THERMAL EFFICIENCY AND SPECIFIC FUEL CONSUMPTION OF COMMON HOUSEHOLD COOKSTOVES IN BAUCHI

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ABSTRACT

Five different stoves using two biomass fuels, kerosene, liquefied petroleum gas (LPG) and electricity were examined. Fuel and stove parameters were monitored. The result showed that solid biomass stoves have substantially lower thermal efficiencies, higher specific fuel consumption than stoves using liquid and gaseous fuel. In general, efficiencies increases from values of 9.6% for three stone fire using firewood to 78.4% for gas stove employing LPG. Biomass fuels have higher burning rate and specific fuel consumption because the quantity of firewood and charcoal required to raise 1kg of water to boiling point is more when compared to liquefied petroleum gas and kerosene.

SIGNIFICANCE: Thermal parameters which were studied in this work are of importance in the design and use of stoves to promote the utilization of more efficient stoves in terms of fuel usage.

KEYWORDS: Water boiling test (WBT), Thermal efficiency, Boiling point, Fuel, Specific fuel consumption

1. INTRODUCTION

Rural and urban energy systems are characterized by the use of biomass, in the form of wood, charcoal and plant residues for cooking. Biomass is at the bottom rung of the ladder for cooking with charcoal, then kerosene and finally liquid petroleum gas and electricity are towards the top. The domestic energy survey carried out in Bauchi revealed that a settlement (Yelwa) with an average household size of seven has a total energy consumption of 0.18155GJ/household/day with 0.1062GJ from the use of fire wood (Adeyemi and Asere, 2007). A recent survey in a group of villages in South India revealed that the energy consumed for cooking in these villages amounts to 8GJ/capita/year (www.fao.org). This is comparable to the fuel wood demand for domestic cooking in other developing countries. By contrast, the average amount of energy consumed for cooking in the US using gas stoves with pilot lights is 3.1GJ/person/year. If the pilot light is eliminated, energy use for cooking with gas stove would fall to 1.5-2.0GJ/person/year (www.fao.org). This is not comparable to the energy survey in Bauchi which revealed that gas stoves are least patronized. The energy consumption from using LPG for cooking stood at 0.00855GJ/household/day for a settlement like Yelwa while other settlements in the survey area sampled had no energy consumption from the use of LPG (Adeyemi and Asere, 2007). A wide range of fuels are used for household cooking in Bauchi (North East of Nigeria). A survey carried out in the region revealed an over dependence on firewood with 90% of urban and rural households utilizing it either as main fuel for cooking or as a secondary fuel.

Bauchi has a typical tropical climate marked clearly by the dry and rainy seasons. The average annual rainfall is 700mm and the wettest months are in July, August and September. The dry season starts in November and ends in April. It is the dominant urban centre in the state and covers an area of over 35,400 km^2 and most of the 398,190 inhabitants live within the city and its environs. The pace of urbanization has increased substantially as more people move to the city.

The trees commonly used as firewood in the region include : *kaya senegalensis* ("Madau"), *Prosopis Africana* ("kirya"), *Tamarindus indica* ("tsamiya"), *parkia clapertoniana* ("dorawa"), *Terminalia glucoscens* ("baushe") amongst others. Their calorific values range between 15MJ and 18MJ (Adeyemi *et al.,* 2008). Cooking over an open fire is widely practiced in this region. The method for evaluating cook stove performance as described in this paper also apply to open fire cooking (three stone fire). The 3 stone is mostly used for the firewood. It is a simple open fire cooking arrangement and no special skill or investment cost is involved in constructing, operating and maintaining them. The pothole size can be varied to fit pots of various diameters by adjusting the stones (Figure 1). Charcoal is obtained from wood pyrolysis. The charcoal stove is a portable stove fabricated from galvanized iron bucket and grate. It comes in various sizes to fit pots of different diameters (Figure 2).

Kerosene is a middle distillate from petroleum refining and is mainly used in the cities mainly for lighting and warming of left over foods. The common kerosene stove consists mainly of the fuel tank, burner assembly and load bearing assembly. The fuel tank is fitted with cap assembly, a kerosene level indicator and a wick control lever designed for raising and lowering the wicks to control the intensity of the flame. The burner assembly consists of 10 wicks with an inner and outer sleeve. The space between the sleeves is designed to supply more pre heated air to ensure better combustion. At the top of the burner assembly, a load-bearing assembly (22cm) is placed to provide the platform for the pot (Figure 2).

