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Effects of Vessel Pressure on Flame Temperature and Height of Adulterated Kerosene Fuel Samples in a Pressurized Cooking Stove

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ABSTRACT

Kerosene has remained inaccessible and unavailable to majority of Nigerian households and unreliable due to adulteration. Studies have 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. This work presents formulation of linear regression model which represents anticipated effects of vessel pressure variations on flame temperature and height of adulterated kerosene in a pressurized cooking stove. The model validation confirmed the existence of statistical relationships between vessel pressure variations and flame temperature and height. Appling data collected from Experimental results, R^2 *values of 76.9 % was obtained for the model. The result showed that the variation in behavior of vessel pressure could be accounted for by the flame temperature and height. This model will further help in predicting the behavior of adulterated kerosene.*

Keywords: *Kerosene Adulteration, Flame Temperature, Flame Height, Vessel Pressure, Regression Modeling, Fuel Subsidy.*

1.0 INTRODUCTION

Subsidizing fuels has high costs. Moreover, universal price subsidies almost always benefit high income households more than the poor, because richer home consume more energy. Other adverse effects include rampart abuses in fuel markets [1]. Bulk quality assurance parameters such as flash point, flame height, flame temperature, flame width and smoke point are used to ascertain the extent at which adulteration of kerosene become hazardous to humans when used domestically [2]. In India subsidized kerosene is sold at much lower prices than gasoline or diesel and is frequently diverted to the black-market for use as a transport fuel. Approximately 60% of the subsidized kerosene reaches the intended beneficiaries [3]. The achievement of Nigerian government objective of subsidy regime was hindered inefficiency in the product market and large fiscal burden on the government. This led to the policy of gradual removal of subsidy on petroleum products prices since 1986. Even though, the subsidy on kerosene was retained such that kerosene price remained the lowest among major petroleum products in Nigeria, yet kerosene still remain inaccessible and unavailable to majority of Nigerian households and unreliable due to adulteration [4]. Crude oil is a natural occurring mixture consisting predominantly of hydrocarbons with other elements, such as; sulphur, nitrogen, and oxygen, either existing as organic compounds or in some cases as complex of metals [5] [6]. In technical terms, one barrel of Nigerian crude oil has a volume yield of 6.6% automotive gas oil, 20.7% gasoline, 9.5% kerosene and jet fuel, 30.6% diesel, and 32.6% fuel oil and residues [7]. 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. The ultimate analysis composition of kerosene is 84.3 % wt carbon, 14.2 % wt hydrogen, and remainder is sulfur and nitrogen [8]. The high demand and desirability of kerosene is informed by its lower volatility in comparison to gasoline, good oxidative stability and cleaner burning characteristics [9].

According to [10], 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 CO_2, 73 ppm CO, and 3.8 ppm CH_4 , 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 [11].

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 that could facilitated 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 [12].The combustion of kerosene is the process of rapid oxidation with simultaneous evolution of heat and light, that is used for household lighting and cooking .the incessant power outages and inadequate distribution and supply of electricity to especially rural Nigeria constitutes a major challenge and is largely responsible for the increased patronage of kerosene stoves.

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 [13]. 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 [14] [15] [16] [17] [18]. Notwithstanding, some studies have 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 [19]. However, this paper intends to investigate the combustion behavior of adulterated kerosene, with a particular focus on modeling the effect of its vessel pressure variations on flame temperature and height. Therefore, the formulation of a statistical linear regression model is intended to establish a relationship between flame temperature and height, and vessel pressure variations of adulterated kerosene in a pressurized cooking stove.

This work will provide a model for predicting the variations in vessel pressure of adulterated kerosene in a pressurized cooking stove through identifying, validating, and controlling statistically significant control factors (i.e. flame temperature and height) that can influence vessel pressure variations. The implication is that this will help in identifying adulterated kerosene and thereby reduce the circulation of such kerosene fuel.

