



Global Advanced Research Journal of Engineering, Technology and Innovation (ISSN: 2315-5124) Vol. 2(3) pp. 102-110, March, 2013  
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*Full Length Research Paper*

# Thermal efficiency of charcoal fired cookstoves in Ghana

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Accepted 12 March 2013

Biomass is a predominant feedstock for household cooking and heating in developing countries. Charcoal fired cookstoves can be considered an important intermediary for sustainable energy consumption as well as promoting healthy kitchen environments due to the significant reduction in the emission of indoor pollutants associated with smoke in wood fires. The performance indicators (Boiling time, Burning rate, Thermal efficiency and specific fuel consumption) of three popular charcoal fired cookstoves in Ghana (Gyapa, Ahinbenso and the Traditional coalpot) were assessed using the water boiling test (WBT) version 4.1.2 method with Kopie von WBT data calculation sheet 4.1.2 software to generate the performance indicators for five (5) replicate measurements. Charcoal from *neem* was used as fuel. The specific fuel consumption ( $\text{MJmin}^{-1}\text{L}^{-1}$ ) at low power was determined to be  $0.018\pm 0.004 \text{ MJmin}^{-1}\text{L}^{-1}$  for Ahinbenso,  $0.022\pm 0.004 \text{ MJmin}^{-1}\text{L}^{-1}$  for Gyapa and  $0.023\pm 0.010 \text{ MJmin}^{-1}\text{L}^{-1}$  for the Traditional cookstove. These compared favorably with the Global Alliance for Clean Cookstoves' benchmark value of  $0.017 \text{ MJmin}^{-1}\text{L}^{-1}$ . The targeted 45% for thermal efficiency was however, not met by any of the stoves at both high and low power operations. Ahinbenso ( $31.3\pm 1.7\%$  and  $28.3\pm 1.7\%$ ) had the highest efficiency at high power (cold start and hot start respectively) whilst Gyapa ( $35.3\pm 6.11\%$ ) had the highest efficiency at low power operations. From the assessment of the performance indicators Gyapa (1.5) was most efficient, followed by Ahinbenso (1.75) and the Traditional Stove (2.75). The burning rate of bamboo charcoal was also determined to be twice that of neem charcoal for similar dimensions of the charcoal.

**Keywords:** Charcoal fired cookstoves, Thermal efficiency, Water boiling test

## INTRODUCTION

Energy for cooking has been and still remains one of the fundamental energy requirements of humankind. The

energy demands of modern life revolve around the use of hydrocarbons from fossil fuel (Olah, G. A., Goepfert, A. and Prakash, G. K. S., 2009). Cleaner and more efficient cookstoves (high up the energy ladder) has been designed to use electricity, liquefied petroleum gas (LPG) or natural gas of which the energy feedstock are

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predominantly derived from fossil fuels. Current global energy demands show a clear correlation with changes in climatic conditions occasioned by global warming (Cocks, 2009). The need for renewable options has become even more viable as a sustainable concept towards a greener global environment. Biomass feedstock presents this alternative sustainable option in household energy sources. The burning of biomass for energy involves the release of CO<sub>2</sub> which is considered part of the earth's natural carbon cycle and therefore can be deemed to be a carbon neutral activity compared to options higher on the energy ladder which relies on energy from fossil fuel. It is estimated that fuelwood consumption in Ghana is about 20.6 million m<sup>3</sup> annually. (Mason, 2008) Wood supplied for firewood and charcoal production in 2009 was 17,900 Ktons, firewood supply was 9,200 Ktons and charcoal 2,175 Ktons (Energy Commission, 2011). About 84% of households in Ghana use firewood (53.5%) or charcoal (30.6%) for cooking, with LPG (9.5%) and other sources like kerosene (0.6%), electricity (0.3%) and crop residue/sawdust (1.1%) constituting the rest. Charcoal is the dominant source of household cooking fuel in urban areas. 52.6% of the urban population (which constitute half of Ghana's population) depends on charcoal as cooking fuel whilst 13.8% of the population in the rural areas also uses charcoal for cooking (Ghana Statistical Services, 2008). Apart from its convenience in use as compared to wood fire, proximate analysis in the literature shows that charcoal has other advantages such as high percentage of carbon, hydrogen, higher fixed carbon and higher heating value as compared to its antecedent lump wood. It also has lower volatile matter and moisture content (Bhattacharya, S. C., Albina, D. O. and Abdul Salam, P., 2002). The energy density of fuelwood ranges from 12.8 to 15.3 GJ/ton whilst that of charcoal is 28.9 - 31.5 GJ/ton. This means that for the same quantity as wood, charcoal generate more heat with less smoke (Harris, 1999). Traditionally, charcoal production in Ghana predominantly involves the use of cuttings of *Azadiracta indica* (Neem tree) and *Butyrospermum parkii* (Sheanut tree). The pit kiln method is used in the carbonization process, where a shallow pit is dug and the wood is stacked longitudinally along the bottom. The complete pile is covered with vegetation, straw and earth to make an air tight seal around the wood. The wood is lit and the burning allowed to progress from one end of the pit to the other in an atmosphere of little or no oxygen (or air). The process could take around 10–15 days (Agyeman, K. O., Amponsah, O., Braimah, I., and Lurumuah, S., 2012). During carbonization volatile matter which could otherwise pollute the kitchen environment is lost from the wood. The percentage yield of charcoal is usually between 35-45% of the original wood. Cleaner means of producing charcoal through the application of efficient