2. THEORETICAL BACKGROUND

Biomass combustion is a complex process involving chemical kinetics, conductive, convective and radiative heat transfer processes. This suggests that experimental measurements of biomass stove performance are necessary. For a three stone arrangement 8% of the heat is absorbed by water in the pot, 10% is lost by evaporation from pot and 82% is lost to the environment (Baldwin, 1986). To improve the fuel efficiency of a stove, much of the energy stored in the combustible (fuel) should be released as heat (combustion efficiency), as much of the heat generated should be transferred to the pot (heat transfer efficiency) and only as much heat as is needed to boil water or cook is generated (control efficiency).

2.1 Burn rate: This is a measure of rate of fuel consumption while bringing water to boil. It is a ratio of fuel consumed and duration of the test. The burn rate is corrected for the amount of kerosene used as a lighter, the charcoal remaining and the moisture content of the firewood (Ahuja, 2000). The burn rate of liquid fuel is the weight of fuel consumed divided by experimental time.

$$F = \frac{1}{t}\left[\frac{100 \times w_w}{100+M} + \frac{w_k H_k}{H_w} - \frac{w_c H_c}{H_w}\right] \quad \ldots \quad (1)$$

Where: F = burn rate for wood fuel in kg/hr; t = duration of experiment (hours); w_w = weight of wood (kg); w_k` = weight of kerosene (kg); $H_k$`=calorific value of kerosene (kJ/kg); w_c`=weight of charcoal (kg); $H_c$`= calorific value of charcoal (kJ/kg); M= moisture content of wood (%); H_w`= calorific value of wood (kJ/kg)

The Burn rate of liquid fuel is expressed as

$$F = \frac{w_k}{t} \text{ in kg/hr} \quad \ldots \quad (2)$$

Where w_k = weight of kerosene consumed and t = the time duration of the experiment.

2.2 Thermal efficiency: Thermal efficiency is the product of combustion and heat transfer efficiencies. Combustion efficiency measures the extent of which the chemical energy in the fuel is converted into heat and subsequently used to evaporate water in the pot (Ahuja 2000). Heat transfer efficiency indicates what fraction of the heat produced is actually transferred to the pot and water. The amount of heat used to evaporate water is considered as useful heat input to the pot.

Thermal efficiency is calculated from

$$\eta\% = w_i a(T_f - T_i) + \frac{(W_i - W_f)L}{(F \times t \times H_w} \quad \ldots \quad (3)$$

Where: w_i = initial weight of water (kg); a = specific heat capacity of water in (kJ/deg^0C); T_f = final temperature of water (℃); T_i = initial temperature (°C); w_f = final weight of water (kg); L= latent heat of vaporization of water (kJ/kg); F= burn rate in (kg/h); t= duration (hr); H_w =net calorific value of main fuel (kJ/kg).

The thermal efficiency of the fire wood stove is also computed using (VITA) method (www.fao.org). It is thus expressed as

$$\eta\% = \frac{[w_p c_p + w_i a][T_f - T_i] + [w_i - w_f]}{[w_c H_w - w_r H_r]} L \ldots \quad (4)$$

Where: w_p =weight of pot (kg); w_c = fuel wood consumed (kg); c_p = specific heat capacity of aluminum pot; w_r = charcoal remaining (kg); H_r = calorific value of charcoal (kJ/kg).

The thermal efficiency for an electric stove is calculated from (www.energylabel):

$$\eta\% = \left[\frac{1.16\, W_i (T_f - T_i)}{E} + \left[c_p w \frac{T_f - T_i}{3.6 \times E}\right]\right] X100 \quad \ldots (5)$$

Where: E = measured power consumption

2.3 Fire power: This refers to the ratio of fuel energy consumed by the stove per unit time. It is an indicator of the stoves average power output during the high power test (Rob *et al.*, 2007). It is expressed as:

$$P = \frac{w_c H}{60\, t} \quad \ldots \quad (6)$$

Where: w_c = fuel consumed (kg); t = time duration in hours; H = net calorific value of fuel.

3.0 MATERIALS AND METHODS

3.1 Experimental set-up: The water boiling test was used to determine the thermal efficiency of the various cook stoves. This involved heating one kilogram of water in a 20cm diameter, 3 litres aluminum pot on each of the cook stoves to boiling point in a typical kitchen environment. The water boiling test considered the high power cold start phase to determine the specific fuel consumption, fire power, burning rate and thermal efficiency. The following measurements were taken before, during and after the experiment.

i. The weight of pot, cooking water and cooking fuel were taken before the start of the experiment using a weighing scale. The temperature of the water was also taken with mercury in glass thermometer.
ii. The temperature of the water at boiling point and time taken to raise the water temperature to boiling point was recorded. Weight of water after the experiment was recorded.
iii. Prior to the start of the experiment, the calorific value of the solid fuels was determined using the Bomb calorimeter. The moisture content of the wood was determined on wet basis.