2.0 DESCRIPTION OF PRESSURE STOVE

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 vapour 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 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 [20]. 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 [21]. 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 [22].

Plate 1. Pressurized kerosene stove [21].

3.0 METHODOLOGY

Bulk quality assurance parameters such as flash point, flame height, flame temperature, flame width and smoke point are used to ascertain the extent at which adulteration of kerosene become hazardous to humans when used domestically [19]. It is therefore assumed in this work that relationships do exist between vessel pressure variations and other independent variables relating to combustion factors. The construction of statistical models like linear regression can serve as a tool to verify or otherwise refute the presence of relationships between interacting variables [23]. Therefore, the technical approach adopted consists of two major steps. Firstly, linear regression model is formulated to represent anticipated relationships between vessel pressure and flame temperature and height. Secondly, this model was tested for validity and adequacy using statistical tools such as a hypothesis

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testing, Analysis of Variance (*ANOVA*), and Coefficient of determination, R^2. Statistical Package of Social Sciences (SPSS version 16.0) was employed to determine R^2, which is the proportion of variation in the dependent variable explained by the regression model. In *Analysis of Variance* (*ANOVA*), the sum of squares, degrees of freedom, and mean square are computed for two sources of variation, regression and residual. A model with a large regression sum of squares in comparison to the residual sum of squares indicates that the model accounts for most of variation in the dependent variable. The *F*-statistic is the regression mean square divided by the residual mean square and if the significance of the *F*-statistic is small (smaller than 0.05) then the independent variables performs a good work explaining the variation in the dependent variable. *T* statistic helps to determine the relative importance of each variable in the model. *T* values below –2 or above +2 give the favored impression. Regression Co-linearity Diagnostics helps to determine if there are any problems with co-linearity. An important factor in co-linearity diagnostics is; condition indices. A condition index greater than 15 indicates a possible problem and an index greater than 30 suggests a serious problem with multi-co-linearity.

3.1 Linear Regression

In multiple linear regressions, a response variable (*Y*) is related to a set of control variables using the linear model given by equation 1. The construction of a multiple linear regression model essentially requires the estimation of the parameters such as the intercept and regression coefficients associated with control variables of the model.

$$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \dots\dots\dots a_kx_k + \varepsilon \qquad (1)$$

Where:

Y - Is a linear function of *k* control variable $x_1 \dots\dots,\ x_k$ and ε is an error term. a_0 is intercept of the model, and a_1, a_2, a_3 are regression coefficients associated with control variables x_1, x_2, x_3 respectively. Using sample data, model parameters can be estimated using the coefficients $b_0, b_1, b_2, b_3 \dots\dots b_k$ of the regression equation, associating response variable Y with its control variables $x_1, x_2, x_3 \dots\dots x_k$ as shown below:

$$Y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \dots\dots\dots b_kx_k \qquad (2)$$

Where; b_0 is intercept of the model of the sample data, b_1 is regression coefficient associated with the control variable x_1 of the sample data, b_2 is regression coefficient associated with the control variable x_2 of the sample data and b_3 is regression coefficient associated with the control variable x_3 of the sample data.

3.2 Variables Selection

The relationship of flame temperature (*FT*) and flame height (*Fh*), both independent variables with vessel pressure (*Pv*), a dependent variable, is to be derived. The specific definitions and units of measurements of these variables are defined as follows; Flame temperature *(FT*) represents a measure of the degree of hotness of the visible part of the fire (^{o}C).; flame height (*Fh*) measures the height of the visible part of fire in meters.; Vessel pressure (*Pv*) measures the operating pressure of the pressurized stove in bars.

The above factors are selected as control variables influencing vessel pressure based on;

i) The presence of physical or logical influence of these factors on vessel pressure variations. For example, as height of flame increases, vessel pressure in bars would increase as a result of the extra energy requirements for combustion [19].

ii) It is predicted that as flame temperature is changed, it is logical to conclude that vessel pressure in bars would change accordingly [19].

