A Comparative Analysis of the Combustion Behavior of Adulterated Kerosene Fuel Samples in a Pressurized Cooking Stove

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Abstract
An experimental study was conducted to establish the influence of cylinder pressure on the combustion behavior of a pressurized kerosene cook stove. The test was carried out under ambient room conditions, by pressurizing and ignitingthe cook stove containing kerosene fuel at a maximum pressure of 1 bar. The combustion flame temperature, flameheight and structure and colour were arefully measured andrecorded from a pressure gauge mounted on the fuel tank, a thermocouple, vernier height meter and by direct flamephotography. The same process was repeated for vessel pressures of 0.8, 0.6, 0.4, 0.2, and 0 bar after an interval period of two minutes, and for B5, B10, B15, and B20 kerosene oil blends and B100 (i.e. 100

Index terms— pressurised kerosene stove, combustion temperature, flame height, statistical validation, kerosene-diesel adulteration, economic benefit

1 Introduction

rude oil is a natural occurring mixture consisting predominantly of hydrocarbons with other elements, such as; sulphur, nitrogen, and oxygen e.t.c, either existing as organic compounds or in some cases as complex of metals [1,2]. In technical terms of one barrel of Nigerian crude oil has a volume yield of 6.6% automotive gas oil, 20.7% gasoline, 9.5% kerosene and jetfuel, 30.6% diesel, and 32.6% fuel oil and residues [3]. The kerosene fraction belongs to the group of hydrocarbon called paraffin, which has lower specific gravity than aromatic hydrocarbon of the same boiling point. The main components of kerosene are paraffin, cycloalkanes (naphtha) and aromatic compounds, where paraffin is the highest composition. Ultimate analysis composition of kerosene is 84.3 % wt Carbon, 14.2 % wt Hydrogen, and remainder is sulfur and nitrogen [4]. The high demand and desirability of kerosene is informed by its lower volatility in comparison to gasoline, good oxidative stability and cleaner burning characteristics [5].

According to Moh [6], kerosene stove consists of wick or the pressurized stove types. The thermal efficiency of kerosene stove is between 20 -40 % depending on stove and cooking equipment design. Flue Gas emission of pressurized kerosene stove has been reported as follows; 2749 ppm CO2, 73 ppm CO, and 3.8 ppm CH4 , and could be higher if the fuel is adulterated. Existing literature has revealed that if the combustion process is incomplete, CO gas will be produced and a number of fuels will be not combusted, and will result in lower flame temperature, low heating rate and decrease in the thermal efficiency of the stove [7]. The amount of CO gas and other unburnt fuel products usually depends on the configuration of the heating equipment and other factors, such as the flash point of the fuel, air-fuel mixing, ignition, temperature controlling combustion chamber and catalyst respectively. Despite the fact that researchers have for many years tried to improve combustion systems design to enhance complete combustion and lower air pollution, low combustion heat efficiency, unburned fuel and air pollution (such as; CO, NOx, SOx and soot) are still a prevalent problems in combustion systems ??8]. The simultaneous evolution of heat and light occasioned by the combustion kerosene is used for household cooking and lighting .The incessant power outages and inadequate distribution and supply of electricity to especially rural Nigeria constitutes a major challenge presently, has increased the patronage of kerosene stoves.

2 Abstract -

In Nigeria, official statistics has revealed that an average of about 9 million liters of kerosene is consumed daily, and the bulk of the consumers come from the rural poor, low-income and middle-class economic class [9]. However, the growing demand for this most sought-after cooking and heating fuel has made the illicit practice of kerosene adulteration and its untold consequences commonplace in the country ??10, 11, 12, 13, and 14]. Even though some studies has been carried out on the evaporation of kerosene droplets at elevated temperature and pressure, existing data and information on evaporation and combustion of kerosene remain insufficient ??15]. To this end, this paper intends to investigate the combustion behavior of adulterated kerosene, with a particular focus on the effect of vessel pressure variations on flame temperature, flame height and flame structure and colour. In addition, the need to establish the economic feasibility of kerosene -diesel fuel adulteration activities through a preliminary cost analysis will also form an essential component of this research.

