


Research Article

Design of an Improved Cooking Stove Using High Density Heated Rocks and Heat Retaining Techniques

Anthony A. Bantu,¹ Gilbert Nuwagaba,¹ Sarah Kizza,¹ and Yonah K. Turinayo ²

¹Department of Engineering and Environment, Uganda Christian University, P.O. Box 4, Mukono, Uganda

²National Forestry Resources Research Institute (NaFORRI), National Agricultural Research Organisation (NARO), P.O. Box 1752, Kampala, Uganda

Correspondence should be addressed to Yonah K. Turinayo; t2rinayonah@gmail.com

Received 18 July 2018; Accepted 15 October 2018; Published 28 October 2018

Academic Editor: Jayanta Mondol

Copyright © 2018 Anthony A. Bantu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In sub-Saharan Africa, dependence on wood fuel has caused significant depletion of vegetative resources. Whereas there exist hundreds of improved cooking stoves, many have not reached their maximum potential because their designs are predominantly focused on either fuel efficiency or reduced smoke. This research designed and fabricated an improved charcoal stove using high density rocks and heat retaining techniques. The aim was to retain heat and minimise heat losses in cooking devices with a sole purpose of reducing the amount of fuel used during cooking. The stove design herein incorporates the interaction of physical and thermal properties of granite rocks with heat loss theories to give a thermal efficient unit. The stove was estimated to cost US\$ 36 which compared favourably with most of the improved charcoal stoves on international market (US\$ 3–50 US\$). This study revealed that, by introducing the new stove design and insulation, the granite rocks depicted high thermal storage properties with potential for reducing fuel use by over 78% with reference to the open fire stove. The designed granite rock stove therefore paves way for the use of high density rocks in improved cook stoves to achieve high performance energy efficient systems that can sustainably put to use vegetative resources.

1. Introduction

Many of the world's population living in developing countries lack access to modern energy services for economic and social development. Besides, its existing energy system is unsustainable [1]. A large proportion of the households do not have access to grid electricity. Yet, those relying on electricity for cooking experience intermittent power supply. Although liquid petroleum gas burns quite effectively, it is expensive and not viable for a common man. More so, there has been persistent escalating fossil oil prices and fuel crisis which has drawn attention to the need for producing viable alternatives to kerosene and gas for domestic cooking [2]. Solar, another potential alternative source of energy, is noticeably location-specific in terms of utilisation. Its associated problems are linked to energy storage for use during the period of modest or no sunshine, as well as need for technological artifacts, which are currently scarce in the

developing countries [3]. However, several renewable energy resources including hydroelectricity, solar, and biomass are promoted due to their high availability and responsiveness to the environment.

In Africa, biomass is a traditional and the most reliable fuel source of energy used for cooking by over 69% of the population [4]. However, its increased utilisation by inefficient technologies has raised fears over the long-term forest degradation with loss of environmental services (e.g., watershed protection) and biodiversity [5]. Biomass is quite difficult to burn completely in the most commonly used traditional household-sized stoves [6]. Frequent use of stoves developed by improper combustion designs may result into indoor air pollution, impacting negatively on the health of household members, particularly women and children [1]. For instance, Nahar [7] reported that about 2 million annual excess deaths of women and children in developing countries are linked to indoor air pollution, precisely due

to exposure to carbon monoxide and the volatiles (benzene and formaldehyde) liberated in the form of smoke [8]. Such exposures lead to acute respiratory infections, low birth weights, lung cancer, chronic obstructive lung diseases, and eyes problems [9]. Thus, faster technological development is vital in advancing charcoal stove and its environmental performance.

Although charcoal is believed to be an affordable, available, and the most convenient fuel source for households, its use in inefficient stoves would produce significant amounts of indoor air pollution and make it unsustainable. Therefore, continual technology development will suppress charcoal's detriments and enhance its efficient utilisation while reducing significantly environmental impact.

This work therefore aims at developing a more efficient and safe charcoal burning stove that can reduce fuel consumption rates and indoor air pollution. Even though a lot has been done to promote "improved cook stoves" in the developing countries, little has been emphasised on quality combustion during their design and development [10]. This is attributed to limited scientific information on design features and materials of stove construction. In sub-Saharan Africa however a number of stove models are designed and fabricated by local artisans using locally available materials such as mud, clay, dry grass, ant-hill soil, and clay bricks. But no attempts have been made on high density rocks such as granite.

This paper deals with the development of a charcoal stove prototype from locally available materials including granite rock, stainless steel, and the glass wool. It describes the design features, thermodynamic performance, and thermophysical properties of the granite rock used in thermal-energy storage (TES) system fabrication. According to previous studies on thermophysical properties of granite rock, a suitable TES system should have high values of thermal conductivity, specific heat capacity, material density, and low values of porosity [11–13]. High thermal storage efficiencies are as a result of high values of thermal conductivity, specific heat capacity, and density. High density and specific heat capacity values lead to a large volumetric heat capacity hence permitting compact storage in the systems, whereas low values of porosity indicate large bulk density and uniaxial compressive strength [14, 15].

