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Determination of Thermal Efficiency and Fuel Consumption Rate of a Pressure Cooker Fueled with Blends of Waste Vegetable Oil and Kerosene

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ABSTRACT

In Nigeria, before the removal of subsidy on kerosene in 2016, the product was accessible to low-income individuals and is intended to be used as a fuel for cooking, lighting, or heating. Recently, kerosene is rapidly vanishing from rural families and it is becoming inaccessible due to its ever-rising cost. Therefore, to ease the hardship of low-income individuals to have access to high thermal efficiency cookers with affordable fuel, a study was carried out to determine the thermal efficiency and fuel consumption rate of a pressure cooker fueled with a blend of waste vegetable oil and kerosene. Based on this, a low-cost pressure cooker was developed with locally available materials to aid the atomization of fuel during cooking. Along with this, vegetable oil was blended with kerosene to enhance the quantity of kerosene used to fuel the pressure cooker. This cooker fueled with blends of vegetable oil and kerosene was analyzed for its thermal efficiency and fuel consumption rate and was also compared to the conventional kerosene stove. The result shows that the constructed pressure cooker has a thermal efficiency of 52% which is 20% more than the conventional kerosene stove but the developed pressure cooker consumes more fuel (48.62 ml) than the conventional kerosene wick stove (33.78 ml). Though the pressure cooker consumes more fuel, the thermal efficiency per time with respect to the fuel consumed is much better than conventional kerosene stoves which makes the developed cooker cheaper and more affordable both to low-income earners and for rural dwellers.

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Introduction

Domestic fuels have continued to make large amount of primary energy consumed over the years therefore, cannot be underestimated due to their significant contribution to the country's GDP. However, the high price of contemporary cooking energy such as kerosene is a key barrier in many undeveloped and emerging nations leading a larger percentage of households to continue using traditional fuels like charcoal and firewood as cooking fuel which has constituted a hazard to the ecosystem due to the emission of poisonous gases during its use (Edward et al. 2021; Ogundahunsi et al. 2022a). As a result, women and children who are involved in cooking are more likely to develop acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD), and lung cancer (Desalu et al., 2012).

Some alternative cooking energy source that is safe and environmentally friendly has become increasingly important. Most alternatives commonly used are; biogas, briquette, and bioethanol (Mukund et al., 2017; Ogundahunsi et al. 2022b). The major challenge in the use of these biofuels is the biochemical and thermochemical processes involved in their production which may not be easy for rural or local dwellers to comprehend (Onuoha, 2010). Aside from the use of these alternative forms of cooking energy, different techniques have also been explored in addressing the challenges associated with the aforementioned energy used which causes havoc to the environment. One of these techniques includes atomization or gasification of the fuel used (Onuoha, 2010).

Before 2016, the use of kerosene as a cooking fuel gained prominence due to its availability and accessibility for Nigerian households. But recently, there has been a decline in its usage due to the subsidy removal on this fuel causing a continuous price increase thereby making it unaffordable to low-income earners and rural dwellers (Ogundari et al., 2018). For effectiveness and to address this challenge, Moh (2010) developed a kerosene high-pressured cooker and it was discovered that the thermal efficiency of wick stoves was found to be lower than that of a kerosene high-pressured cooker with a power of 179.922 kW and could burn 1 liter of kerosene at a constant pressure of 1 MPa in 3.5 minutes, generating a massive quantity of heat energy of 38.2 MJ. In another related development, Mukund et al. (2017) studied the use of cotton seed oil-kerosene blends in a kerosene high-pressure cooker incorporated with a copper coil for heat absorption from the burner to heat the blends for viscosity regulation. The research shows that the fuel burn better with high-temperature blue flame combustion features thereby reducing the discharge of harmful gases.

Groundnut oil, castor oil, coconut oil, and other edible oil had been found to compete with the demand for consumption which makes it unsuitable to be used as fuel in this regard (Oniya and Bamgboye, 2014). The use of waste vegetable oil from the household kitchen makes it less competitive with consumption. Blending kerosene with this waste oil enhances the octane number, heating value of the fuel thereby enhancing its thermal efficiency when used (Bayindir, 2007). The main aim of the research also includes the conversion of waste domestic resources into a usable fuel for domestic energy.

In this study, an efficient and effective low-cost pressure cooker was constructed and a blend of waste vegetable oil with kerosene was used as fuel for combustion. This is with an effort to ease the hardship of low-income individuals to have access to high thermal efficiency cooker with affordable fuel.

