Efficient Charcoal Stoves: Enhancing their Benefits to a Developing Country using an Improved Design Approach.

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Abstract: **Programmes and interventions to improve household wood and charcoal stove efficiencies have been launched in many developing countries over the past two decades. This work seeks to improve benefits accompanying the use of improved charcoal stoves by proposing a design with a better thermal efficiency.**

Efficient stoves have many benefits, including: improved livelihoods of workers involved in their production; health and safety benefits from the reduction or removal of smoke in their homes; reduced fire risk and risk of burn injuries; improved quality of life by reducing the amount of time to search for wood needed for cooking; reduced fuel costs; slowing deforestation and thus preserving natural habitats and biodiversity, as well encourage the use of locally manufactured technology in developing countries.

A new charcoal stove, Stove AA, was developed and constructed. It was observed that it had improved combustion of fuel and the utilization of heat generated. After testing this design against two conventional charcoal stoves and two improved charcoal stoves (Gyapa and Ahenbeso) it was observed that, Stove AA had the highest thermal efficiency, 10.43% and Gyapa the least, 5.21% . Stove AA had the least fuel consumption rate, 0.72 kg/hr, followed by the conventional stoves with about 0.73 and 0.89 kg/hr; then Ahenbeso with 0.93 kg/hr and finally the Gyapa with 1.23 kg/hr.

Keywords: **Thermal efficiency, fuel consumption rate, efficient cookstoves, particulate matter, black carbon emission, boiling test.**

I. INTRODUCTION

About 75% of Ghana's fuel is fuel wood and charcoal; that comes to a total annual consumption of about 700,000 tonnes [1]. Everyday energy needs of more than 40% of the world's population are met using stove technologies that have changed little since prehistoric times [2]. Most of them are Biomass cookstoves that emit 22% of global black carbon (BC) emissions, which is the second strongest contributor to current global warming [3]. BC emissions have an atmospheric life time of 8 to 10 days and results in localized impacts [4]. Some cooksotves with inefficient fuel combustion release products like methane and carbon monoxide that have higher global warming potential than carbon dioxide [5]. Figure 1 shows a link between a country's income status and the type of household fuels used. It can be observed that the higher the income status, the less solid fuel used as a household source of energy.

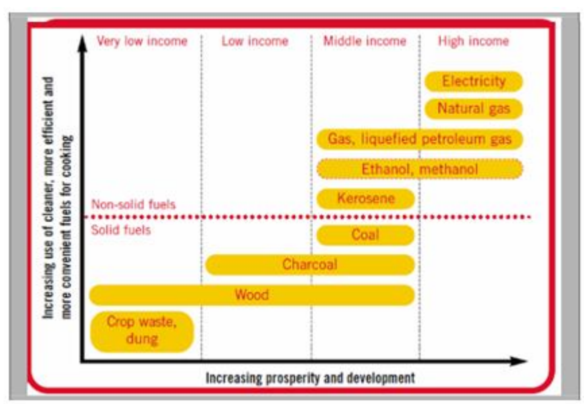


Figure 1 Energy Ladder: A link between household energy used and level of development [6].

Air pollution from cooking with charcoal and other solid fuels are a major risk factor in many respiratory, cardio-vascular and ocular diseases. In Ghana, exposure to indoor air pollution causes the annual loss of 502,000 disability adjusted life-years (DALY). It comes to an estimated 16,600 deaths due to indoor air pollution per year [1]. Results from ambient pollution studies carried out in California, USA show that an effect of particulate matter (PM) concentration of PM 2.5 on birth weight was 25% increased risk, and a mean difference of 36 g for the lowest vs. the highest exposure groups. The study found no independent effect of CO on birth weight. A small effect of PM of 15% increase in risk, however, was also found for pre-term birth, with no effect of CO exposure. The PM was also found to increase the risk of respiratory causes of post-neonatal mortality.[7]

A study in Ethiopia revealed that savings from using an improved stove as a percentage of the country's total income for the upper income group was 3.3%, for the middle income group was 6.5% and for the lower income group, an astonishing 25%; this implies a significant poverty alleviating effects on users and producers of the improved stoves [8]. Improved cooking stoves have gone a long way to improve the living conditions of many families by reducing hazardous smoke from living area of most people. Smoke characterized most cooking stoves in the rural areas, but now as a result of the introduction of more efficient stoves, the trend is the reduction in the use of such fires with its resulting improvement in the conditions of the living areas of most people who used to live with smoke and other emissions from poor cooking stoves.