2. Materials and Methods

2.1. Construction Materials

2.1.1. Fiber Glass. A section of the stove wall was made from glass wool because this material is a poor conductor of heat due to its low thermal conductivity and thus will prevent heat loss by conduction. Through saving as much heat as possible, the fuel combustion efficiency of the stove is improved; it means saving even much more fuel. In addition, the fiber glass material is locally available.

2.1.2. Stainless Steel. Stainless steel was chosen as a material because of its availability on the local market. Technically, it undergoes allowable deformation and is resistant to corrosion in high temperatures. Steel has a longer service life than most

metals and because of this, its design life costs are minimal.

2.1.3. Granite Rocks. Rocks are considered an attractive storage material for thermal-energy storage at high temperatures due to their thermal physical and mechanical properties [11, 12]. The rock selected was granite because of its high density, good thermal properties, and ready local availability.

2.2. Designing and Construction of the Stove. In order to come up with the desired stove design and its desired performance, proper reflection into factors such as fuel type, calorific value, air flow rate, insulation, local resources, stove power output, safety consideration, reactor cross-sectional area, diameter, and height are of great importance. In the present study, the size of the combustion chamber and the amount of fuel required to accomplish the cooking task were evaluated following work done by Kiwana [16] and Maxwell [17], as well as reasonable assumptions depicted in Table 1. Fuel (carbonised agrowaste briquettes and charcoal) for experimental design was selected based on its local availability within Kampala district.

The combustion chamber dimensions were based on the Kenyan ceramic jiko stove because of its prominence on the Ugandan local market and availability of dimensional data. The jiko stove has a basal internal diameter of 160mm and fire box depth of 100 mm [17]. A combustion chamber with an internal diameter of 120mm and height 100mm was fabricated. Thus, taking the combustion chamber (inner chamber) as the focal point, the outer chamber (concentric to the combustion chamber) was fabricated at an internal diameter of 170 using granite rock, glass wool, and stainless steel at 23mm, 48mm, and 1.0mm thick, respectively.

2.3. Testing of Thermal Properties of Granite Rock and the Improved Cook Stove

2.3.1. Specific Gravity Test of Granite Rock. Granite rocks used were sampled from the East African granite dealers, Kampala district-Uganda. These rocks were obtained by randomly selecting representative samples from the cut debris stock piles. By hand picking, samples were collected at random points from the stock piles of different rock sizes. Specific gravity test was conducted according to AASHTO [18] to determine the density of granite for the different rock masses. Initially, the density of the hand crashed 14/10mm granite rock sample was calculated using (1), where M1 is mass of gas jar and plate, M2 is mass of gas jar, plate, and aggregates, M3 is mass of gas jar, plate, aggregates, and water, and M4 is mass of gas jar, plate, and water.

$$\text{Specific gravity} = \frac{(M2 - M1)}{(M4 - M1) - (M3 - M2)} \quad (1)$$

Given 1 g/cm^3 as the density of water, this implies that it buoys up anything within it by 1 gram per cubic centimetre of displacement. Because of this, the weight in air minus the weight in water is equal to the volume of the rock sample in cm^3 .

TABLE 1: Thermal design assumptions for the cooking stove.

No-	Material	Parameter	Units	Values	Reference
1	Fuel (carbonised agro-waste briquettes)	Calorific value	MJ/kg	21.7	Kiwana, 2016
2	Charcoal	Calorific value	MJ/kg	29.8	Kiwana, 2016
3	Water	Density	g/ltr	1000	Global Alliance for
4	Water	Specific heat capacity	J/g.K	4.186	Clean Cookstoves, 2014
5	Granite rock	Thermal conductivity	W.m ⁻¹ . K ⁻¹	2.68	Eppelbaum, 2014
6	Air	Thermal conductivity	W.m ⁻¹ . K ⁻¹	0.02	Lienhard IV, 2000
7	Stainless steel	Thermal conductivity	W.m ⁻¹ . K ⁻¹	16	Young, 1992
8	Glass wool	Thermal conductivity	W.m ⁻¹ . K ⁻¹	0.04	Young, 1992
9	Flame	Theoretical Maximum temperature	K	2123	Yusuf, 2011
10	Cook stove	Theoretical thermal efficiency	%	35	
11	Cook stove	Energy loss	%	65	

2.3.2. *Water Absorption Test.* In line with AASHTO [18], the water absorption test was conducted to determine the amount of water absorbed under specified conditions. This is mainly due to the effect water usually has on heat transfer in rocks through conduction. The data obtained therefore helped shed light on the performance of the granite rock in humid environments. During the experiment, the granite rocks were hand crushed to 14/10mm aggregates before the test could be carried out. Water absorption was expressed as increase in weight percent based on (2), whereby A is weight of oven dry sample in air and B is weight of saturated surface dry sample in air

$$\% \text{ water absorption} = \left[\frac{(B - A)}{A} \right] \times 100 \quad (2)$$

2.3.3. *Thermal Test of Granite Rock.* After lining the granite rock chamber with stainless steel, charcoal fuel was ignited within the combustion chamber. The maximum temperature reaching the granite rock (423 K) was attained after 41 minutes on average and this was recorded.