To justify the presence of such informative relationships between these factors, scatter diagrams are used to clearly indicate the validity of initial selection of control variables.

3.3 Models Assumptions

The following assumptions are made:

i) There was a linear relationship between the vessel pressure and the related control variables (application of scatter diagrams).

ii) That multi co-linearity was not present between the control variables (flame temperature and height).

iii) That the random errors (o) are independent and normally distributed with constant variance and zero mean [24].

4.0 Formulation of Multiple Linear Regression Model (MLRM)

4.1 Model Formulation.

Based on the selected variables and model assumptions, the following multiple linear regression model was formulated for the relationship between vessel pressure and flame temperature and height of adulterated kerosene in a pressurized cooking stove.

***Model* : Vessel pressure versus Flame temperature and height.**

$$Exp(Pv_c / FT, Fh) = b_{oc} + b_{1c}FT + b_{2c}Fh \qquad (3)$$

Where:

$Exp(Pv_c / FT, Fh)$ - is the expected value of vessel pressure in bars given the independent variables FT and Fh, b_{oc} is intercept of the model, b_{1c} is regression coefficient associated with flame temperature of the mode and b_{2c} is regression coefficient associated with flame height of the model.

4.2 Statistical Tests on Regression Model Parameters

4.2.1 Hypothesis 1: Testing model validity

Model hypothesis for model validity is as presented in equation 4:

$$\begin{aligned} &H_0 : b_{jc} = 0, \quad j = 1, 2 \\ &If\ H_0\ is\ rejected,\ then\ H_1 : at\ least\ one\ b_{jc} \neq 0 \end{aligned} \qquad (4)$$

This hypothesis is intended to test validity of the presence of a relation between Vessel pressure and any of the independent variables. If the null hypothesis is rejected, then there are some independent variables that do actually affect vessel pressure.

4.2.2 Hypothesis II: Individual testing of coefficients of the multiple linear regression model.

Hypothesis IIa: for Flame temperature (FT) is as presented in equation 5.

$$H_0 : b_{1c} = 0 \quad vs \quad H_1 : b_{1c} \neq 0 \ \ for\ the\ model \qquad (5)$$

The null hypothesis assumed that there was no statistically significant relationship between Vessel pressure and Flame temperature rate (FT).

Hypothesis IIb: for Flame height (Fh) is as presented in equation 6:

$$H_0 : b_{2c} = 0 \quad vs \quad H_1 : b_{2c} \neq 0 \ \ for\ the\ model \qquad (6)$$

The null hypothesis assumed that there was no statistically significant relationship between Vessel pressure and Flame height (Fh).

5.0 DATA COLLECTION

The data used in this work is as presented in Table 1.

Table 1: Experimental data of Vessel pressure versus Flame temperature and height

Pv	FT	FH
1.0	340.0	9.0
1.0	310.0	9.02
1.0	300.0	8.2
1.0	287.0	9.1
1.0	270.0	10.7
1.0	310.0	12.4
0.8	320.0	8.0
0.8	280.0	8.7
0.8	294.0	7.8
0.8	280.0	7.5
0.8	268.0	8.5
0.8	300.0	11.5
0.6	310.0	7.1
0.6	270.0	8.0
0.6	290.0	7.4
0.6	275.0	7.9

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0.6	260.0	7.9
0.6	292.0	9.3
0.4	303.0	7.0
0.4	254.0	7.9
0.4	286.0	6.7
0.4	270.0	6.1
0.4	258.0	7.0
0.4	280.0	7.1
0.2	290.0	6.9
0.2	243.0	5.1
0.2	280.0	6.0
0.2	262.0	6.0
0.2	242.0	6.07
0.2	260.0	6.0
0.0	282.0	6.5
0.0	237.0	2.8
0.0	186.0	5.9
0.0	166.0	5.9
0.0	137.0	5.3
0.0	237.0	5.3

Source: [19]

Table 2. Properties of fuel used.

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

Source: [28].

Table 3. Specific heat capacities of some fuels.