Materials and Methods

The materials used for the construction of the experimental pressured cooker were acquired from the steel and scrap metal materials market at Gate, Ibadan, Nigeria, the kerosene used was purchased at GASTAB filling station, at New Garage, Ibadan, Nigeria, the waste vegetable oil was obtained from some selected cafeterias in Oluyole extension, Apata, Ibadan, Nigeria, while the burner and fuel tube/hose were obtained from New Garage, Ibadan, Oyo State, Nigeria.

Design Consideration

The pressure cooker was designed and fabricated at a low or minimum cost to allow easy acceptability by all classes of people especially low-income earners. The kind of material used for the fabrication of the pressure cooker was based on the strength, stability, and rigidity of the material during construction. In designing the pressure cooker, safety precautions were taken to protect the operator during operation. The parts of machine are chosen that they may last for longer period before any sign of damage may be noticed.

This is one of the most important factors to be considered when selecting materials. The materials must be readily available at low cost to ease the construction work and maintenance. In respect of the above fact, the materials used in the production of this machine were sourced locally in nearby markets in Ibadan, Oyo State, Nigeria.

The constructed cooker parts must be prevented from moisture as to prevent corrosion of the pressurized cooker. This is achieved by painting the cooker.

Mechanism of the Pressurized Cooker

The mechanism of the pressurized cooker is based on the first principle of applied thermodynamics which is the formulation of the law of conservation of energy in the context of thermodynamics processes (HTML1, 2024) It is also based on the Pascal principle in fluid mechanics in which a fluid at rest in a closed container, a pressure change in one part is transmitted without loss to every portion of the fluid and to the walls of the container (HTML2, 2024).

To accomplish this, the entire fabrication or construction includes basic operations such as cutting, turning, threading, welding, brazing, and painting.

Components Description

The major working components of the cooker are the fuel cylinder, burner, frame/pot sit, pump barrel, plunger, O-ring (oil seal) cover, and push rod. Table 1 presents the material used for the construction of each component.

Table 1. Material used for construction of each components

Components	Material Choice
Burner	Stainless Steel
Frame	Mild Steel
Regulating Valve	Mild Steel
Cylinder	Aluminum Alloy
Pressure Valve	Mild Steel
Pressure release valve	Mild Steel
Bolt and Nut	Mild Steel
Pipe (Hose)	Rubber

Cylinder

The fuel cylinder as shown in Fig. 1 contains the pressurized waste oil-kerosene blend which is incorporated with a plunger, O-ring (seal) cover, push rod, and a metal handle. The fuel cylinder is made from a mild steel tube of 35 mm in diameter and 2.5 mm in thickness. The tube is used to reduce friction to a minimal value to ensure full contact between the tube wall and the plunger. The pump length is 220 mm and a 1.5 mm pitch thread of length 15 mm is cut for the cap. A 6.5 mm central hole is drilled through the remaining thickness of the cap to accommodate the push rod. The unthreaded end of the pump barrel is covered by welding a 3 mm thick flat plate of the same pump external diameter. A 6 mm hole was drilled centrally and tapped, a push rod of length 200 mm from both ends. These ends are then threaded for the attachment of the plunger and handle.

Burner

The burner as shown in Fig. 2 atomized the burnt fuel used in heating and it is held securely in place by an angle iron that is fastened to the frame. A pipe was connected to the fuel cylinder which supplies the burner with the blend, and the other end was connected to the burner.

Frame

Frame/pot sit shown in Fig. 3 and 4 supports the burners and carries the cylinder. It is fabricated using a 2 by 2 ft rectangular mild steel angle iron.

Cost Analysis

The cost analysis for the developed pressure cooker is shown in Table 2.