Samples of the rock were as well heated between room temperature (297.8 K) and 567 K in an oven to determine their ability to withstand heat without disintegrating. The rocks were heated and observations made for change in weight for the granite material under test. This was done at time intervals of 20 minutes for 120 minutes with increasing temperature in the oven. Also the changes in the physical structure of the rock were noted.

2.3.4. *Water Boiling Test (WBT).* WBT assessed the overall performance of a cookstove via three phases which consisted of (1) bringing water to a boil from a cold start; (2) bringing water to a boil when the stove is hot; and, (3) maintaining the water at simmering temperatures. In WBT experiment, water was heated to boiling point; the time taken to boil a given quantity of water, specific firewood consumption besides evaluating thermal efficiency at both high and low energy input was done. The test was conducted in accordance with Volunteers in Technical Assistance [19].

TABLE 2: Summary of laboratory test results for specific gravity and water absorption tests (see Figure S1–S3 in the Supplementary Materials for comprehensive analysis).

Sample Test Identification	Specific gravity	Water Absorption (%)
14/10 mm Hand crushed aggregates	2.72	0.42

3. Results and Discussion

3.1. *Classification of Granite Rock.* As presented in Table 2, the specific gravity of the granite rock was found to be 2.72, implying that the rock was of high density.

Given the fact that there was little (0.42%) water absorbed by the rock (Table 2), negligible amount of heat would be required to drive it off. Therefore, the moisture content of the rock would not have any significant effect on its heat retention properties. This makes it a suitable material for the stove construction.

The effect of temperature on the physical properties of the rock was also evaluated based on the practical experience of constructed stove operations and oven tests. From the oven test experiment, the granite rock recorded an initial temperature of 297.8 K and mass of 401.65g. There was a gradual decrease in mass with increasing temperature over time (Figure 1, see Figure S4 in the Supplementary Materials for comprehensive analysis).

After 120 minutes of oven heating, the granite rock recorded a constant mass of 401.21g at constant temperature of 567 K, indicating maximum moisture loss from the rock. Despite the slight change in colour (dusty pale white) of the rock, there was no visible fracture observed. Similarly, the maximum temperature reaching the granite rock in the constructed stove was recorded as 423 K (after 41 minutes of operation) at minimum moisture content (Figure 1) and no sign of fracture. This implies that the granite rock would be able to perform in the stove without disintegrating after successive cooking times.

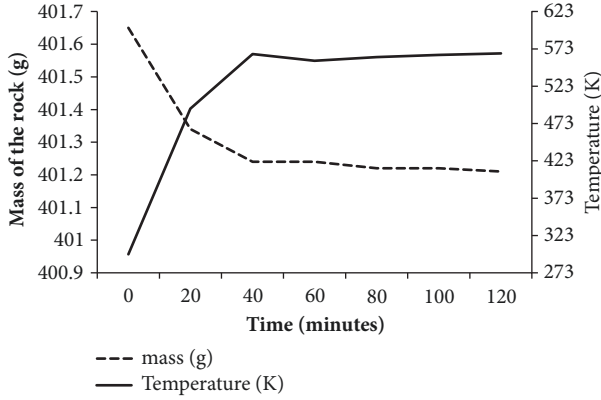


FIGURE 1: Relationship between mass of granite rock and temperature with time.

3.2. Choice of Fuel for Experimental Design. For the improved stove design, solid fuels were evaluated. The selection to evaluate carbonised agrowaste briquettes and charcoal fuels was taken based on local availability within Kampala district.

Based on (3), we need to transmit 1,538,355J of energy to a pan to boil 4.9-liter of water ($\approx 4900\text{g}$) from room temperature (298 K) to 373 K (at sea level) given its specific heat capacity of 4.186 J/g.K [20, 21].

$$H = mc\theta \quad (3)$$

where H is the heat required, m is the mass of substance, and θ is the temperature difference.

$$\begin{aligned} & (4.186 \text{ J/g.K}) \times 4900\text{g} \times (373 \text{ K} - 298 \text{ K}) \\ & = 1,538,355\text{J of energy to water} \end{aligned} \quad (4)$$

At 100% efficiency whereby all the fuel is transferred to the water, we would require

$$\frac{1538355}{21700} = 70.89 \text{ g of briquettes} \quad (5)$$

Assuming a thermal efficiency of 35%, and energy loss of 65%, 2025g of briquette fuel would be required to boil 4.9 liters of water as shown below.

$$\frac{70.89}{0.35} = 2025 \text{ g of briquettes} \quad (6)$$

Therefore, the fuel chamber needs to be designed to hold at least 2025g of briquettes.