Figure 1: WBT on three stone arrangement

Figure 2: WBT on kerosene and charcoal stoves

4.0 RESULTS AND DISCUSSION

Table 1: Thermal characteristics of various stoves

Parameters	3 stone fire	Charcoal stove	Kerosene stove	LPG	Electricity
$w_p\,(kg)$	0.436	0.436	0.436	0.436	0.436
$w_i\,(kg)$	1.000	1.000	1.000	1.000	1.000
$w_f\,(kg)$	0.956	0.960	0.960	0.990	0.957
T_i (°C)	29.0	29.0	29.0	29.0	29.0
T_f (°C)	97.0	97.0	97.0	97.0	97.0
$(w_i - w_f)$	0.044	0.040	0.040	0.010	0.043
$(T_f - T_i)$°C	68.0	68.0	68.0	68.0	68.0
Time(hrs)	0.1674	0.2718	0.1138	0.076	0.1583
c_p(kJ/kg°C)	0.92	0.92	0.92	0.92	0.92
a(kJ/kg°C)	4.18	4.18	4.18	4.18	4.18
H (kJ/kg)	18400	27600	43300	45000	-
L(kJ/kg°C)	2260	2260	2260	2260	2260
E(kWh)	-	-	-	-	0.170
Specific fuel consumption	0 .225	0.123	0.0265	0.0093	-
Fire Power (W)	6928	2834	2734	1513	-
Burning rate(kg/min)	0.022	0.0061	0.0037	0.002	-
η%	9.66	11.46	34.0	74.2	50.85

Table 2: Cost of fuel for boiling 1 kg of water

Type of Fuel	Cost of Fuel (Naira)
Firewood	1.52
Charcoal	2.24
Kerosene	2.55
LPG	2.58
Electricity	2.78

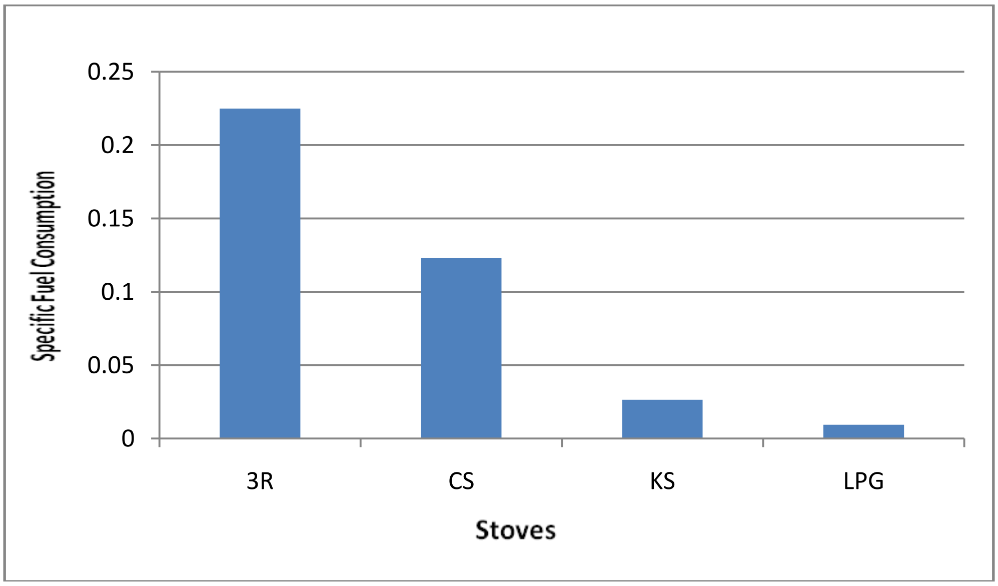

Figure 3: Specific fuel consumption of tested cookstoves (Key: 3R- three stone fire, CS-charcoal stove, KS- kerosene stove, LPG-gas burner)

The firewood stove has a specific fuel consumption of 0.2259. This is high when compared to kerosene stove with 0.0265 and LPG stove with approximately 0.01.