3 II.

4 Materials and Methods

5 a) Fuel Properties

The kerosene and diesel fuel samples were collected from an NNPC approved gas station in Bauchi -Nigeria. The comparative specifications and properties of the petroleum fuels used in this study are as presented in table 1. In accordance with standardized ASTM D97-93 test procedures, the densities of the blended fuel samples were also determined [16]. with air and burns in a sootless, blue cooking flame. The flame continues to heat fuel in the fuel line, either via a loop of the fuel line passing through the flame (or a heat sink) on the stove that maintains the proper temperature, and a steady supply of vaporized fuel is drawn from the tank to the jet [18]. Additional pumping increases the vessel pressure and makes the flame larger. The turning action of a small "air screw" (usually located in the filler cap) releases the vessel pressure and reduces the flame size [19]. The stove (refer to plate 1), which uses pressure and heat to vaporize the fuel before ignition, provides a hotter and more efficient burning without sooty emissions [20].

Plate 1 : Pressurized kerosene stove c) Experimental Methods

The oil knob of the pressure stove was unscrewed to allow 1 liters of unadulterated kerosene oil into the tank. The oil knob and air release screw was tightened; the cylinder was pressurized with manual pumping action about three to five times. As soon as the kerosene oil comes out from the burner tip, the air Source: [17] The kerosene pressure stove understudy is fed fuel from a tank under pressure created by gravity and a hand pump. To light the stove, the burner assembly is pre-heated with a small amount of alcohol burned in a circular "spirit cup" or priming pan just below the burner. Once heated, the tank is pressurized by means of a hand pump integrated into the tank, which forces the kerosene from the tank up through the rising tube in the ascending pipe to the pre-heated burner head for heating and vaporization. The kerosene is then forced under pressure through a descending tube to the vapour nozzle. The vapourized kerosene gas is sprayed through a jet in the middle of the burner, where it mixes warm up for 30 seconds, the air release screw was tightened and the cylinder was further pressurized to a maximum cylinder pressure of 1.0 bar with a manually operated hand pump. The kerosene rises inside the burner and vaporizes. The kerosene vapor is ignited and the combustion process is initiated, the heat from the flame keeps the burner hot enough to continue the vaporization process and the fuel in the tank warms up to keep the stove pressurized and burns ??22]. The vessel pressure, flame temperature, height and structure were carefully measured and recorded with a pressure gauge mounted on the fuel tank, a thermocouple, vernier height meter and by visual observation for a period of two minutes. The readings are taken for the different vessel pressure levels of 0.8, 0.6, 0.4, 0.2, and 0 bar, and repeated for B5 fuel oil blend (i.e. 5% diesel and 95% kerosene oil), B10, B15, and B20 kerosene oil blends and 100 B (i.e. 100%) diesel oil respectively. The experiment was replicated and the mean values of results at different vessel pressure levels for fuel samples were computed and presented as figures 1 and 2.

Furthermore, giving a burner orifice diameter and area of 0.0003m and 7.07 x 10 -8 m 2 , and vessel outlet pipe diameter and area of 0.012m and 1.13 x 10 -4 m 2 , the Bernoulli's equation was used to calculate the escape velocity of the fuel at the orifice, and was subsequently used to determine the volumetric and mass flow rate of the fuel samples [23], and their results plotted against the vessel pressure levels. In addition to study the effect of vessel pressure on flame structure, direct flame photography was employed.

6 d) Statistical validation

The experimental results were also subjected to statistical (i.e. ANOVA and T-test) analysis using the SPSS statistical package; to establish if the multiple linear regression models of the 36 fuel samples comprising of kerosene, B5, B10, B15, B20, and 100B diesel oil combusted at varying vessel pressure levels ranging from 1-0 bar, to ascertain their significance and validity, and also demonstrate if the flame temperature and flame height were truly interacting factors. The vessel pressure was considered as the dependent variable while the flame heights and temperatures of the fuel samples are considered as the independent (i.e. control) variables.