Similarly, 51.6g of charcoal with average calorific value = 29.8 MJ/Kg = 29800J/g [16] would generate 1,538,355J of energy required to boil 4.9 liters of water (see (3)) if fuel conversion efficiency was 100%.

$$\frac{1538355}{29800} = 51.6 \text{ g of charcoal} \quad (7)$$

For a thermal efficiency of 35%, 147g of charcoal fuel is therefore required, as shown below:

$$\frac{51.6}{0.35} = 147 \text{ g of charcoal} \quad (8)$$

Therefore, the fuel chamber needs to be designed to hold 147g of charcoal.

Since 100% efficiency is not practical for improved cook stoves, the decision to use charcoal as a fuel for the stove design was based on a more practical 35% efficiency target. It was observed that more briquettes would be required to achieve the same cooking task as charcoal. Therefore, charcoal was a preferred choice of fuel.

3.3. Design of the Stove Prototype. The convective and conductive heat transfer through the stove wall were calculated using Fourier's heat relation (see (9)).

$$Q = KA \frac{(T_1 - T_2)}{X} \quad (9)$$

where Q is heat flow rate (W/m^2), A is total cross-sectional area of conducting surface (m^2), X is thickness of specimen (m), and T is temperature (K).

According to Baldwin [22], use of Fourier's heat equation for examination of heat transfer across a stove wall generates values that are too large. This is because the heat transferred into and out of an object depends not only on the conductivity to and from the surfaces but also on the conductivity within the object itself, dirt, or oxide layers and air at the surface of the material.

Thus, (9) is arranged using the thermal resistance concept as shown in

$$Q = \frac{A(T_1 - T_2)}{1/h_1 + x/K + 1/h_2} \quad (10)$$

where h is the convective heat transfer obtained from

$$h = A \left(\frac{\Delta T}{L} \right)^b \quad (11)$$

A and b are constants depending on geometry and flow conditions.

L denotes length.

For vertical cylinders, $h = 1.31 (1358)^{1/3}$ [23]

$$= 14.51 \text{ W/m}^2\text{K} \quad (12)$$

Given the height (179mm) and the diameter (375mm), Figure 2, the surface area of stove was estimated as 0.32 m^2 following (13).

$$\begin{aligned} A &= \pi r (2h + r) \\ &= 3.14 * 187.5 (2 * 179 + 187.5) \\ &= 321165.125 \text{ mm}^2 \text{ or } 0.32 \text{ m}^2 \end{aligned} \quad (13)$$

This value was used for only stainless steel since granite and fiber glass do not cover the bottom of the stove, whereas, for granite and fiber glass, the surface area was estimated using

$$\begin{aligned} A &= 2\pi rh \\ &= 2 * 3.14 * 187.5 * 179 \\ &= 210772.5 \text{ mm}^2 \text{ or } 0.21 \text{ m}^2 \end{aligned} \quad (14)$$

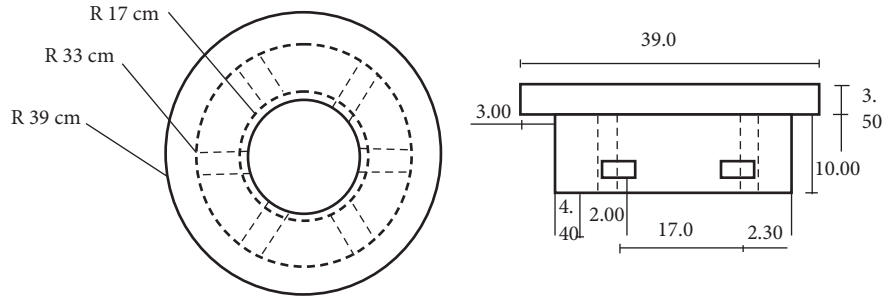


FIGURE 2: Plan and front elevation drawings of the designed stove (all dimensions in cm).

Taking theoretical maximum temperature = 2123 K [23] and based on reasonable assumptions, thermal conductivity of granite, $K_g = 2.68 \text{ W/mK}$ [24]; fiber glass, $K_f = 0.04 \text{ W/mK}$ [25]; and stainless steel, $K_s = 16 \text{ W/mK}$ [25], total resistance was estimated as 9.768 K.W^{-1} (see (15))

$$\begin{aligned}
 \text{Total resistance} &= \frac{1}{h1A} + 3 \frac{Ls}{KsA} + \frac{Lf}{KfA} + \frac{Lg}{KgA} \\
 &+ \frac{1}{h2A} \\
 &= \frac{1}{14.51 * 0.32} + 3 * \frac{0.0015}{16 * 0.32} \\
 &+ \frac{0.078}{0.04 * 0.21} + \frac{0.023}{2.68 * 0.21} \\
 &+ \frac{1}{14.51 * 0.32} \\
 &= 0.215 + 8.79 * 10^{-4} + 9.296 \\
 &+ 0.041 + 0.215 \\
 &= 9.768 \text{ K.W}^{-1}
 \end{aligned} \tag{15}$$