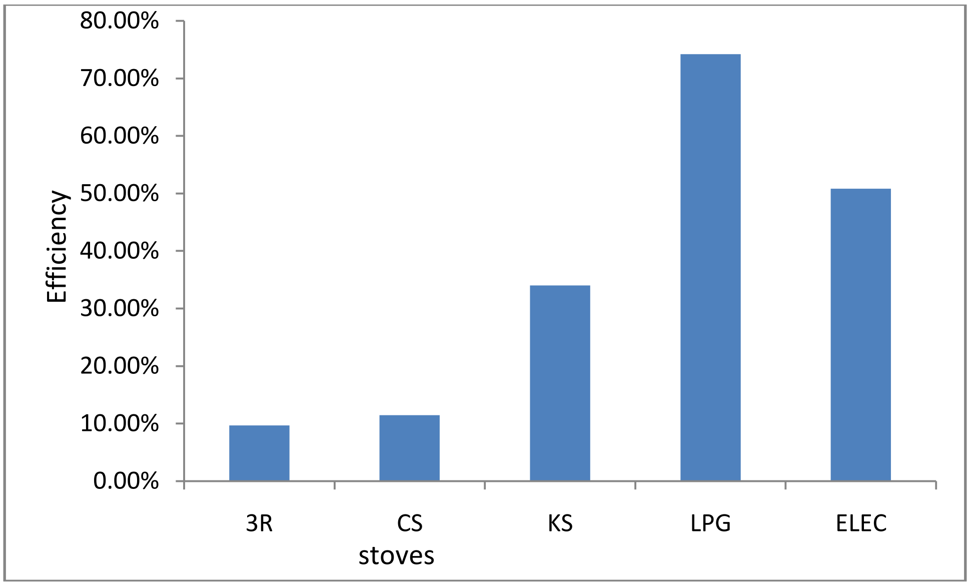

Figure 4: Efficiency of cookstove/fuel combination (Key: 3R- three stone fire, CS- charcoal stove, KS- kerosene stove, LPG-gas burner ELEC- electric stove)

The bar graph shows the experimental results for the thermal efficiencies of the three stone arrangement, charcoal stove, kerosene stove, LPG stove and electric stove. It is observed that the three stone arrangements have the least efficiency of 9.66% closely followed by the charcoal stove with 11.46%. Highest efficiency was recorded in the LPG stove. It has a value of 74.2%. This implies that LPG stoves release more heat than other stoves studied. The result also revealed that charcoal stove had the longest time duration in bringing 1kg of water to boiling point. At the start of the test, 19minutes 14 seconds was used to bring water to boil but subsequently, the time taken dropped to 13minutes 23seconds. This was because during the second test, the charcoal was charged and glowing fully. The kerosene stove had a time duration of 6minutes 50 seconds to bring water to boil with a fuel consumption of 0.025kg. The second test lasted 6minutes 44seconds with consumption of 0.023kg of kerosene. This implies an average time duration of 6minutes 48seconds for a kerosene stove (wick type) to bring 1kg of water to boiling point.

The 2000W electric stove consumed 0.20kWh in 11minutes 57 seconds in the first test and subsequently 0.170kWh in 9minutes 30seconds. The test environment doesn't have voltage fluctuation problems. For the electric stove, the average time duration is 10minutes 56seconds. Three stone arrangement had an average time duration of 10minutes 20seconds to bring 1kg of water to boiling point. The cost of boiling 1kg of water using the various fuels is shown in Table 2. The result showed that the electric stove had the highest cost. This is due to the fact that there are some other charges (maintenance fee, VAT) which is added to the tariff of 6.60 Naira per kWh for a three phase meter. The test environment uses the prepaid meter. This is followed by LPG, kerosene, charcoal and the cheapest is the firewood. This is why there are hardly any large scale shifts from firewood to modern fossil fuels. It is easily accessible to households and remains in very high demand at the expense of Nigerian forests.

5.0 CONCLUSION

Five types of fuel using various stoves have been studied for efficiency and specific fuel consumption using the water boiling test. Other parameters like burning rate and fire power were also determined. The burning rate increased from LPG, kerosene, charcoal with the firewood stove having the highest. The LPG stove has the highest thermal efficiency followed by the electric stove, kerosene stove, charcoal stove and the firewood stove. Rating the efficiency in terms of the cost, the electric stove is least efficient. Time taken to boil water on the stoves categorized the charcoal stove to be the least efficient while LPG stove has the highest efficiency. The firewood stove had the highest specific fuel consumption which implies that it consumes more fuel than other stoves to bring water to boil. LPG stoves have the highest efficiency taken into consideration thermal efficiency, cost, time duration and specific fuel consumption of all the stoves.

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