Studies have demonstrated that there have been statistically significant reductions in the occurrence of acute respiratory infection and conjunctivitis among women and children under five in households that use improved stoves compared with those who did not. This implies that, there are good health benefits for families from the reduction or removal of smoke in their homes among others. [8].

The improved stoves have improved the quality of life for women. Women usually play the role of cooking and for that matter engage in the search for fuel for cooking. Such fuels are sometimes difficult to come by. They therefore have to, sometimes, travel long distances and spend a lot of time to search for such fuels. With the use of such improved stoves, the energy and time needed to be invested in the search for fuel is reduced, thereby freeing up time for more productive activities as engaging in productive economic activities to improve their lives and that of their families. The use of improved stoves with its fuel efficient characteristics has helped to reduce the demand of fuel for cooking, which in effect has also affected the prices of fuel for cooking. There is therefore a relative reduction in prices of cooking fuel and has also added to the economic improvement of the livelihoods of most rural families.

The reduction in the demand of fuel for cooking brings about the reduction of the pressure on the forests for wood for fuel. This subsequently slows down deforestation and consequently soil erosion, protecting watersheds and preserving natural habitats of living organisms that affect the ecosystem and thus improves biodiversity.

The introduction of the improved stoves, a local technological development, has boosted the moral of the local entrepreneur and confidence in the local people that they can solve their own problems and meet their needs without foreign intervention. That is, introducing locally manufactured technology with optimized energy efficiency has improved technological self-reliance. The technical artisans that produce the stoves have created jobs for themselves and for all involved, in one way or the other, in their production. The production, maintenance and distribution of the improved cookstoves have created jobs in different ways.

The design of an improved stove depends generally on the purpose for which the stove is meant. There is the need to look at some classification of these stoves and the purposes which they serve for that matter.

A. Classification of Improved Stoves

According to FAO the Improved Cooking Stoves can be classified in terms of: function, construction material, portability, and the type of fuel used [9][10] .

1) Function – An Improved Cooking Stove which performs mainly one function, for example, cooking or any other single special function such as fish smoking, baking, roasting, milk simmering, etc. can be classified as a *Mono-function* stove. When used for more than one purpose it can be classified as a *Multi-function* stove. [9].

2) Construction material – Improved Cooking Stoves are mainly made with single materials such as metal, clay, fired-clay or ceramics and bricks. In other designs, more than one material is used for different important components. Classification based on the material helps in selecting an appropriate design on the basis of locally available raw materials. [9].

3) Portability – On the basis of the ability to move it from one place to the other, an Improved Cooking Stove can be classified as fixed or portable. Metal and ceramic Improved Cooking Stoves are normally portable in nature and can be moved indoors or outdoors, while clay/brick, clay/stone Improved Cooking Stoves are generally high mass and thus are fixed. Based on portability, they can further be sub-divided into different categories depending on the number of holes for cooking pots available; they could be single, double, triple or more holes. [9]

4) Fuel type – Another way of classifying improved stoves is based on the fuel used. The performance of different Improved Cooking Stoves, of similar design and materials, will depend on the type of fuel used. Four major types of fuel are: charcoal, fuelwood, granular/loose and stick-form agri-residue, and briquetted biomass.

Using the information on the types and purposes of the stoves, appropriate materials and methods can be decided on and used to design a more efficient stove.