Hence the energy lost by the stove would be 186.12W based on

$$Q = \frac{\Delta T}{\text{Total resistance}} \tag{16}$$

Using room temperature of 305K

$$\begin{aligned}
 &= \frac{2123 - 305}{9.768} \\
 &= \frac{1818}{9.768} \\
 Q &= 186.12 \text{ W} \\
 Q &= 186.12 * 3600 = 670032 \text{ J}
 \end{aligned} \tag{17}$$

Yet, it has been found that the stove would release a total of 1,538,355J of energy to water at 100% efficiency (see (3)). This implies that more than half ($1,538,355 - 670,032 = 868,323$) of the energy produced by the charcoal fuel goes to the water.



FIGURE 3: The stove made from granite rock.

Thus, the losses through the stove wall were workable for the stove design.

3.4. Features of the Stove. The stove (Figure 3) consists of a combustion chamber (inner retort) constructed using a 2.0mm thick stainless-steel material.

The combustion chamber is designed to receive solid biomass fuel (charcoal) and enhance complete combustion of combustible gas released during charcoal burning process. The combustion chamber is imbedded in a cylinder (outer retort) constructed using granite rock and glass wool (Figure 4). The combustion chamber and outer retort are designed in a way that a 30mm gap is left in between to provide a free movement of air and enhance resistance to heat transfer to the inner wall of the outer retort. This minimises heat loss given the low thermal conductivity ($1.6 \text{ W.m}^{-1} \text{ K}^{-1}$) of the granite rock and air (0.02 to $0.05 \text{ W.m}^{-1} \text{ K}^{-1}$), compared with stainless steel (16 to $64 \text{ W.m}^{-1} \text{ K}^{-1}$) used in the construction of the combustion chamber [26]. This leads to large amount of heat from the burning charcoal to concentrate at the bottom of the cooking pan, thus increasing thermal efficiency.

3.5. Thermal Performance of the Stove. Indicators including thermal efficiency, water boiling rate, specific fuel consumption, fire power, and fuel use reduction were used to evaluate

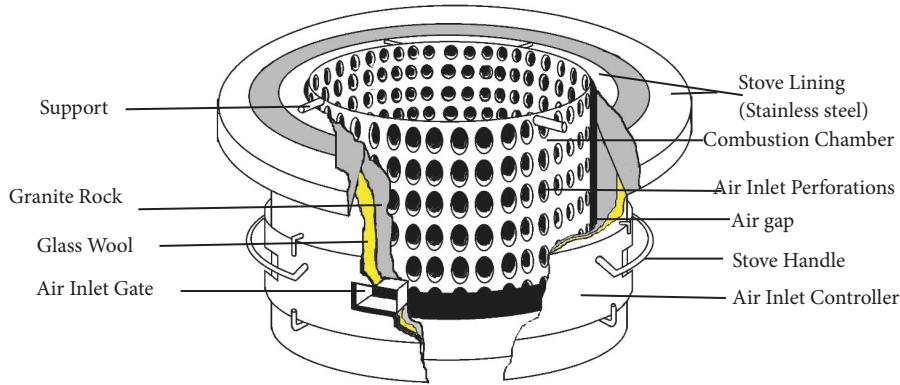


FIGURE 4: Major components of the stove.

the performance of the designed stove. Data used in the evaluation (Table 3) were generated by WBT experiment using a recommended protocol [19].

The thermal efficiency, a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot [20, 21], was calculated using

$$\begin{aligned} \text{Overall efficiency} &= \frac{\text{Total heat absorbed by water}}{\text{total heat produced}} * 100\% \\ h_c &= \frac{\text{Heat energy required to boil water} + \text{Energy for veporisation}}{\text{Heat energy released by a given quantity of fuel}} * 100\% \\ &= \frac{MwCw\Delta T + Mwvh}{FcmLHV} * 100\% \end{aligned} \quad (18)$$

where Mw is mass of water in sauce pan, Cw is specific heat capacity of water, ΔT is local boiling temperature-initial temperature of water (K), Fcm is fuel consumed (moist) (g), LHV is net calorific value (J/g), Mwv is mass of water vaporised (g), and h is specific enthalpy of vaporisation (J/g). For example, for the 2nd test run, the thermal efficiency was calculated as

$$\begin{aligned} &= \frac{2875 * 4.186 * (96.8 - 24.5) + 100 * 2260}{125 * 29800} * 100\% \\ &= 29.4\% \end{aligned} \quad (19)$$

While thermal efficiency is a well-known measure of stove performance, better indicator may be sought especially during the low power phase of the water boiling test. This is because a stove that is very slow to boil may have a very good looking thermal efficiency since large amount of water was evaporated. However, the fuel used per water remaining may be too high since so much water was evaporated and so much time was taken while bringing the pot to a boil [20, 21]. With respect to this, indicators such as specific consumption, water boiling rate, fire power, and fuel use reduction were calculated as well.

