alter the efficiency as there are major heat losses to the surroundings and the air needs to be pre heated again for the combustion to restart. Removing the pot to add fuel also exposes the cook to harmful gases if the combustion process is not carried out properly. In order to address this issue, it is recommended that a small door be cut in the clay shroud to refuel the stove. This door would have to have a closing mechanism to limit the heat losses and the gas emissions, once the stove is refuelled. The opening would have to be big enough for small rice husk chips to go through. It is to be expected that the dimension of this opening would be ≈7" in diameter.

Overall, the design of the 'insulating three-brick' stove is quite promising as an alternative to the current 'three-stone fire' stove. Although the 'insulating three-brick' stove presents some interesting physical results, its success in the West African villages still needs to be determined by having the villagers build it and evaluate its performance themselves.

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Appendices

Table 2: Emissions of various flue gases over a period of one minute.

Date / time	sec Runtime	% O2	ppm CO	ppm NO	ppm NOx	°C Tamb	% CO2	% EFF	°C Tstack
04/04/2012 15:39:27 tt	0	20.67	15	0.0	0.0	24.3	-	-	27.5
04/04/2012 15:39:28 tt	1	20.67	15	0.0	0.0	24.3	-	-	27.5
04/04/2012 15:39:29 tt	2	20.68	15	0.0	0.0	24.3	-	-	27.5
04/04/2012 15:39:30 tt	3	20.68	14	0.0	0.0	24.2	-	-	27.5
04/04/2012 15:39:31 tt	4	20.68	14	0.0	0.0	24.2	-	-	27.6
04/04/2012 15:39:32 tt	5	20.68	13	0.0	0.0	24.2	-	-	27.6
04/04/2012 15:39:33 tt	6	20.68	12	0.0	0.0	24.2	-	-	27.6
04/04/2012 15:39:34 tt	7	20.69	11	0.0	0.0	24.3	-	-	27.7
04/04/2012 15:39:35 tt	8	20.68	10	0.0	0.0	24.3	-	-	27.7
04/04/2012 15:39:36 tt	9	20.68	9	0.0	0.0	24.3	-	-	27.8
04/04/2012 15:39:37 tt	10	20.69	8	0.0	0.0	24.3	-	-	27.9
04/04/2012 15:39:38 tt	11	20.69	7	0.0	0.0	24.3	-	-	27.9
04/04/2012 15:39:39 tt	12	20.70	6	0.0	0.0	24.4	-	-	27.9
04/04/2012 15:39:40 tt	13	20.70	5	0.0	0.0	24.4	-	-	28.0
04/04/2012 15:39:41 tt	14	20.71	5	0.0	0.0	24.4	-	-	27.9
04/04/2012 15:39:42 tt	15	20.72	4	0.0	0.0	24.3	-	-	27.9
04/04/2012 15:39:43 tt	16	20.72	4	0.0	0.0	24.3	-	-	27.8
04/04/2012 15:39:44 tt	17	20.73	3	0.0	0.0	24.4	-	-	27.9
04/04/2012 15:39:45 tt	18	20.73	3	0.0	0.0	24.4	-	-	27.7
04/04/2012 15:39:46 tt	19	20.74	2	0.0	0.0	24.5	-	-	27.6
04/04/2012 15:39:47 tt	20	20.74	2	0.0	0.0	24.6	-	-	27.4
04/04/2012 15:39:48 tt	21	20.75	3	0.0	0.0	24.6	-	-	27.0
04/04/2012 15:39:49 tt	22	20.76	3	0.0	0.0	24.6	-	-	26.9
04/04/2012 15:39:50 tt	23	20.76	3	0.0	0.0	24.7	-	-	26.9
04/04/2012 15:39:51 tt	24	20.76	3	0.0	0.0	24.7	-	-	26.8
04/04/2012 15:39:52 tt	25	20.76	2	0.0	0.0	24.7	-	-	26.4
04/04/2012 15:39:53 tt	26	20.77	2	0.0	0.0	24.6	-	-	27.3
04/04/2012 15:39:54 tt	27	20.77	2	0.0	0.0	24.6	-	-	28.8
04/04/2012 15:39:55 tt	28	20.78	2	0.0	0.0	24.6	-	-	31.9
04/04/2012 15:39:56 tt	29	20.78	3	0.0	0.0	24.6	-	-	36.2
04/04/2012 15:39:57 tt	30	20.78	4	0.0	0.0	24.6	-	-	39.0
04/04/2012 15:39:58 tt	31	20.78	9	0.0	0.0	24.6	-	-	39.0
04/04/2012 15:39:59 tt	32	20.78	15	0.0	0.0	24.6	-	-	37.7
04/04/2012 15:40:00 tt	33	20.76	24	0.1	0.1	24.6	-	-	36.2
04/04/2012 15:40:01 tt	34	20.75	34	0.1	0.1	24.7	-	-	34.3
04/04/2012 15:40:02 tt	35	20.74	44	0.2	0.2	24.7	-	-	32.5
04/04/2012 15:40:03 tt	36	20.72	60	0.2	0.2	24.6	-	-	29.9
04/04/2012 15:40:04 tt	37	20.71	64	0.2	0.2	24.6	-	-	29.3
04/04/2012 15:40:05 tt	38	20.71	65	0.2	0.2	24.7	-	-	29.0
04/04/2012 15:40:06 tt	39	20.72	64	0.1	0.1	24.7	-	-	28.6
04/04/2012 15:40:07 tt	40	20.73	61	0.0	0.0	24.7	-	-	28.2
04/04/2012 15:40:08 tt	41	20.74	52	0.0	0.0	24.6	-	-	27.5
04/04/2012 15:40:09 tt	42	20.75	47	0.0	0.0	24.6	-	-	27.6
04/04/2012 15:40:10 tt	43	20.76	42	0.0	0.0	24.5	-	-	31.4