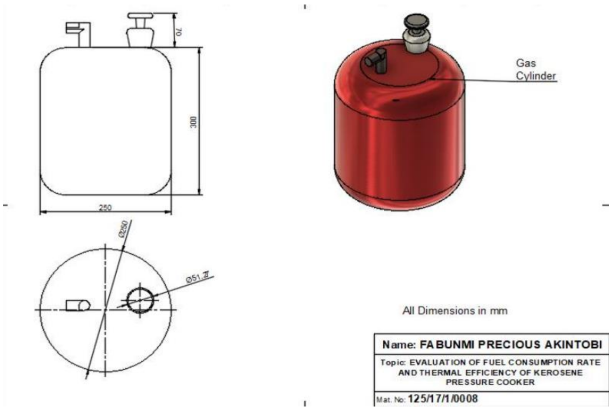

Figure1. Schematic diagram of cylinder

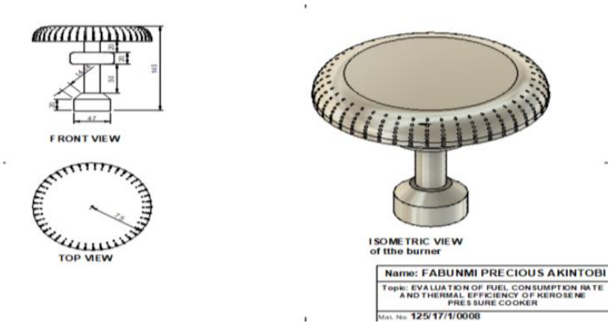

Figure 2. Schematic diagram of the burner

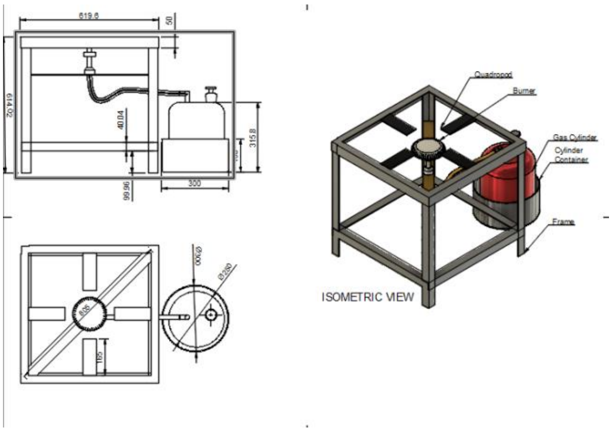

Figure 3. Schematic diagram of the frame

Figure 4. Assembled view of the designed pressure cooker

Table 2. Bill of Engineering Measurement And Evaluation (BEME)

Item	Material	Specification	Unit Cost #	Quantity	Prorated Cost
Electrode	Mild Steel	Gauges 12	1200	1 pack	1200
Kerosene cylinder	Aluminum		15000	1	15000
Burner	Mild Steel	9.5cm radius	1000	1	1000
Hose		80cm long	400	2	800
Control valve	Mild Steel		2000	1	2000
Bolt and Nut		M12	1000		1000
Paint	Black and red		2500		2500
Frame Stand	Angle Iron Mild Steel	(2 × 2) mm Full length	16000	1½	24000
Cutting Disk			1200		1200
Grinding Disk			1200		1200
Workmanship			7000		7000
Miscellaneous			6200		6200
Total					63,100

Design Calculation

Determination of Flow through Pipe and Burner

The Cylinder Pressure, P_1 is assumed to be 1MPa,
P_2 = Atmospheric pressure = 1013 00Pa
D_1 =Rising Tube Diameter = 0.008 m
D_2 = Vapor Nozzle diameter = 0.001m
ρ = Blend density =810 kg/m3
V_1 = Rising tube blend velocity
V_2 = Vapor nozzle blend velocity
g = gravitational acceleration = 9.81m/s
From D_1 and D_2
A_1 = Rising tube area=$0.503 \times 10^{-4} m^2$
A_2 = Vapor nozzle area = $7.85 \times 10^{-8} m^2$

Using Bernoulli's equation; this equation helps show that as the pressure increase in a tube, the flow rate decreases. (HTML3, 2024)

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + h_f + h_c \qquad (1)$$

Where:

$$h_f = \frac{4fLV_1{}^2}{2gD_1} = \text{Frictional head loss (neglected)} \quad (2)$$

$$h_c = 0.5 + \frac{V_2{}^2}{2g} = \text{h Otrifice of Vapor nozzle headloss} \quad (3)$$

$$and\ Z_1 = Z_2$$

Eq. 1 becomes

$$\frac{(P_1 - P_2}{\rho} = \frac{(V_2{}^2 - V_1{}^2)}{2} + \frac{(0.5V_2{}^2)}{2} \quad (4)$$

Therefore, $V_1 = 1.225\, V_2 - 47.11$ (5)

But from (eq 4), Continuity Equation,

$$A_1V_1 = A_2V_2$$

$$V_1 = \frac{A_2V_2}{A_1} = \left[\frac{D_2}{D_1}\right]^2 V_2$$

Therefore, $V_1 = 0.001561\ V_2$ (6)