The water boiling rate was obtained the following equation:

$$= \frac{\text{time to boil water (min)}}{\text{Effective mass of water boiled (g)}} * 1000 \quad (20)$$

The water boiling rate for the 2nd test run was calculated as

$$\begin{aligned} &= \frac{43}{2775} * 1000 \\ &= 15.50 \text{ min/ltr} \end{aligned} \quad (21)$$

Specific fuel consumption measures the amount of fuel required to boil (or simmer) 1 liter of water. It is calculated (see (22)) by the equivalent dry fuel used minus the energy in the remaining charcoal, divided by the liters of water remaining at the end of the test [20, 21].

$$= \frac{\text{fuel consumed (g)}}{\text{effective mass of water boiled (g)}} * 1000 \quad (22)$$

The specific fuel consumption for the 2nd test was obtained using (24) as

$$\begin{aligned} &= \frac{125}{2775} * 1000 \\ &= 45.05 \text{ g/liter water boiled} \end{aligned} \quad (23)$$

Fire power: a useful measure of the stove's heat output was also calculated following (24).

$$= \frac{\text{fuel consumed (g)} * LHV (J/g)}{\text{time to boil water (min)} * 60} \quad (24)$$

TABLE 3: Data from WBT (see Figure S5 in the Supplementary Materials for comprehensive analysis).

s/n	Parameters	Tests (n = 4)				mean	stdev
		1	2	3	4		
1	Mass of water boiled (g)	2925	2875	2850	2800	2862.5	52.0
2	Specific heat capacity of water (J/g.K)	4.186	4.186	4.186	4.186	4.186	0
3	Water boiling temperature (K)	369.8	369.8	369.8	369.8	369.8	0
4	Initial water temperature before test (K)	297.7	297.5	294.8	296.2	296.55	1.34
5	Water vaporised (g)	100	100	75	100	93.75	12.5
6	Latent heat of veporisation (J/g)	2260	2260	2260	2260	2260	0
7	Fuel consumed (g)	150	125	100	145	130	23
8	Lower Heating Value of char (LHV), J/g	29800	29800	29800	29800	29800	0
9	Effective mass of water boiled (g)	2825	2775	2775	2700	2768.8	51.54
10	Time to boiling water (min)	42.00	43.00	39.00	40.00	41.00	1.83
11	Fuel consumed (g)	150	125	100	145	130	22.73

TABLE 4: Summary of results on thermal performance of the stove.

S/n	Performance index	Unit of measure	Tests (n = 4)				MEAN	STDEV
			1	2	3	4		
1	Thermal efficiency	%	24.8	29.4	35.7	25.2	28.8	5.1
2	Water boiling rate	min/ltr	14.9	15.5	14.1	14.8	14.8	0.6
3	Specific fuel consumption	g/liter water boiled	53.1	45.0	36.0	53.7	47.0	8.3
4	Fire power	kW	1.77	1.44	1.27	1.80	1.57	0.26
5	Fuel Use Reduction	%	76.1	79.7	83.8	75.8	78.8	3.7

The fire power for the 1st test run was calculated as follows:

$$= \frac{150 * 29800}{42 * 60} \quad (25)$$

$$= 1773.8 \text{ W}$$

Given the specific fuel consumption of 222 g/liter water boiled for the 3-stone stove (Kris De Decker, 2015), the fuel use reduction attained by the developed improved cook stove was estimated using

$$= \frac{\text{specific fuel consumption}(3 - \text{stone stove}) - \text{specific fuel consumption}}{\text{specific fuel consumption}(3 - \text{stone stove})} * 100\% \quad (26)$$

For instance, fuel use reduction in the 1st test run was calculated as

$$= \frac{222 - 53.1}{222} * 100\% \quad (27)$$

$$= 76.1\%$$

Table 4 shows a summary of results on stove performances. It was found that, after 4 test runs of the water boiling test, the designed improved stove had a mean thermal efficiency of 28.8%. This means that 28.8% of the total energy produced by the fuel is used to boil water in the pot.

Comparisons (Figure 5) were made with locally existing stoves such as the Lorena stove, brick stove, Envirofit

TABLE 5: Comparisons between the cost of the granite rock stove and conventional stoves.