pyrolytic kilns (Duku, M. H., Gu, S. and Hagan, E. B., 2011) and (Syred, C., Griffiths, A.J., Syred, N., Beedie, D., and James, D., 2006) as well as the derivation of the source of raw material from waste (Duku, M. H., Gu, S. and Hagan, E. B., 2011) and (Sjølie, 2012) makes the use of charcoal as a fuel for domestic energy have a high prospect. For example, there is the thought of introducing charcoal produced from fast growing tree species like bamboo as a mitigating step against the over exploitation of timber species for fuel purposes in Ghana. Indoor emissions (in the kitchen environment) remain a serious drawback to the direct burning of biomass for cooking. Indoor emissions contribute significantly to cases of respiratory diseases in developing countries where these biomass cookstoves are most frequently used (Pennise, D., Brant, S., Agbeve, S. M., Quaye, W., Mengesha, F., Tadele, W. and Wofchuck, T., 2009) and (Saldiva, P. H. N. and Miraglia, S. G.E. K., 2004). The emission of polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs) and carbonyls as well as carbon monoxide can be quite high irrespective of whether wood is used or charcoal (Kabir, E., Kim, K-H., Ahn, J-W., Hong, O-F. and Sohn, J. R, 2010) and (Bhattacharya, S. C., Albina, D. O. and Abdul Salam, P., 2002). Earlier work though shows that charcoal is a much cleaner fuel than burning wood in terms of the emission of PAHs and particulate matter (PM), not taking into account the pollutant emission during the charcoal production (Oanh, N. T. K. and Dung, N. T., 1999). The Global Alliance for Clean Cookstoves has goals intended to drive technology developments that can support the widespread adoption of affordable, user-desirable stoves that provide significant health benefits, labor and financial savings, and soil and forestry benefits. The development of biomass cookstoves has benchmarks on indoor emissions, efficiency, safety and cost. The International Standards Organization's International Workshop Agreement using Volunteers in Technical Assistance (VITA) WBT 4.1 Protocol set a base benchmark for thermal efficiency of a cookstove at a high power thermal efficiency of 45% and a low power specific fuel consumption of 0.017 MJ/min/L. ([http://www1.eere.energy.gov/biomass/pdfs/cookstove\\_meeting\\_summary.pdf](http://www1.eere.energy.gov/biomass/pdfs/cookstove_meeting_summary.pdf)., 2011 (Assessed on 20th June 2012). The emission of all types of pollutants per unit of useful heat is reported in the literature to decrease with increasing stove efficiency (Bhattacharya, S. C., Albina, D. O. and Abdul Salam, P., 2002). Hence, improved thermal efficiency of cookstoves will not only inure to environmental and cost benefits but also health benefits. It is therefore, imperative to assess the thermal efficiencies, specific fuel consumption, the boiling time and the burning rates of charcoal from a variety of tree species in charcoal fired cookstoves on the Ghanaian

market. The study will ascertain whether the benefits of policy interventions which are targeted to improve human health through sustainable energy production and consumption are being realized.

## MATERIALS AND METHODS

Traditional “coalpot” stove, Ahinbenso, Gyapa are the three commonly used charcoal fired metal cookstoves in Ghana. The stoves were bought from the open market.

### Stove description

The metal cookstoves of cylindrical shape are mostly fabricated with scrap metal. Gyapa has a ceramic charcoal compartment fitted into its design to reduce heat loss.