7 III.

8 Results and Discussion

From the result presented in figures 1 and 2, the effect of vessel pressure on flame temperature and flame height, fuel combustion, flame structure and color, are discussed accordingly. a) Effect of vessel pressure on flame temperature It could be seen from figure 1 below that as the vessel pressure of the test stove increases the flame temperature the flame temperature also increases.

However, if the flame temperature of kerosene pressurized at 1 bar (i.e. maximum experimental pressure) is considered as the benchmark, it was observed that the flame temperatures for B2, B10, B15, B20 fuel blends and diesel fuel are lower than the kerosene by 8.82%, 11.76%, 15.58%, 20.59% and 8.82%. Hence, samples of kerosene fuel, B5, B10 and B15 fuel blends exhibited the highest flame temperatures in the group respectively. According to Martin et. al. [24] the higher temperatures recorded is attributed to the increased the rate of combustion reactions, and concentrations of reactants caused by the higher vessel pressure. However, the higher temperature of kerosene in this case could be ascribed to its relatively higher calorific value over diesel fuel (refer to table 1) and its fuel blends. This is because high pressure is equivalent to high escape velocity and longer spray length, providing opportunity for the fuel to fully atomize and granting excess air access to the combustion process.

test shows that there is a correlation between vessel pressures versus flame height. it could also be seen from figure 2 that the flame height at maximum vessel pressure for B5, B15, B20 fuel blends and diesel fuel are higher than the benchmark by 0.22%, 1.11%, 18.89% and 37.77%. This is with exception of B10 fuel blend that is lower than the benchmark by 8.88%. This exceptional behavior of B10 fuel sample with respect to its flame height could be ascribed to the partial blockage of the It is obvious that from figure 2 that the performance of the pressurized kerosene stove under spray nozzle by sooty deposits. However, the foregoing has clearly shown that vessel pressure influences the flame height, while the higher flame height of diesel fuel could be attributed to incomplete combustion and overventilation -i.e. the volumetric flow rate of air is in excess of the stoichiometric amount required for the volumetric flow rate of fuel to burn completely [25]. optimal performance will be close to the pressure at which fluid velocity will equal flame velocity. The combustion quality of the fuels and blends are largely influenced by the calorific values of the fuels, their ignition ability, and stoichiometric mixture, concentrations of the reactant and the specific heat capacity of the fuel. The calorific (heating) value of kerosene is about 1.98% higher than diesel fuel (refer to table 1). The implication of this result is that kerosene and the B5, B10, B15, B20 fuel blends, possess the tendency to combust more efficiently with higher emanation of heat than diesel for reasons that adiabatic combustion (flame) temperature increases for higher heating values, inlet air and fuel temperatures and for stoichiometric air ratios approaching one.

In addition, the self-ignition ability of hydrocarbon fuels -represented by the cetane number, also impacts on the combustion process, as it affects the ignition delay time. It has been reported that the higher the cetane number, the shorter the ignitions delay of hydrocarbon fuels and vice versa [26]. To this end, it is important to mention that the Nigerian diesel fuel has a cetane number in the low 40s, while the Nigerian kerosene has an average cetane number of 49 [17]. This implies that the careful blending of kerosene and diesel fuel could result in a blended fuel with cetane numbers in the high end of the range [27]. Hence, this also explains the relatively lower ignition delay period (i.e. 0.0015s) of kerosene in comparison to diesel fuel sample (0.002s).