II. MATERIALS AND METHOD

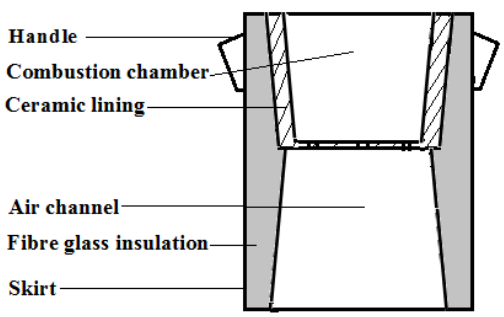
The desired design characteristics of the improved stoves was put together after analyzing information on the existing improved stoves. The desired characteristics could be summarized into three main design objectives. The design process therefore was guided by those design features. It concentrated on three main design features for improved fuel efficiency. The first was that the improved cook stove's design should achieve higher combustion efficiency. Secondly, the design should have a good insulation and improved heat retention to minimize loss of heat to the environment. The third point was that there should be a further reduction in heat loss by optimizing heat transfer between the stove and the cooking pan or pot.

A. Combustion Chamber Design.

There are several design factors that could be integrated into the stove to improve combustion. The study of Bryden et al. was used mostly in the design of the combustion chamber. Bryden et al. [11] suggests that to improve combustion, there should be good draft into the fire and good insulation around fire to help it burn hotter, since hotter fire burns more of the combustible gases and produce less particulate matter (PM). There should be less use of heavy, cold materials like earth and sand around the combustion chamber [11]. The combustion chamber was made with ceramic material. Clay was moulded to form a tapered chamber in the shape of a truncated cone with holes underneath to allow ashes to drop downwards out of the combustion chamber and also allow the flow of air upwards into the chamber. Figure 2 (a) shows a photograph and 2 (b) a schematic diagram of the design. It was allowed to dry and afterwards burned in a kiln to improve on its strength and heat resistance.

(a)

Figure 2 a. Photograph of the improved stove ;



(b)

Figure 2 b. Schematic Diagram of a section through the Improved Stove Design

B. Stove Body Design

The body was made with sheets of steel. The outer wall was moulded into a cylindrical skirt. A second mould was made in the form of a truncated cone. The two moulds were put together using additional steel sheets and rivets to form the desired shape as shown in Figure 2 (b).

The hollow space between the two moulds was filled with fiber glass to insulate the stove for better heat retention. Two handles were moulded with steel sheets and riveted to the skirt. Steel rods were bent to produce a stand for the cooking pot on the stove. Three of such supports were made and fixed at the top of the combustion chamber. The support was fixed in such a way as to allow hot air escaping from the chamber to flow around the cooking pot to provide further heating of the pot.

C. Test of Stove

After the design and construction of the Improved stove, tests were performed to compare the performance of the designed stove to that of other conventional and efficient stoves. Two conventional steel plate stoves were selected and two efficient stoves namely the Gyapa and Ahenbeso stoves were selected. During the tests the mass of charcoal used was measured by weighing the charcoal before and after a liter of water just begins to boil, and finding the difference. Time taken to boil the water was measured using a stop watch.

The results of the water boiling test were used to calculate the performance parameters of the stoves. Different graphs were plotted using the boiling tests results and the calculated performance parameters.

III. RESULTS AND DISCUSSION

Charcoal as fuel is burnt completely to carbon dioxide and ash rather than carbon monoxide and ash. This increases the combustion temperature of the fuel and gives out more heat. In the burning process, charcoal and oxygen creates a pyrolysis reaction where fuel gas is released and travels up through the combustion chamber. The fuel gas fully combusts when it comes into contact with more oxygen from air entering the combustion chamber. This two-stage combustion process is more efficient because it captures and uses fuel gas that would otherwise be released into the atmosphere as with single stage combustion processes, such as with an open fire. The two stage combustion provides a more complete combustion of the fuel and consequently reduces emissions.

Roth [12] emphasizes that combustion is a series of oxidization reactions, which can take place effectively only if sufficient oxygen is available. Should oxygen available be insufficient, the combustion would be incomplete and unburnt smoke or carbon monoxide will be emitted.

The taper of the combustion chamber was partly to allow easy extraction of ash and a slow rearrangement of the charcoal as it burns out. On the other hand it also aids in the flow of air from underneath the chamber as the space beneath the combustion chamber was tapered upwards to form a Venturi-shaped system that promotes a better fluid flow dynamics that will promote a draft.