Figure 1 shows the predominantly used charcoal fired cookstoves in Ghana which was used in this study. The Ahinbenso cookstove had a hemispherical combustion chamber (charcoal compartment) with perforations and a curved surface area of 942.87 cm<sup>2</sup> with air inlet of area 138.50 cm<sup>2</sup>.

Gyapa also had a hemispherical combustion chamber with a bottom perforated ceramic lining and a curved surface area of 726.10 cm<sup>2</sup> with air inlet of area 65.00 cm<sup>2</sup>. The Traditional “coalpot” stove had a truncated pyramidal combustion chamber with a surface area of 1093.00 cm<sup>2</sup> and air inlet area of 127.00 cm<sup>2</sup>.

### Fuel used

Charcoal was used as the fuel. The charcoal was produced from lump woodcuttings of *Azadirachta indica*, common names are Neem tree and Indian Lilac. Charcoal from bamboo was also used to assess the burning rate of charcoal from different tree species.

The net calorific value of the dry charcoal used in the calculations as quoted from the literature was 28200 kJ/kg and the self ignition temperature of the two types of charcoal was determined to be 250 °C. The charcoal was lighted with a piece of paper as a starting material.

### Pot for Water Boiling Test

Standard 7 L stainless steel cooking pots were used in the study to boil 5 L of water.

## Methods

### Ambient conditions

The stoves were tested in a simulated kitchen environment well ventilated with a light breeze. The ambient conditions of room temperature and humidity were determined with a Teston TH-018 meter and the average room temperature of 29±2 °C and relative air humidity 77±12% was recorded during the test period.

### Determination of the moisture content of charcoal

The moisture content of the charcoal was determined by pre-weighing a sample of the charcoal and placing in an open-air oven at 105 °C for 2 hours. The sample was then allowed to cool to room temperature in a desiccator with silica blue gel as drying agent and re-weighed. The moisture content was calculated as a ratio of the weight loss due to moisture drying and the weight of the charcoal with moisture as depicted in Equation 1

$$\text{Moisture Content } (\%) = \frac{\text{Weight of Charcoal with moisture (g)} - \text{Weight of dried Charcoal (g)}}{\text{Weight of Charcoal with moisture (g)}}$$

Equation 1

### Determination of the ash content in charcoal

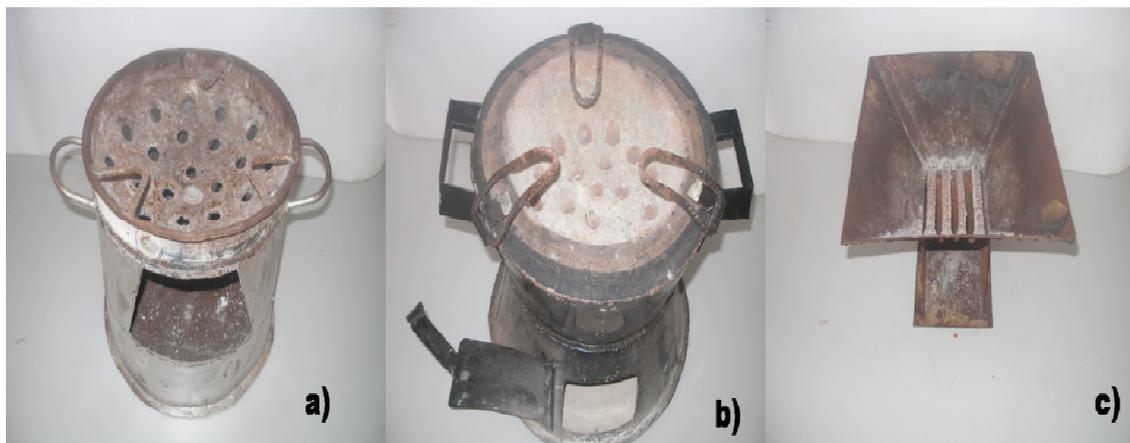
2.65 g of a charcoal sample is weighed in a pre-weighed ceramic crucible. The crucible is then loaded in a furnace and heated to 750 °C for 2 hrs. The crucible with content is then cooled in a desiccator to 25 °C and re-weighed to determine the mass of the content. The percentage ash content is then determined using Equation 2.

$$(\%) \text{ Ash Content} = \frac{\text{Weight of ash (g)}}{\text{Dry weight of charcoal (g)}} \times 100$$

Equation 2

### Average weight of charcoal used

The charcoal compartment was filled to the maximum capacity for the stoves. The amount of charcoal used in the test varied with volume of the combustion chamber of the stoves, Ahinbenso (1722.97 cm<sup>3</sup>), Gyapa (1232.35 cm<sup>3</sup>) and Traditional Stove (6928.40 cm<sup>3</sup>). The average weights of charcoal used in the different tests were 635 g (Ahinbenso), 670 g (Gyapa) and 870 g (Traditional charcoal stove).