The combustion efficiency of liquid hydrocarbon fuels could also be better enhanced if the air-fuel ratio is chemically corrected (i.e. stoichiometric). It could be seen from the illustration in figure 3 that the stoichiometric mixture of kerosene (15.6) is higher than that of diesel fuel **??**14.6). Hence, it implied that more mass of air is required to burn 1kg of kerosene, and partly explains why kerosene and its blended fuel samples under test, burns more richly at higher vessel pressure than diesel fuel. The combustion process is most efficient when the mixture of air and fuel is slightly rich [28]. It is important to add that combustion can be made more efficient, and the amount of energy released maximized if the correct mixture of air is provided to support the combustion process. Excess air however, reduces the ultimate temperature of the product and the amount of energy released. Therefore, an optimum air to 0 0.5 By same token, it could be seen from figure 3 that the fuel mass flow rate increases with vessel pressure, and at maximum vessel pressure (i.e. 1 bar) the mass flow rate of fuel samples B5, B15, B20 fuel blends and diesel fuel rose higher than the benchmark by 0.64%, 0.72%, 0.76%,1.20% and 3.28%. The higher densities and relative densities Figure 3 : Relationship of fuel mass flow rate and vessel pressure (refer to table 2 below) of diesel over kerosene could be responsible for the relatively higher mass flow rate of kerosene -diesel blends and diesel fuel. This is understandable in view of the fact that the implicit variable within the governing functions include mass flow rate, atmospheric pressure, orifice size, flow velocity, flame velocity and the calorific value of the fuel. Furthermore, a further study would be required to optimize the performance of the pressurized kerosene cooker. The guess is that substituting vessel pressure at fuel ratio can almost and always be determined depending on the rate, extent of combustion and final temperature.

Hence, the air pressurization of the fuel in the cylinder increases the density of air in the cylinder and allows for the fuel/air mixture to escape through a nozzle to ensures better atomization and also enhance fuel droplet vaporization, gasification and combustion. It is important to note that diffusion rates vary with pressure, and the rates of overall combustion reaction vary approximately with the pressure squared. In same vein, it worthy of note that the rate at which the droplets evaporates and burns is generally considered to be determined by the rate of heat transfer from the flame front to the fuel surface [25]. Nonetheless, considering the double film model for the combustion of liquid fuel (i.e. one film separating the droplet surface from the flame front and the other separating the flame from the surrounding oxidizer atmosphere) with the droplet surface assumed to be slightly below the normal boiling temperature of the fuel, it could be seen from the sf region in figure 4, that the fuel evaporates at the droplet surface and diffuses toward the flame front where it is consumed, and the heat is conducted from the flame front to the liquid fuel and vaporizes [30,25]. The fuel and oxidizer meets at stoichiometric proportions, and react at the flame front. Air from the surrounding atmosphere diffuses into the flame front. While, heat and other combustion products are transported to the surrounding atmosphere (along the s ? region) in compliance with Fick's law of diffussion. According to Martins, et. al. [24], higher pressure could also increase the rate of combustion reactions by increasing the concentrations of the reactants to generate higher combustion temperatures with shorter and more compact flames. Another reason that could be attributed for the higher combustion temperature of kerosene and its blended samples is it specific heat capacity. It could be seen from table 3 of the specific heat capacities of some fuel that kerosene with 2010 J/kgK demonstrated a higher value than diesel fuel (1750 J/kgK) and implied that more energy is required to warm kerosene by 1 degree K. From the images of the flames obtained in plate 2, it could be seen that the flames are bluish at 1bar for kerosene, B5, and B10 blends; at 0.8bars for kerosene, and B5 blends; and at 0.6 bars for kerosene only. Furthermore, light bluish flames were also observed for; B15 blends at 1bar; B10 and B15 at 0.8 bars; kerosene, B5, B10, B15 at 0.6 bars; kerosene, B5, B10, B15, B20,at 0.4 bars; and kerosene, B10, B15, B20 at 0.2 bars . The somewhat fan-shaped bluish flames are suggestive of combustion under-ventilation produced when air supply is reduced below the recommended stoichiometric mixture [24].