04/04/2012 15:40:11 tt	44	20.77	37	0.0	0.0	24.5	-	-	36.7
04/04/2012 15:40:12 tt	45	20.78	33	0.0	0.0	24.5	-	-	38.0
04/04/2012 15:40:13 tt	46	20.79	27	0.0	0.0	24.6	-	-	41.4
04/04/2012 15:40:14 tt	47	20.78	27	0.0	0.0	24.7	-	-	42.2
04/04/2012 15:40:15 tt	48	20.76	30	0.2	0.2	24.6	-	-	45.2
04/04/2012 15:40:16 tt	49	20.74	35	0.3	0.3	24.6	-	-	49.9
04/04/2012 15:40:17 tt	50	20.71	54	0.3	0.3	24.6	-	-	52.5
04/04/2012 15:40:18 tt	51	20.68	68	0.4	0.4	24.7	-	-	52.9
04/04/2012 15:40:19 tt	52	20.66	84	0.4	0.4	24.7	-	-	47.2
04/04/2012 15:40:20 tt	53	20.62	102	0.5	0.5	24.7	-	-	44.1
04/04/2012 15:40:21 tt	54	20.59	120	0.6	0.6	24.7	-	-	41.8
04/04/2012 15:40:22 tt	55	20.55	147	0.6	0.6	24.6	-	-	37.0
04/04/2012 15:40:23 tt	56	20.55	156	0.5	0.5	24.5	-	-	35.8
04/04/2012 15:40:24 tt	57	20.56	161	0.5	0.5	24.5	-	-	35.2
04/04/2012 15:40:25 tt	58	20.58	162	0.4	0.4	24.5	-	-	35.1
04/04/2012 15:40:26 tt	59	20.60	160	0.3	0.3	24.4	-	-	35.8
04/04/2012 15:40:27 tt	60	20.63	155	0.2	0.2	24.4	-	-	38.5

Calculations:

1. The following calculations seek to find the critical radius which would prevent heat transfer to the surroundings. First the Reynolds number was computed to find the nature of the flow. Then the Prandtl number was found in order to compute the Nusselt number. Once the Nusselt number was found, the convective heat transfer coefficient could be calculated. By having the h value, it was then possible to calculate the critical radius. Note that all the air/ clay values (k, ρ, c_p...) were looked up on the "engineering toolbox" website. An example is provided below. The Nusselt number correlation was found in the Holman textbook (Holman, J.P.2010. Heat Transfer. 10th. Boston, MASS. McGraw-Hill.)