**Figure 1.** Physico-chemical characterization of the charcoal fuels Charcoal fired cookstoves in Ghana fabricated from scrap metals, a) Ahinbenso, b) Gyapa and c) Traditional stove ("coalpot").

### Water boiling test

The methods for the testing followed the Water Boiling Test version 4.1.2: Cookstove emissions and efficiency in a controlled laboratory setting protocol by boiling 5 L of water in a 7 L stainless steel pots. Five (5) replicate tests were conducted for each stove and the results were generated from Kopie von WBT data calculation sheet 4.1.2 software. The statistical averages of the five (5) replicate tests with standard deviation were computed from the spreadsheet.

The Gyapa stove was heated in an open air oven at 105 °C for 3 h before allowing to cool in a casing with silica gel desiccant to prevent re-absorption of the moisture. The precautionary measure was necessary to expel trapped moisture in the ceramic lining of the stove which when lost in the testing process may give a false impression of high consumption of fuel.

The dimensions of the charcoal from neem (average length and width  $\pm$  standard deviation) was  $77.8 \pm 23.0$  mm and  $36.1 \pm 15.7$  mm whilst that from bamboo was  $63.4 \pm 21.7$  mm and  $36.6 \pm 9.0$  mm. Figure 2 shows the size distribution (lengths) of the charcoal used. Table 1 shows some characteristic physical properties of the charcoal (from neem and bamboo sources) used in the test such as moisture content, ash content and weight per surface area of the charcoal.

### Determination of the performance of the stoves

The WBT results of the cookstoves tested at high power operations for cold start and hot start as well as low power operations (simmering) are as shown in Table 2 to Table 4

### Boiling time

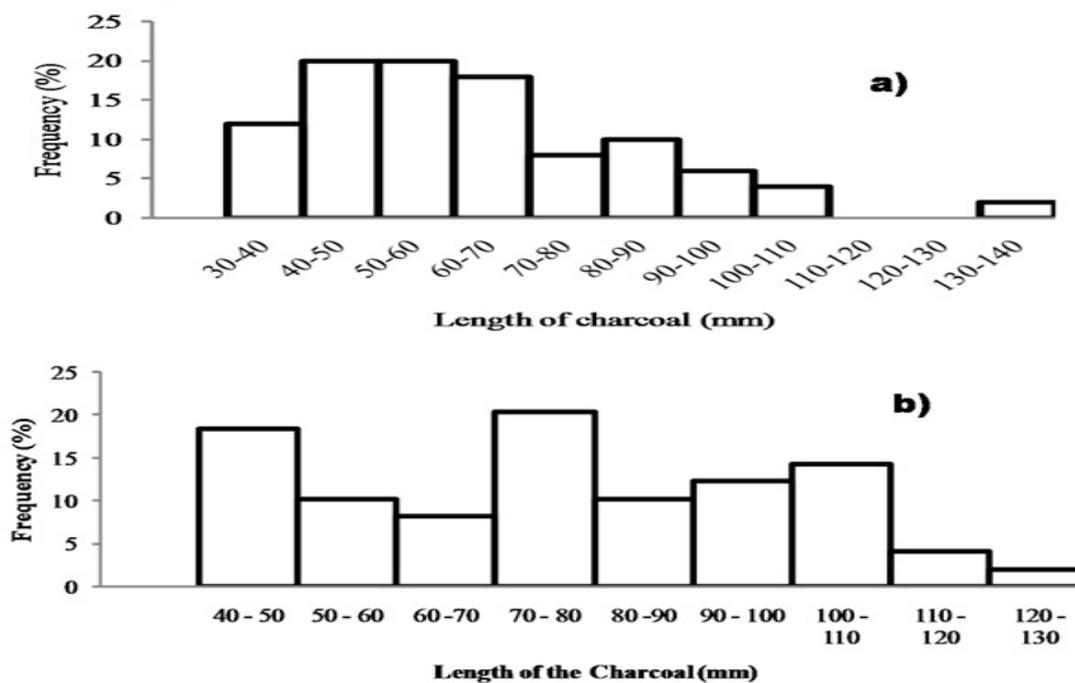
The boiling time of the stove is a measure of its cooking time. Comparing the boiling time for 5 L of water with 95% confidence level, Gyapa stove ( $49.7 \pm 3.5$  min. and  $34.0 \pm 4.9$  min.) was the quickest to boil followed by Ahinbenso ( $60.0 \pm 2.3$  min. and  $61.0 \pm 11.1$  min.) with the Traditional stove ( $95.7 \pm 22.5$  min. and  $73.0 \pm 4.9$  min.) being the slowest with results stated from high power operation testing of the stoves at cold start and hot start respectively.