V_1 in Eq 3

Therefore, V_2 = 38.52 m/s, V_1 = 0.077 m/s
Rising tube blend velocity V_1 = 0.077 m/s
Vapor nozzle blend velocity V_2 = 38.52 m/s

Determination of Volumetric Fuel Flow Rate

From $Q = A_2V_2$
But, $A_2 = 7.85 \times 10^{-8}$m 2
V_2 = 38.52 m/s
Therefore, $Q = 7.85 \times 10^{-8} m^2 \times 38.52$ m/s
$Q = 5.22 x 10^{-6} m^3/s$
Vapor nozzle flow rate at 1MPa = $5.22 \times 10^{-6} m^3$

Determination of Mass Fuel Flow Rate

From $m = \rho Q$
$\rho = 810\ kg/m^3$
$Q = 5.22 \times 10^{-6} m^3/s$
Therefore,
$m = 810 \times 5.22 \times 10^{-6} m^3/s = 4.228 \times 10^{-6} kg/s$
Mass flow rate, $M = 4.228 \times 10^{-3}$ kg/s

Air Volume Needed to Burn One Mole of the Blend Products Totally

C: x = b
O: 2a = 2b + d
H: y = 2d
N: 3.76a = e
The hydrocarbon in air equation is

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow bCO_2 + dH_2O + eN_2$$

Thus, for $C_{10}H_{22}$ (Kerosene)

C = b= 10
H: y = 2d = 22; d = 11
$O: 2a = 2b + d; a = \frac{2b + d}{2} = \frac{(2 \times 10) + 11}{2} = 15.5$
N: 58.28 = e

Combustion Equation is now

$$C_{10}H_{22} + 15.5(O_2 + 3.76N_2)\ 10CO_2 + 11H_2O + 58.28N_2$$

Blending process of the used vegetable oil with kerosene

Firstly, the blend of waste vegetable oil with kerosene was made in 3:7 as suggested by Mukund et al. (2017). After which, the blend was poured through a sieve containing funnel through the refill port, the cap of the port was then firmly tightened making sure there was no air leakage from the port. The pressure release valve was also locked properly by turning the knob in the clockwise direction. When all these processes had been carried out, the pumping process was started. After several strokes had been taken, pumping was stopped. Thereafter, an atomized or pressurized blend flowed into the burner and came out in fine spray from the burner spray nozzle to burn the fuel with a bluish flame for cooking purposes. This process continued for a period that the pressure in the tank could provide. To extinguish the flame, the pressure release valve is turned in the anticlockwise direction thereby depressurizing the fuel tank, and the flame is allowed to gradually turn off on its own.

Performance Evaluation of the Pressure Cooker

The water boiling test was done to evaluate the performance characteristics of the developed pressure cooker and compared it to the standard wick kerosene stove that was chosen as a benchmark. The water boiling assay is often acknowledged as a quick and easy way to evaluate the effectiveness of various stoves in field tests. To aid stove designers in understanding how well energy is transported from the fuel to the cooking pot, the water boiling test (WBT) simulates the cooking process in approximate detail.

The device had three test runs.

Following is a list of testing equipment:

a) A 1000 ml beaker, used to collect the hot water after testing
b) A thermometer to gauge the water's temperature at any time during the test.
c) Measuring cups (10 ml to 1000 ml) are glasses that are used to gauge how much fuel the burner uses in a given amount.
d) A weighing scale is used to measure the amount of fuel that will be utilized both before and after testing.

Thermal Efficiency of the Pressure Cooker

This procedure involves filling a room-temperature aluminum vessel of the right size with a set volume of water. After a steady state has been seen (according to Bureau of Indian Standard), the vessel, stirrer, and lid are placed on the burner. Initially, the weight of the pressure cooker alone is measured using a weighing machine with accuracy of 1 g. Through a weighing balance machine, the weight of the vessel (including the lid and stirrer) filled with water is individually recorded. To record the initial temperature (T_1) of the water, a mercury thermometer with an accuracy of 0.5°C is utilized.

Once the temperature is reached (90±0.5°C), the vessel is unloaded, and the weight of the pressure cooker is then determined. Fuel consumption is determined by the difference between the beginning and final weights. Parallel stirring is carried out to keep the vessel's temperature constant until the experiment is complete, or until the water reaches (T_2) 90±0.5°C. It is noted how long it took the water to heat up to the desired temperature of 90°C.