In addition, the seemingly elongated orange colored flames manifesting in the combustion of remaining fuel samples in the group, is indicative of over-ventilation, partial (incomplete) combustion, and is also associated with the emission of soot. It was reported that the orange color of diffusion flame in the luminous zone is due to the radiation of carbon particle, formation of soot on the fuel side of the flame, and burnt in the reaction zone to produce the flame temperature Source: [31] [25]. The flames arising from these fuel samples reflects the predominance of diesel fuel, and the evidence of inefficient combustion in these cases could be attributed to the relatively higher specific gravity (0.893), kinematic viscosity (2.7mm 2 /s) and lower calorific value (44500 kJ/kg) of diesel fuel over kerosene (refer to table 1). These prevailing properties could also inhibit effective atomization and consequently leads to undesirable combustion performance. According to Linck ,et al. [32], vessel pressure affects flame structure of combusting liquid fuels, and the flame structure depends to a large extent on the features of the combustion air flow and fuel spray through the nozzle, and the effects of flame structure on the combustion behavior, including the composition of the exhaust gases, have also been reported. In the current investigation, the nozzle formed solid-cone spray, with the fuel droplets occurring throughout the cone.

e) Result of statistical validation Validated summary of experimental data shown in table 2, gave a computed value for the R 2 as 0.769, thus indicating that the regression was "strong" as about 76.9% of the variation in the vessel pressure could be accounted for by the control variables. The ANOVA analysis in the regression result, shown in table 2, gave a computed value for the F-statistic as 54.794 while the corresponding table value of 3.27 at 0.05 level of significance (q) and (2,35) degrees of freedom showed that the multiple linear regression model was significant and valid. Also large regression sum of squares **??**3.

9 f) Comparative cost analysis

Comparative cost analysis has been made for B5 (95% kerosene and 5% diesel fuel), B10, B15, and B20 blended fuel samples and diesel fuel. The cost analysis has been made for the consumption of 1litres of fuel by a household at the current official retail pump prices, namely, N155 for diesel fuel and N50 kerosene in Nigeria [34,35]. With the new price regimen, it could be seen from figure 3 below that the present cost of one liter of B5, B10, B15, B20 blended fuel samples are 10.5%, 21.0%, 31.5%, and 42.0% higher than the cost of one liter of kerosene. Hence, the present pricing policy of petroleum products in Nigeria has clearly revealed that kerosene-diesel fuel adulteration is not economical, and will no doubt discourage the illicit practice, unlike in the previous pricing regimen that puts the cost per liter of kerosene higher than that of other petroleum products such as gasoline and diesel, which makes it a prime candidate for adulteration with diesel as it also occurs presently in India [36].

10 Regression Standardized Residual

11 Conclusion

From the foregoing, the following could be concluded: i.

Tested samples of kerosene fuel, B5, B10 and B15 fuel blends exhibited thehighest flame temperatures due to higher rate of combustion reactions, and concentrations of reactants occasioned by the higher vessel pressure, and their relatively higher calorific value. ii.

At the maximum vessel pressure, the flame heights for B5, B15, B20 fuel blendsand diesel fuel are higher than the flame height generated from kerosene fuel. The influence of vessel pressure on the flame height was confirmed. iii.

The combustion quality of kerosene and its blends are to a large extent, affectedby the calorific values of the fuels, ignition ability, and stoichiometric mixture, reactant concentrations and their specific heat capacities. iv. The vessel pressure also affects flame structure of combusting liquid fuels, and the flame structure depends to a large extent on the features of the combustion air flow and fuel spray through the nozzle. A bluish flame was observed at 1bar for kerosene, B5, and B10 blends; at 0.8bars for kerosene, and B5 blends; and at 0.6 bars for kerosene fuel. Finally, the adulteration of kerosene with diesel fuel would not yield any economic benefit in terms of profit.