Statistical comparison, by t-test analysis ( $p < 0.05$ ) within the experimental error, of the three stoves at high power operations (cold start and hot start) showed no significant difference between the boiling time at hot start and cold start for the Traditional stove, however, Gyapa and Ahinbenso recorded significant differences in the boiling time between cold and hot starts with cold starts taking a longer period to boil similar quantity of water.

### Thermal efficiency

Thermal efficiency is the ratio of the work done by heating and evaporating water to the energy embodied in the fuel. The thermal efficiencies at high power (cold and hot start) for the three stoves with 95% confidence level were determined, in the order of decreasing efficiency, to be Ahinbenso ( $31.3 \pm 1.7\%$  and  $28.3 \pm 1.7\%$ ), Gyapa ( $23 \pm 1.1\%$  and  $27.3 \pm 5.7\%$ ) and the traditional cookstove ( $22.7 \pm 1.7\%$  and  $24.0 \pm 3.0\%$ ) as shown in Table 2 to Table 4.

Comparing the thermal efficiency of each of the stoves at hot start and cold start, statistical analysis of the results using the t-test for unequal variance indicated that the t- observed was in each case less than the t-



**Figure 2.** The size distribution of charcoal a) shows the distribution of charcoal from bamboo with length  $63.4 \pm 21.7$  mm and b) shows the distribution of from neem tree with length  $77.8 \pm 23.0$  mm

**Table 1.** Physical properties of the charcoal from bamboo and neem tree sources

Type of Charcoal	surface area/g (cm <sup>2</sup> /g)	Moisture content (%)	Self ignition temp. (°C)	Ash content (%)
Bamboo	0.744	9.32	250	5.55
Neem	1.488	8.02	250	10.45

**Table 2.** Performance of stoves at high power operations (Cold start)

Performance indicators	Gyapa	Ahinbenso	Traditional Stove
	95% Confidence level		
Boiling time (min)	49.7±3.5	60.0±2.3	95.7±22.5
Burning rate of fuel (g/min)	6.3±0.7	4.0	4.0±1.1
Thermal efficiency (%)	23.0±1.1	31.3±1.7	22.7±1.7
Specific fuel consumption (g/L)	63.3±1.3	56.0±2.0	86.5±1.0

**Table 3.** Performance of stoves at high power operations (Hot start)

Performance Indicators	Gyapa	Ahinbenso	Traditional Stove
	95% Confidence level		
Boiling time (min)	34.0±4.9	61.0±12.6	73.0±4.9
Burning rate of fuel (g/min)	7.7±1.3	5.0±1.13	5.0±1.1
Thermal efficiency (%)	27.3±5.7	28.3±1.7	24.0±3.0
Specific fuel consumption (g/L)	55.7±16.1	62.0±3.0	78.7±15.4

tabulated for each of the stoves tested at hot start and cold start and hence there was no significant difference ( $p < 0.05$ ) in efficiency of the stove during operations at high power. The mean thermal efficiency of the

cookstoves at high power was determined to be 29.8% for Ahinbenso, 25.2% for Gyapa and 23.4% for the Traditional stove.

At cold start (high power) operations, a comparative

**Table 4.** Performance of stoves at low power operation (simmering)

Performance Indicators	Gyapa	Ahinbenso 95% Confidence level	Traditional Stove
Burning rate of fuel (g/min)	3.0	2.3±0.7	2.7±1.3
Thermal efficiency (%)	35.3±6.9	23.3±8.2	23.3±2.6
Specific fuel consumption (g/L)	34.3±5.6	28.6±6.6	36.3±16.0