The thermal efficiency (ηth) of the pressure cooker is calculated.

$$\eta th = \frac{Heat\ Output}{Heat\ Input} = \frac{(mw.cw - mp.cp)(T_2 - T_1)}{mf.CV} \qquad (1)$$

The symbols for the specific heat of the water, the mass of the vessel with lid and stirrer, the specific heat of the vessel with lid and stirrer, and the mass of the water are Cw, mp, Cp, and mw, respectively. The temperatures of water are T_1 and T_2, respectively. Similar to ordinary burners, the thermal efficiency has been tested.

Results and Discussion

The developed pressure cooker was tested to determine its fuel consumption rate and thermal conductivity. Plate 1 and 2 show the picture of the pressurized cooker constructed. Table 2 presents the result obtained in this study. The pressure cooker was found to operate with a volumetric fuel flow rate of 5.22×10^{-6} m^3/s and mass fuel flow rate of 4.228×10^{-3} kg/s. As observed from the result, the developed pressure cooker consumes more fuel (48.62 ml) than the conventional kerosene wick stove (33.78 ml). The difference in fuel consumption may be attributed to different fuel properties of oil and kerosene blends and ordinary kerosene. The result obtained for the conventional kerosene wick stove is closer to the result obtained by Fatai et al. (2018) with a report of 32.56 ml consumption of fuel for a kerosene cooker.

Using a comparison of water boiling tests, the thermal efficiency of the developed pressure cooker with that of a traditional kerosene wick burner were analyzed and compared in Table 3. The analysis showed that the pressure cooker has higher thermal efficiency (52%) compared to a conventional kerosene wick stove (32%). It was also observed that the pressure cooker produced less carbon than conventional kerosene stove. The wick burner was found to take longer than the pressure cooker to bring water to a boil. This result is similar with the findings of Kaushik and Muthukumar (2020) that worked on the thermal and economic performance assessments of waste cooking oil/kerosene blend operated pressure cooker with porous radiant burner. In the result, a thermal efficiency of 45.3% and 36.2% for pressure cooker and conventional kerosene wick stove respectively were obtained.

Conclusion

In an effort to ease the hardship of low-income individuals in Nigeria to have access to high thermal efficiency cooker with affordable fuel, a study was carried out to determine the thermal efficiency and fuel consumption rate of a pressure cooker fueled with a blend of waste vegetable oil and kerosene. The issues that many Nigerians are currently facing as a result of the erratic supply of energy and the ongoing rise in cost of kerosene were taken into consideration when this study was initiated. Additionally, the risks to the environment and human health posed by using tradition fuels such as charcoal and firewood for cooking were considered. Also, the numerous drawbacks of the traditional kerosene stove were also emphasized, and the developed pressure cooker solved these drawbacks associated with the sooty flame issue. Therefore, the result shows that the constructed pressurized cooker has a thermal efficiency of 52% which is 20% more than the conventional kerosene stove but the developed pressurized cooker consumes more fuel (48.62ml) than the conventional kerosene wick stove (33.78ml). This result of the thermal efficiency of this pressure cooker is a similar to the result obtained by smith et al., (2000) for a kerosene pressure cooker which gives 49% thermal efficiency. It also falls within the range of the thermal efficiency ranging from 47-56% for a pressure cooker for the research carried out by Tschinkel and Tschinkel, (1975). This is also close to the result obtained by Prasad et al., (1983) for a pressure cooker where the thermal efficiency is 50%.


(a) (b) (c) (d)

Plate 1. (a) Cylinder, (b) Pipe (Hose), (c), Frame (d) Burner

Table 3. Thermal Efficiency Test of the Pressure Cooker

	Developed Pressure Cooker				Conventional Kerosene Stove			
Parameter	1	2	3	Average	1	2	3	Average
Test vessel water wt (kg)	4.20	3.70	6.10	4.60	4.40	4.90	4.30	4.53
Initial water temp (^0C)	20.00	32.00	27.00	26.00	29.00	22.00	34.00	28.33
Final water temp (^0C)	90.00	90.00	90.00	90.00	90.00	90.00	90.00	90.00
Time taken(min)	20.00	13.00	25.00	19.33	28.00	22.00	31.00	27.00
Specific fuel consumption(ml)	52.08	44.51	49.28	48.62	28.17	31.70	41.46	33.78
Therm. Efficiency (%)	47.00	55.00	55.00	52.00	39.00	26.00	31.00	32.00

The pressurized cooker developed proposed an alternative, cheap, and affordable cooker both for low-income earners and rural dwellers. For further studies, the fuel properties should be investigated to evaluate its suitability in an internal combustion engines.


Plate 2. The Prototype Assembly

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