Stove Performance	Cook stove technologies								Source
	The Granite Rock Stove	Traditional wood burning	Improved wood-burning	Traditional charcoal-burning	Improved charcoal-burning	Kerosene	Propane (LPG)	Electric	
Capital Cost (US\$)	36		5 – 50	3 – 6	3 – 50	10 – 60	60 – 120	100 – 500	Jeuland and Pattanayak 2012
Efficiency, %, (MJ useful energy/MJ produced Heat)	28.8	7 - 15	13 - 40	18 - 21	15 - 37	40 - 50	50 - 60		

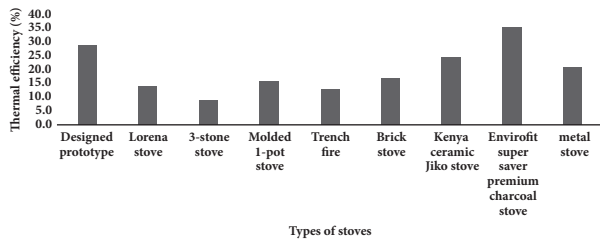


FIGURE 5: Comparisons between thermal efficiencies % of different stoves.

supersaver premium stove, molded 1-pot stove, Kenya ceramic jiko stove, metal stove, trench fire, and the traditional 3-stone stove. Previous studies [27, 28] show that the above-mentioned stoves had thermal efficiency values of 14%, 17%, 35.7%, 16%, 24.5%, 21%, 13%, and 9%, respectively.

With a thermal efficiency of 28.8%, the designed prototype stove achieves tier 2 in the IWA tiers of performance [29]. This shows a substantial improvement over the baseline traditional 3-stone stove.

3.6. Cost of the Granite Rock Cooking Stove versus Conventional Stoves. Every household cooking system incurs different costs and benefits depending on diverse energy technologies employed. These costs are related to the capital cost of a newly developed stove and/or design modifications, cost of fuels required, cost of stove distribution or marketing, money, and time spent for regular stove operation and maintenance [30]. In this study, the capital cost of the granite rock stove was estimated at US\$36 and compared favourably with conventional charcoal burning stoves (US\$3–US\$50) in accordance with Jeuland and Pattanayak [30] (Table 5).

Given the fact that the granite rock stove depicts a relatively high thermal efficiency (28.8%) and fuel use reduction (78.8%) (Table 4), there is a higher likelihood for it to operate under reduced cost, making it cheaper than the conventional stoves.

4. Conclusions

The improved cooking stove was designed and fabricated using locally available materials including granite rocks, stainless steel, and glass wool and was estimated to cost US\$

36. Based on its water boiling test results, 78.8% fuel use reduction was achieved over the baseline open fire stove. This was attributed to the thermal retention storage properties of the granite rock. The granite rock, besides glass wool, significantly contributed to the reduction on estimated heat (about 670kJ) that would be lost through the stove wall. This enhanced its thermal efficiency. Based on comparisons with performance standards and properties of the conventional stoves, the designed granite rock stove is a substantial improvement technology and can thus lessen the pressure put on forestry resources. However, further studies including carbon and particulate matter (PM) emissions are recommended for future design improvements to suit public health standards. Studies on use of other forms of fuel such as briquettes and wood chippings could as well be conducted to establish fuel alternatives to charcoal.

Data Availability

The data underlying the findings of this research can be accessed on either the Uganda Christian University, Hamu-Mukasa Library online catalogue, or other online sources. The online sources among others include (i) <https://www.safefuelandenergy.org/files/517-1.pdf>, (ii) <https://www.unn.edu.ng/publications/files/images/USMAN,%20OJONIMI%20YUSUF.pdf>, (iii) <https://www.amazon.com/How-make-Kenyan-ceramic-jiko/dp/B0007C8G84>, and (iv) <https://www.pciaonline.org/testing>.

Disclosure

The authors received no form of financing in the research and publication of this work. All financing directed for this project work was of their own resourcing.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors appreciate the intellectual input from all persons at the Department of Engineering and Environment, Uganda Christian University; their guidance helped to focus

this research. The authors also appreciate the personnel at National Forestry Resources Research Institute (NaFORRI), National Agricultural Research Organisation (NARO), for allowing them to use their facilities and equipment to carry out the water boiling test which helped them describe the thermal performance of the designed stove.

Supplementary Materials

Figure S1: certificate of analysis for specific gravity and water absorption tests carried out. Figure S2: water absorption results for granite rock aggregates. Figure S3: specific gravity results for granite rock aggregates. Figure S4: thermal test results. Figure S5: water boiling test results. (*Supplementary Materials*)