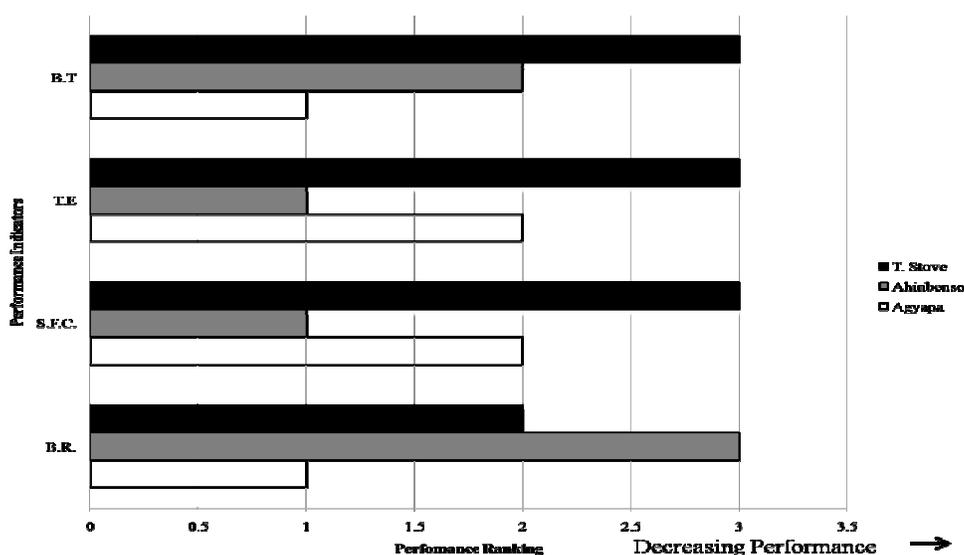


Figure 3. A performance ranking of three (3) charcoal fired cookstoves in Ghana with performance indicators; Boiling time (B.T), Burning rate of fuel (B.R), Thermal efficiency (T.E) and Specific fuel consumption (S.F.C). The highest performance was ranked 1 and the weakest ranked 3.

study of the three different stoves showed that Ahinbenso (31.3±1.7%) was significantly different from Gyapa (23±1.1%) and the Traditional stove (22.7±1.7%), however, there was no significant difference between the thermal efficiency of the Traditional stove and Gyapa. Also no significant difference was observed in the thermal efficiencies of the three stoves at hot start.

At low power operation, no significant difference was observed, within the margin of experimental error, between the thermal efficiency of Gyapa (35.3±6.1%) and Ahinbenso (23.3±8.2%) however, Gyapa was significantly different from the Traditional stove (23.3±2.61%). The thermal efficiency at low power for Ahinbenso was statistically similar to that of the traditional stove. The recommended temperature for safe cooking of food is between 60 °C and 95 °C (<http://www.idph.state.il.us/about/fdd/safecooktemp.htm> (Assessed on 2nd July, 2012)), hence simmering operation of the stoves best simulates the mode of operation of stoves during cooking therefore thermal efficiency at low power was important in assessing the cooking performance of a cookstove.

The results from the determination of thermal

efficiencies of the stoves indicated that Gyapa was the most efficient among the three stoves at low power whilst Ahinbenso was most efficient of the three stoves at high power. The reason can be adduced to the fact that the ceramic body that lines the combustion chamber reduces heat losses through radiation and convection thus, makes available the heat absorbed by the ceramic body during low power operations. Similarly, the cooling of the flue gas near the combustion chamber walls could lead to quenching that reduces the efficiency at high power. (Claus, R. W., Wear, J. D. and Liebert, C. H., 1979).

### Burning rate

The process of burning fuel in a combustion chamber of a system determines the resulting system performance. The burning rate of the charcoal in both the Traditional stove and Ahinbenso were very similar at  $4.0 \pm 1.1$  g/min and  $5.0 \pm 1.1$  g/min respectively for cold and hot starts and do not show any significant difference statistically at 95% confidence level. Gyapa, however, had a faster fuel

burning rate of  $6.3 \pm 0.7$  g/min and  $7.7 \pm 1.3$  g/min respectively for cold and hot starts.

A number of factors have been established in the literature to have effect on the burning rate of the solid fuel. Some of the factors are; air and fuel mixture ratio ([http://www.em-ea.org/Guide Books/book-2/2.1 Fuels and combustion.pdf](http://www.em-ea.org/Guide_Books/book-2/2.1_Fuels_and_combustion.pdf) (Assessed on 12th July, 2012)), the combustion chamber geometry (Leger, B., Miron, P. and Emidio, J. M., 2003), Homogeneity in size of the fuel, with usually smaller sizes ensuring that fire has the minimum excess air due to high surface area of solid fuel ensuring complete combustion ([http://www.em-ea.org/Guide Books/book-2/2.1 Fuels and combustion.pdf](http://www.em-ea.org/Guide_Books/book-2/2.1_Fuels_and_combustion.pdf) (Assessed on 12th July, 2012)), and cold metal walls of the combustion chamber (Claus, R. W., Wear, J. D. and Liebert, C. H., 1979). The influence of these factors is pre-determined by the stove design as well as the specifications of the fuel type.