Fuels	Specific heat capacity (J/kg K)
Gasoline	2220
Kerosene	2010
Diesel	1750

Source: [19]

5.1 Effect of vessel pressure on flame temperature.

According to [19], it was established that as the vessel pressure of the test stove increases 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 B5, 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% (refer Table 1 and Figure 1). Hence, samples of kerosene fuel, B5, B10 and B15 fuel blends exhibited the highest flame temperatures in the group respectively. According to [25], the higher temperatures recorded are attributed to the increased in 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 2) 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.

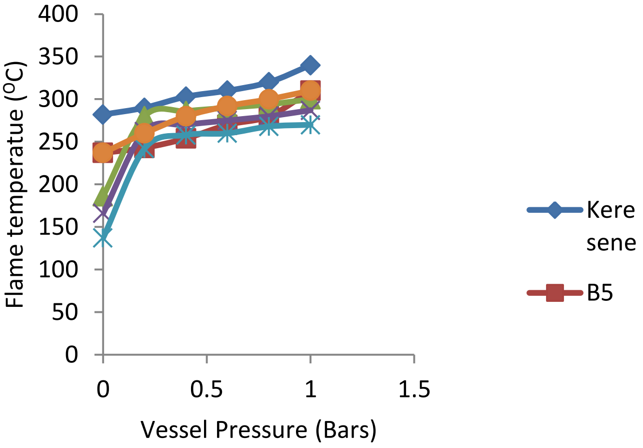

Figure 1. Flame temperature versus vessel pressure.

5.2 Effect of vessel pressure on flame height.

According to [19], it is obvious that from the performance of the pressurized kerosene stove there is a correlation between vessel pressures versus flame height (see Figure 2). 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 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 over-ventilation -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 [26].

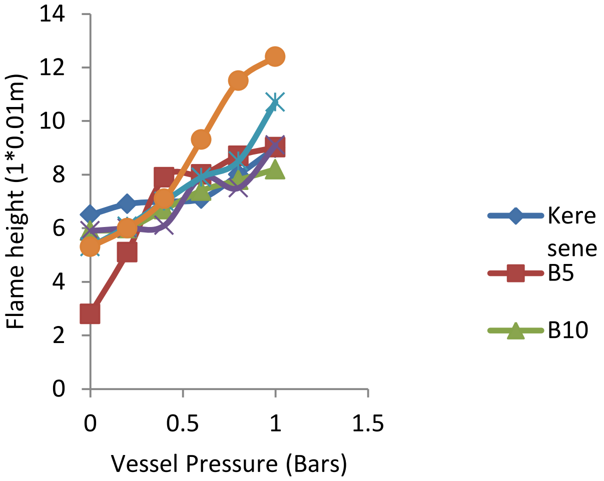

Figure 2. Flame height versus vessel pressure.

5.3 Effect of vessel pressure on fuel combustion.

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 2). 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 [27]. 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 [28]. 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 [29]. 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 [30]. 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 fuel ratio can almost and always be determined depending on the rate, extent of combustion and final temperature.

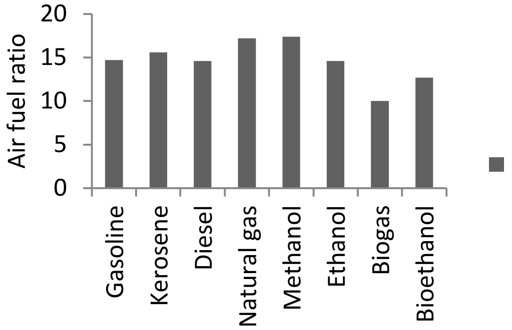

Figure 3. The stoichiometric ratio of different fuels [31].

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 [26]. 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 [32] [26]. 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 [25], 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.