References

- [1] K. R. Smith, "Fuel combustion, air pollution exposure, and health: the situation in developing countries," *Annual Review of Environment and Resources*, vol. 18, pp. 529–566, 1993.
- [2] A. Olorunsola, "The development and performance evaluation of a briquette burning stove," *Nigerian J. Renewable Energy*, vol. 7, no. 1, pp. 91–95, 1999.
- [3] B. O. Bolaji, "The Use of Sawdust as an Alternative Source of Energy for Domestic Cooking and as a Means of Reducing Deforestation," *Global Journal of Environmental Sciences*, vol. 4, no. 1, pp. 73–76, 2005.
- [4] J. S. Sawin, "Renewables 2017 Global Status Report," 2013, http://www.ren21.net/wp-content/uploads/2017/06/GSR2017_Ful.
- [5] ESMAP, "Introducing Energy-efficient Clean Technologies in the Brick Sector of Bangladesh. Washington DC: Energy Sector Management Assistance Program (ESMAP), 2011".
- [6] WEO, "Energy for Cooking in Developing Countries, 2006," <https://www.iea.org/publications/freepublications/publication/cooking.pdf>.
- [7] M. K. M. Nahar, "Indoor Air Pollutants and Respiratory Problems among Dhaka City Dwellers," *Archives of Community Medicine and Public Health*, pp. 32–36, 2016.
- [8] N. R. P. Bruce, "Indoor air pollution in developing countries: a major environment and public challenge," 2000, Bulletin of the World Health Organization: <https://www.peertechz.com/articles/indoor-air>.
- [9] J. K. Kaoma, "Efficiency and emission characteristics of two Zambia cookstoves using charcoal and coal briquettes. Stockholm Environment Institute, 1994".
- [10] O. Adria, "Residential Cooking Stoves and Ovens. Good Practice Technology: Rocket Stove. Wuppertal Institute for Climate, Environment and Energy, 2014".
- [11] V. Becattini, "Determination of specific heat capacity of rocks by DSC before and after high temperature thermal recycling. Zurich: Deptment of earth sciences, 2017".
- [12] V. Becattini, T. Motmans, A. Zappone, C. Madonna, A. Haselbacher, and A. Steinfeld, "Experimental investigation of the thermal and mechanical stability of rocks for high-temperature thermal-energy storage," *Applied Energy*, vol. 203, pp. 373–389, 2017.
- [13] S. Khare, M. Dell'Amico, C. Knight, and S. McGarry, "Selection of materials for high temperature sensible energy storage," *Solar Energy Materials & Solar Cells*, vol. 115, pp. 114–122, 2013.
- [14] F. G. Bell, *Engineering in rock masses*, Elsevier, 2013.
- [15] W. E. Lee, *Ceramic microstructures: property control by processing*, Springer Science & Business Media, 1994.
- [16] D. Kiwana, "fuel performance of feacal sludge briquettes in Kampala, Uganda. Centre for Research in Energy and Energy Conservation, 2016".
- [17] K. L. C. Maxwell, "How to make the Kenyan ceramic jiko. Nairobi: Ministry of energy, 1983".
- [18] AASHTO, "Standard Method of Test for Specific Gravity and Absorption of Coarse Aggregate T84/85," *American Association of State Highway and Transportation Officials*, 2014.
- [19] Volunteers in Technical Assistance, "esting the Efficiency of Wood-burning Cookstoves: Provisional International Standards. The partnership for clean indoor air, 1985".
- [20] Global Alliance for Clean Cookstoves, "Handbook for Biomass Cookstove Research, Design and Development: A practical guide to implement recent advances, 2014".
- [21] Global Alliance for Clean Cookstoves, "The water boiling test 4.2.3 cookstoves emissions and efficiency in a controlled laboratory setting, 2014".
- [22] S. F. Baldwin, "Biomass Stoves: Engineering Design, Development, and Dissemination ., Virginia, Volunteers in Technical Assistance, 1987".
- [23] U. O. Yusuf, "Experimental performance evaluation of charcoal stove. Department of mechanical engineering-University of Nigeria, 2011".
- [24] L. Eppelbaum, I. Kutasov, and A. Pilchin, "Thermal Properties of Rocks and Density of Fluids," in *Applied Geothermics*, Lecture Notes in Earth System Sciences, pp. 99–149, Springer, Berlin, Germany, 2014.
- [25] H. D. Young, *Physics*, vol. 1, Addison-Wesly Publishing Company & Inc, 18th edition, 1992.
- [26] J. H. IV. Lienhard, *A Heat Transfer Textbook*, Cambridge, Mass, U.S.A, 3rd edition, <http://www.mie.uth.gr/labs/ltte/grk/pubs/ahtt.pdf>.
- [27] Envirofit, "Smart cooking technology for better living. 2016 product catalogue, 2016".
- [28] M. J. Turinayo, "Performance characterization of improved wood cooking stoves for monitoring household energy interventions in Uganda. Kampala: National Forestry Resources Research Institute (NaFORRI), 2011".
- [29] ISO/TMBG Technical Management Board- groups, "IWA 11:2012 Guidelines for Evaluating Cook stove Performance. ISO, 2012".
- [30] M. A. Jeuland and S. K. Pattanayak, "Benefits and costs of improved cookstoves: Assessing the implications of variability in health, forest and climate impacts," *PLoS ONE*, vol. 7, no. 2, Article ID e30338, 2012.