12 V. Acknowledgement

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2

Figure 1: 2 ©

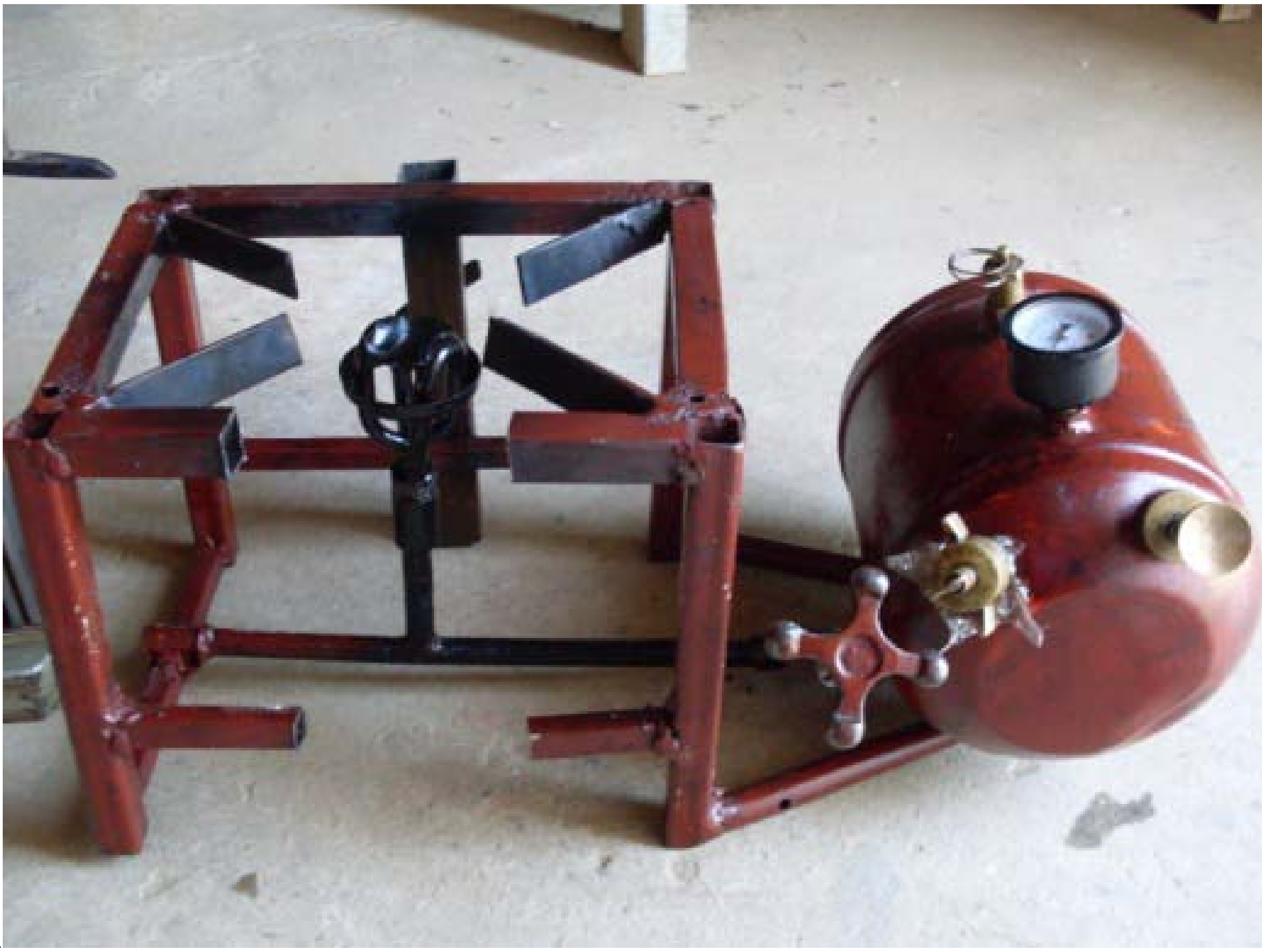
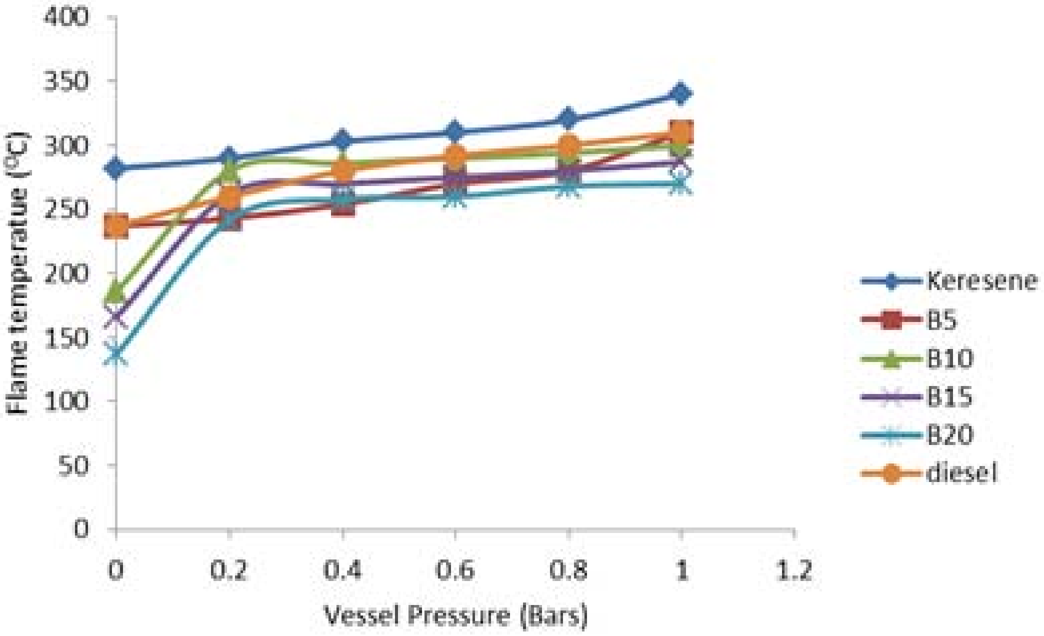
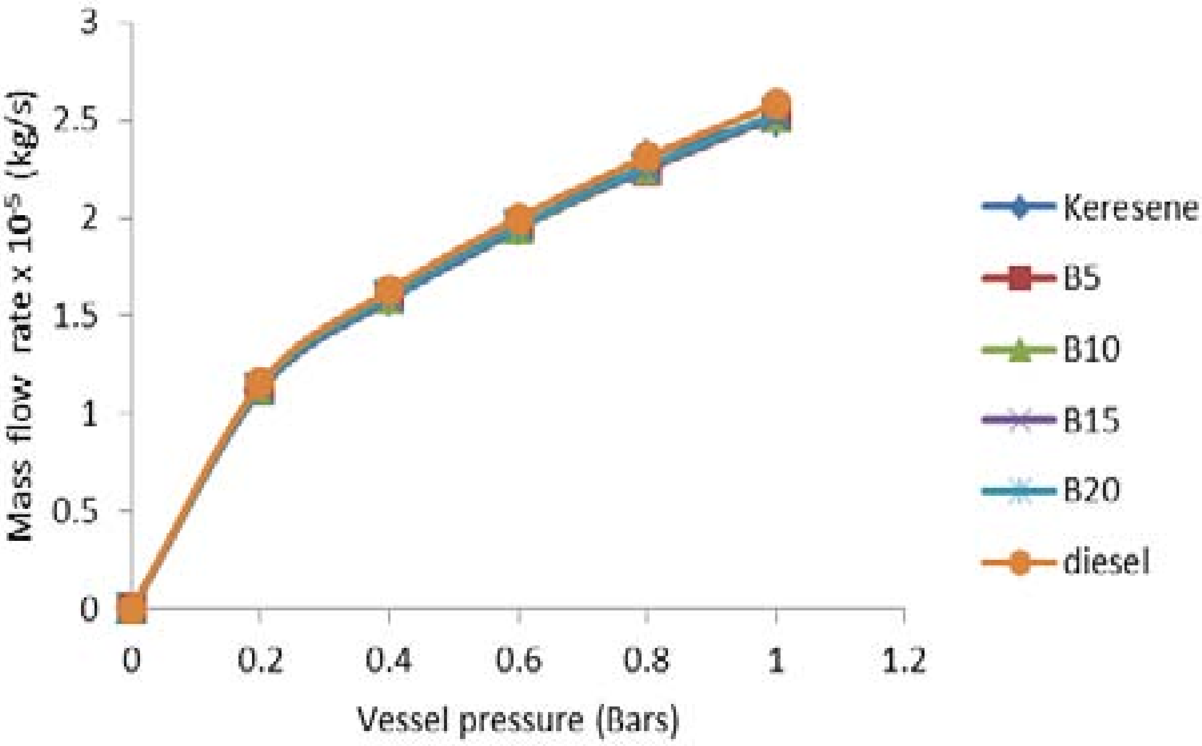
1 