In effect improving combustion for the stove took into consideration the creation of a good draft, the Insulation around the fire for a hotter burn, the use of lightweight, heat-resistant materials for insulation to reduce warm-up time, circulation of air to have contact with all surfaces of the fuel to aid in complete combustion, limited fuel capacity, and limited cold air intake into the combustion chamber but more warm air intake to maintain complete combustion.

The chemical reactions that take place during combustion are:

$2C + O_2 = 2CO$ Initial exothermic reaction to generate heat for heating.

$2CO + O_2 = 2CO_2$ Further exothermic reaction to boost heat generation of the stove and reduce emissions.

$CO_2 + C = 2CO$ endothermic reaction that occurs at very hot areas that tends to prevent overheating of the stove.

The insulation of the stove body with fiber glass material sandwiched between two sheet metal layers was improvement that gives a better stove insulation and improves general heat retention to minimize loss of heat to the environment.

There is the promotion of further reduction in heat loss by allowing further heat transfer between the stove and the cooking pan or pot. This can be effected by increasing the pot surface area, directing heat through narrow channels around the pot, maintaining turbulent, fast-moving airflow around the pot to avoid boundary layer effects and using materials that have a high heat thermal conductivity for the pots. The stove is designed with a skirt to fit a range of pot sizes and shapes while still leaving narrow gaps to promote good heat transfer to the pot. The support for the cooking pan places the cooking pot at a position that allows it to be surrounded by hot air leaving the chamber that further heats the pot.

The capability to test emissions was not available. Assuming proper combustion rates as per the design specifications, emissions should be within a safe range.

Table 1 shows results of the test conducted using one liter of water for the boiling tests.

TABLE 1: TEST RESULTS

Type of Charcoal Stove	Mass of Charcoal use [g]	Time Taken t boil
Conventional stove 1	150	10 min. 8 s
Conventional stove 2	120	9 min. 53 s
Gyapa	200	9 min. 43 s
Ahenbeso	150 g	9 min. 41 s
Stove AA	100 g	8 min. 20 s

The power output, fuel consumption rate and thermal efficiency of the stove were calculated using equations 1 to 3.

The power output of the stove is a ratio of the product of fuel mass and fuel energy to the change in time.

$$\text{Power Output} = \frac{\Delta Fuel\ Mass\ (kg) \times Energy\ of\ Charcoal\ \left(\frac{kCal}{kg}\right)}{\Delta Time\ (s)} \quad (1)$$

The fuel consumption rate is calculated as a ratio of fuel consumption to operating time.

$$\text{Fuel Consumption Rate} = \frac{Chaercoal\ Used\ (kg)}{Operating\ Time\ (hr)} \quad (2)$$

Percent thermal efficiency is the ratio of mass of product in the cooking pot, heat capacity and temperature change versus fuel mass and fuel energy. That is:

$$\text{Thermal Efficiency} = \frac{Mass\ of\ Water\ (kg) \times Heat\ Capacity\ of\ water\ \left(\frac{kCal}{kg^{\circ}C}\right) \times \Delta Temperature(^{\circ}C)}{\Delta Fuel\ Mass\ (kg) \times Energy\ of\ Charcoal\ \left(\frac{kCal}{kg}\right)} \times 100\% \quad (3)$$

Table 2 shows the results obtained from the calculations.

Results from the boiling tests and calculations of the power output, fuel consumption rate and the thermal efficiency were plotted for all the five stoves used in the tests.

A Power Output

The power out from the stoves was calculated using Equation 1. The results are presented in Table 2.

TABLE 2: STOVE PERFORMANCE

Type of Charcoal Stove	Time Taken to boil [min]	Power Output [W]	Fuel Consum-ption Rate [kg/hr]	Thermal Efficiency [%]
Conventional Stove 1	10.133	7229.0	0.8882	6.95
Conventional Stove 2	9.883	5929.5	0.7285	8.69
Gyapa	9.717	10051.3	1.2349	5.21
Ahenbeso	9.683	7565.0	0.9295	6.95
Stove AA	8.333	5860.4	0.7200	10.43

Figure 3 shows the power output from each of the stoves, drawn using the results from Table 2.