A fuel rich combustion process leads to high emission while a lean fuel combustion process reduces maximum power. The right mix leads to higher combustion temperature and hence increased efficiency for charring materials (Harmathy, 1978). Assessing the surface area to volume ratio of the combustion chambers of the three stoves, the traditional stove had the lowest ( $0.158 \text{ cm}^{-1}$ ) followed by Ahinbenso ( $0.547 \text{ cm}^{-1}$ ) and Gyapa ( $0.589 \text{ cm}^{-1}$ ).

A high surface area to volume ratio of the combustion chamber will lead to a cooling effect on the flue gas making it burn slower. Wall cooling requires approximately 40% of the total air mass flow rate to produce combustion chamber exit gas temperatures of about 1500 K. Thus, a very small air mass flow quantity would be left for combustion, which would be inefficient for fuels with low calorific values where a large proportion of the air is required for the combustion process (Leger, B., Miron, P. and Emidio, J. M., 2003). Also a ceramic coating lowers liner temperatures by acting as a thermal barrier to convective heat because of its low thermal conductivity. It also well reduces radiation heat because its thermal absorptivity is lower than that of the bare metal (Claus, R. W., Wear, J. D. and Liebert, C. H., 1979). Thus ceramic liners reduce the burning rate of fuel in the packed bed, since turbulence as a result of air draft through the fuel bed which would otherwise increase the burning rate is subdued. Comparing the burning rate of charcoal in Ahinbenso, Gyapa and Traditional stove however, the fastest burning rate was observed in Gyapa (with ceramic liner) than in the other stoves with bare metal. This could be due to the fact that there are other design parameters that far more than compensate for the effect of surface area to volume ratio and wall cooling in the determination of the burning rate in the cookstoves. The effect of the particle size of the charcoal and the homogeneity of the charcoal on the

burning rate and thermal efficiencies is not expected to be significant since similar size charcoal was used for each stove test.

However, air is sucked inside the stove through the grate and passes through the charcoal bed in the combustion chamber where it mixes and burns. Hence a combination of the dimension of the air inlet and the stove geometry could be important parameters in creating the suction to allow optimum air flow (Kausley, S. B. and Pandit, A. B., 2010). The interplay of the dimension of the air inlet in relation to the combustion chamber geometry in generating a natural draft leading to air acceleration into the combustion chamber could be a key reason for the difference in burning rate of the charcoal in the Gyapa (7.0 g/min.) and the Ahinbenso and the traditional stove which had an average burning rate of 4.5 g/min. Gyapa had an air inlet with surface area  $65 \text{ cm}^2$  about half the size of the air inlet for the Traditional stove ( $127.0 \text{ cm}^2$ ) and the Ahinbenso ( $138 \text{ cm}^2$ ).

The constriction will force hot air to rise up through the perforations at the base of the combustion chamber, thus increasing the air flow by drawing cooler air from the surrounding through the inlet into the chamber. Combustion will thus have the optimum fuel-air mix ratio through the creation of turbulence around the charcoal bed and hence burn faster as well as reduce smoke in Gyapa than in the Traditional stove and in Ahinbenso as observed.

Another factor contributing to the lower burning rate in the Traditional stove and the Ahinbenso was that their combustion chamber wall was fabricated with metal which is likely to cool faster as a result of air turbulence around the stove. This led to heat losses due to radiation and hence reduced the flue gas temperature thus quenching the flue gas and reducing the burning rate.

Comparing the burning rate of bamboo charcoal and neem charcoal in an Ahinbenso cookstove, the results showed that the bamboo charcoal had a high burning rate ( $9.0 \text{ g min}^{-1}$ ) at high power cold start as compared to charcoal from neem ( $4.0 \text{ g min}^{-1}$ ). Bamboo charcoal ( $63.4 \pm 21.7 \text{ mm}$  and  $36.6 \pm 9.0 \text{ mm}$ ) had a relatively smaller dimension than neem charcoal ( $77.8 \pm 23.0 \text{ mm}$  and  $36.1 \pm 15.7 \text{ mm}$ ) and the surface area per unit mass of neem charcoal ( $1.488 \text{ cm}^2 \text{ g}^{-1}$ ) was about twice that of bamboo charcoal ( $0.744 \text{ cm}^2 \text{ g}^{-1}$ ). Hence, the diffusion of thermal energy across the surface of bamboo charcoal covers a shorter distance.