Figure 2: Figure 1 :



2

Figure 3: Figure 2 :



4

Figure 4: Figure 4 :

3


Figure 5: Figure 3 :A

2


Figure 6: Plate 2 :

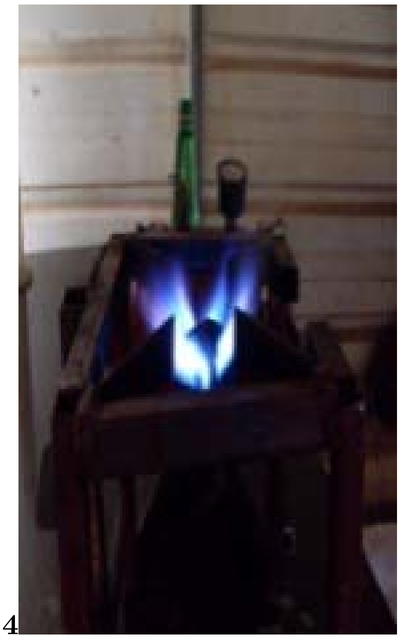
4 

Figure 7: -Figure 4 :

1

Property	Unit	Diesel	Kerosene
Chemical formula	-	$C_{12}H_{26}$	$C_{10}H_{22}$
Calorific value	kJ/kg	44500	45400
Self-ignition temperature	o C	725	640
Final boiling point	o C	369	249
Ignition delay period	s	0.002	0,0015
Flame propagation rate	cm/s	10.5	11.8
Flame temperature	o C	1715	1782
Kinematic viscosity @ 39 o C	mm^2/s	2.7	2.2
Specific gravity @ 15.6/15.6 o C	-	0.893	0.843
Colour	-	Red	Soybolt (20min)
Sulphur content	wt %	0.16	0.04
b) Description of pressure stove			

Figure 8: Table 1 :

2

Samples	Kerosene	B5	B10	B15	B20	Diesel
Density (kg/m^3)	843	845	848	850	855	893

[Note: c) Effect of vessel pressure on fuel combustion]

Figure 9: Table 2 :

3

Fuels	Specific heat capacity (J/kg K)
Gasoline	2220
Kerosene	2010
Diesel	1750
d) Effect of vessel pressure on flame structure and color	

Figure 10: Table 3 :

3

Parameter	Value	ANOVA Parameter	Sum of squares	Parameter	COLLINEARITY DIAGNOSTICS Condition index	Coefficients	VIF	T-Statist	P
R^2	0.769	Regression	3.228	Constant (b_0)	1.00	-1.163	-	-5.972	S P v
F-Statistic	54.794	Residual	0.972	FT (b_1)	9.860	0.00283	1.447	3.319	S P
Significance of F-statistic	0.000	-	-	FH (b_2)	17.662	0.120	1.447	6.410	-

Figure 5 : Plot of regressive experimental result

multi co-linearity was not a problem in this application as VIF < 4 [33], which clearly demonstrate that flame temperature and flame heights were not significantly interacting factors.

Figure 11: Table 3 :

.1 ( )

A Year

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