$$Re = \frac{\rho * v * D_H}{\mu}$$

$$= \frac{1.29\frac{kg}{m3} * \frac{3m}{s} * 4 * \left(\frac{2\pi(0.1778m) * 0.228m}{\pi(0.1778m)^2}\right)}{1.7 * 10^{-5} Pa * s}$$

= 2335366.903 (turbulent flow)

$$Pr = \frac{\Upsilon}{\alpha} = \frac{c_{p} * \mu}{k}$$

$$= \frac{1.005\ kJ/kg * K * 1.7 * 10-5\ Pa * s}{0.025\frac{W}{m * K}}$$

$=6.863*10^{-4}$

Nu=$0.023 * (Re)^{0.8}(Pr)^{0.33}$

Nu= $0.023 * (2.34 * 10^6)^{0.8}(6.834 * 10^{-4})^{0.33}$

=258.55

h=$\frac{Nu*k_{air}}{D_H}$

=$\frac{2.34*10^6*0.025\frac{W}{m*K}}{10.26}$

=0.62999 $\frac{W}{K*m^2}$

R_2= $\frac{k}{h}$

=$\frac{0.15\frac{W}{m*K}}{0.62999\frac{W}{K*m^2}}$

R_2= 0.238 m ➔9.4”

2. In order to calculate the spacing is required between the combustion chamber and the inner wall of the shroud. This spacing can be found using the air to fuel ratio equation:

$$AFR = \frac{\varepsilon * FCR * SA}{\rho_a}$$

From 1995 to 1998, the average rice consumption per capita was 43kg/year and it is assumed to grow by 2% every year (Balasubramanian, Sie et al. 2007). Therefore, the rice consumption per capita in 2012 is expected to be 56 kg/year which translates to 155.46 g/day. Assuming an average household to be composed of five members, the total rice which needs to be cooked per day is 773g.

It takes about one hour for rice to cook properly with a water to rice ratio of 0.68 (Juliano and Perez 1983).

Cooking rate of water in rice= $0.773\frac{kg}{day}*\frac{1\ day}{24\ hours}*0.66$

$= 0.51\frac{kg}{hour}$

The energy required to cook the rice is given by the following equation:

$$Q = (m * c_p * \Delta t) + m * L$$

$$= 0.51\frac{kg}{hour} * 4.18\frac{kJ}{kg} * (100-20)K + 0.51\frac{kg}{hour} * 2260\frac{kJ}{kg}$$

$$= 1323.144\ \frac{kJ}{hour}$$

Energy density of rice husk briquettes= 11 MJ/kg ((Demirbaş 1999)

Amount of fuel required= $\frac{1323144J}{(11*10^6)\frac{J}{kg}}$= 0.113 kg

AFR=$\frac{\left(\frac{0.3+0.4}{2}\right)*0.113*4.5}{1.25}$= $0.14238 m^3/hour$ ➔ 0.0000396 m^3

Volume of air required= 0.0000396 m^3

Radius= $\sqrt{\frac{0.0000396*1000}{\pi*57}}$ = 0.01487 m➔ 0.59’’

3. The efficiency of the stove was calculated using the water boiling test. The following formula details it:

$$\eta = \frac{c_p \overline{m} \Delta T + h_{fg} m_{fg}}{m_f h_f - m_c h_c}$$

$$=\frac{4.18kJ/(kg*K)*(100-10) + 2257kJ/kg*(0.185\ kg)}{(0.545\ kg)*14267.44\frac{kJ}{kg} - 0.065\ kg*32800\frac{kJ}{kg}}$$

≈ 14.1%

This procedure was repeated six times. The ash content a.H_{fg}, h_c,h_f and the formula were taken from (Masera, Saatkamp et al. 2000) and (Smith 1989).

The following table displays the the results of efficiency and boiling time for the six water boiling tests which were carried out:

Table 3:Boiling time (s), efficiency (%) using the water boiling test

Fuel required (g)	Efficiency (%)	Boiling time (s)
535	13.5	950
535	14.5	900
535	14.09	910
535	14.3	915
535	13.9	960
535	14.25	915