The heat transfer from the ignited charcoal particle to adjoining particles is therefore expected to be quicker. Thus a strong correlation was observed between surface area per unit mass of fuel and its burning rate.

## Specific fuel consumption

Specific fuel consumption (SFC) is the ratio of the mass of fuel consumed to the volume of water heated for each cooking task and is measured in grams (g) of fuel per liter (l) of water. In the simmering test, specific fuel consumption is redefined as the ratio of the mass of fuel consumed to the volume of water remaining after 45 minutes at, or just below, the boiling point or the ratio of equivalent calorific value of fuel to the volume of water remaining per minute measured in g/l (fuel/water) or MJL<sup>-1</sup>min<sup>-1</sup>. Since there is no temperature change in the water during the simmering operation, the only work done on the cooking pot is the evaporation of water. At high power the specific fuel consumption at cold start was not significantly different ( $p < 0.05$ ) from the hot start for Gyapa, however, for both Ahinbenso and the Traditional Stove the specific fuel consumption at cold start and hot start were significantly different. At cold start, the Traditional stove had the highest SFC ( $86.5 \pm 1.0 \text{ g l}^{-1}$ ) whilst Ahinbenso had the lowest SFC ( $56.0 \pm 2.0 \text{ g l}^{-1}$ ). At low power, SFC of Ahinbenso ( $28.6 \pm 6.6 \text{ g l}^{-1}$  or  $0.018 \pm 0.004 \text{ MJL}^{-1} \text{ min}^{-1}$ ) was not significantly different from Gyapa ( $34.3 \pm 5.6 \text{ g l}^{-1}$  or  $0.021 \pm 0.004 \text{ MJL}^{-1} \text{ min}^{-1}$ ) and the traditional stove ( $36.3 \pm 16.0 \text{ g l}^{-1}$  or  $0.023 \pm 0.010 \text{ MJL}^{-1} \text{ min}^{-1}$ ) within the limit of experimental error.

## Ranking cookstoves by rating scale

The stoves were rated along the rating scale of one (1) to three (3), with one (1) representing the highest performance and three (3) the lowest of the performance indicators i.e. thermal efficiency, boiling time, fuel burning rate and specific fuel consumption. The ranking of the three most predominant charcoal fired cookstoves on the Ghanaian market showed that Gyapa with an average score of 1.5, by their performance ratings, ranked highest followed by Ahinbenso (1.75) and the Traditional Stove (2.75). The result is represented in Figure 3-2

## CONCLUSIONS

The specific fuel consumption (MJmin<sup>-1</sup>L<sup>-1</sup>) at low power was determined to be  $0.018 \pm 0.004 \text{ MJmin}^{-1} \text{ L}^{-1}$  for Ahinbenso,  $0.021 \pm 0.004 \text{ MJmin}^{-1} \text{ L}^{-1}$  for Gyapa and  $0.023 \pm 0.010 \text{ MJmin}^{-1} \text{ L}^{-1}$  for the Traditional cookstove. These compared favorably with the benchmark value of  $0.017 \text{ MJmin}^{-1} \text{ L}^{-1}$  set by the Global alliance for clean cookstoves. The benchmark value of 45% for thermal efficiency was however, not equaled by any of the stoves at both high power and low power operations. Ahinbenso ( $31.3 \pm 1.7\%$  and  $28.3 \pm 1.7\%$ ) had the highest

efficiency at high power whilst Gyapa ( $35.3 \pm 6.11\%$ ) had the highest efficiency at low power operations. The measurement of the performance of the three stoves most predominant on the Ghanaian market using the WBT showed that Gyapa (1.5) was ranked highest, followed by Ahinbenso (1.75) and the Traditional Stove (2.75). The burning rate of bamboo charcoal was about twice that of neem charcoal and correlates with the surface area per unit mass of charcoal for the different varieties. Thus investments in interventions in energy, environmental impact and sustainable technologies have been assessed to have significant savings on both the local and global environment.

## ACKNOWLEDGEMENT

We acknowledge the immense assistance in the laboratory work by Messrs Michael Sewordor, Ishmael Aggrey, Leonard Ocran, and Miss Christiana Teiko Osakonor of the Materials and Manufacturing Programme, Council for Scientific and Industrial Research, Institute of Industrial Research. We also acknowledge CookClean Ghana Limited and Noko Kpakpa for their financial support.

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