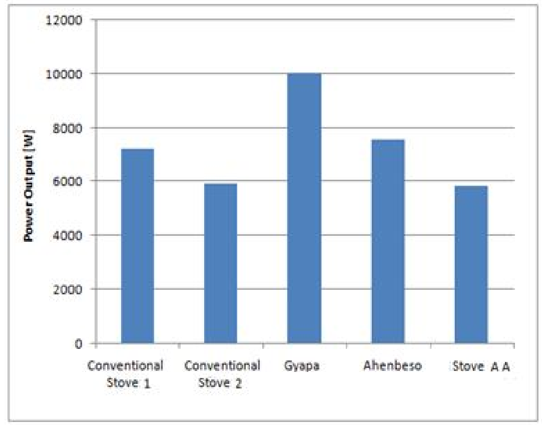


Figure 3 Power Output of the Five Stoves

As far as the power output is concerned, the highest fire power was seen in Gyapa with about 10.1 kW, followed by Ahenbeso with about 7.6 kW and the conventional stoves with 7.2 KW and 5.9 kW respectively. Stove AA did relatively poorer with a power output of 5.8 kW.

B. Fuel Consumption Rate

The fuel consumption rates of the stoves were calculated using Equation 2. The results are presented in Table 2. Figure 4 shows the fuel consumption rates of the stoves drawn using the results from Table 2.

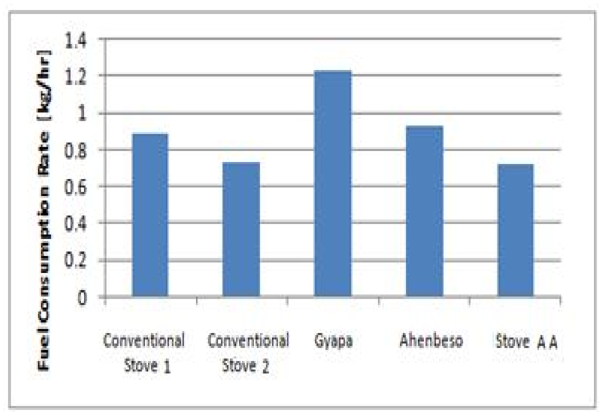


Figure 4 Fuel Consumption Rates of the Five Stoves

With respect to fuel consumption, Stove AA had the least consumption rate of 0.72 kg/hr, followed by the conventional stoves with about 0.73 and 0.89 kg/hr; then Ahenbeso with 0.93 kg/hr and finally the Gyapa with 1.23 kg/hr.

C. Thermal Efficiency

The thermal efficiencies of the stoves were calculated using Equation 3. The results are presented in Table 2. Using these results, a graph was drawn to compare the efficiencies of the five stoves. Figure 5 shows the thermal efficiencies of the stoves, drawn using the results from Table 2.

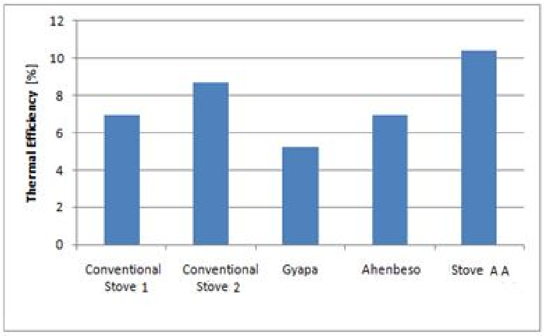


Figure 5 The Thermal Efficiencies of the Five Stoves

Considering the thermal efficiency, Stove AA had the highest. It had 10.43 %, about twice as much as that of Gyapa, 5.21%, which came out as the least thermally efficient. Conventional stoves 1 and 2 had 6.95% and 8.69% respectively, and Ahenbeso 6.95%.

IV. CONCLUSIONS AND RECOMMENDATIONS

The final design meet most of the needs and specification requirements defined for a good cook stove. It can be concluded that the product, Stove AA, has proved to be superior in terms of fuel consumption and efficiency.

The stove is transportable, fuel efficient and has reduced waste of heat generated through thermal losses. It is more fuel efficient and will thus reduce the rate of deforestation, the time and money spent on fuel, and the risk of respiratory infections by improving the air quality for users.

The acceptance and implementation of this stove could create jobs, encourage the use of available local materials and skills, and thereby raise local living standards.

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