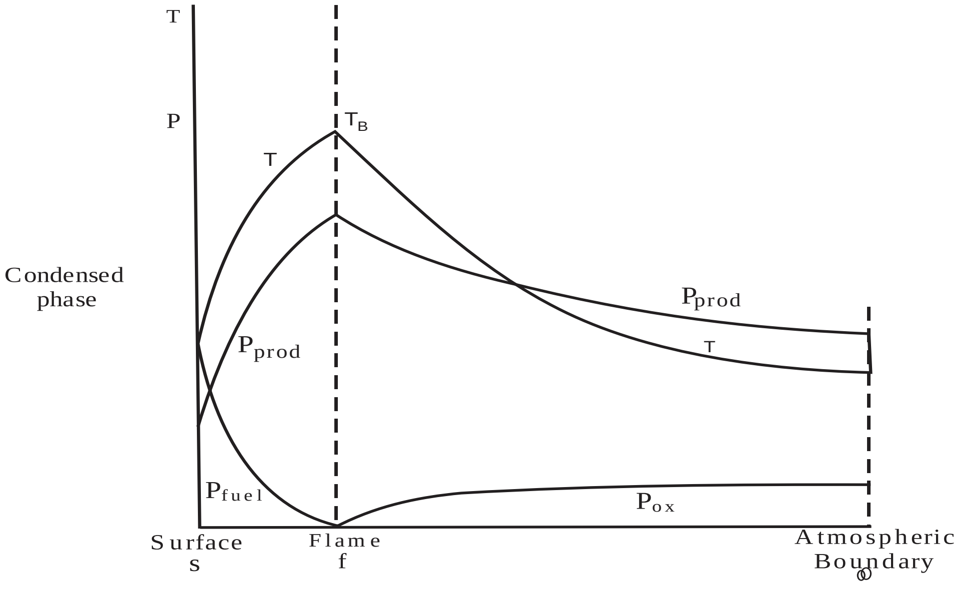

Figure 4. Parameter variation along a radius of a droplet diffusion flame [26].

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.

6.0 Model validation.

The model results shown in Table 4 were generated using Statistical Package for Social Sciences (SPSS version 16.0).

Table 4. Model Summary.

		ANOVA			COLLINEARITY DIAGNOSTICS					RESIDUALS	
Parameter	Value	Parameter	Sum of squares	Parameter	Condition index	Coefficients	VIF	T-Statistic	Parameter	Mean (μ)	Standard Deviation (σ)
R^2	0.769	Regression	3.228	Constant (b_0)	1.00	-1.163	-	-5.972	Standard Predicted value	0	1
F-Statistic	54.794	Residual	0.972	FT (b_1)	9.860	0.002839	1.447	3.319	Standard Residual	0	0.971
Significance of F-statistic	0.000	-	-	Fh (b_2)	17.662	0.120	1.447	6.410	-	-	-

Scatter diagram shown in Figure 5 clearly indicates the validity of initial selection of variables.

The model summary shown in Table 4, 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 4, 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 (3.228) in comparison to the residual sum of squares (0.972) indicated that the model accounts for most of variation in the dependent variable. The coefficients b_0, b_1, b_2 shown in Table 4 are -1.163, 0.002839, and 0.120, respectively; and the results of the T- test indicated that regression coefficients b_1 and b_2 were statistically significant and not equal to zero (as given by hypothesis ii) at 0.025 level of significance and 35 degrees of freedom (Table T-value=$T_{0.025}$, 35 = 2.030). Therefore, the regression equation of vessel pressure (P_v) is expressed in equation 7. It should be noted that the assumptions made were valid for this model with respect to multi co-linearity and residuals' distribution referred to in Table 4. The condition indexes values of 9.86 and 17.662 are for flame temperature (FT) and flame height (FH) respectively. From Table 4, the residuals average was zero with standard deviation of approximately 1.0 (i.e. 0.971) implying that residuals were actually independent (refer to Figure 6). The variance inflation factor (VIF) of 1.447 indicated that 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.

$$Exp(Pv_c\,/\,FT\,,Fh) = -1.163 + 0.002839FT + 0.120Fh \qquad (7)$$

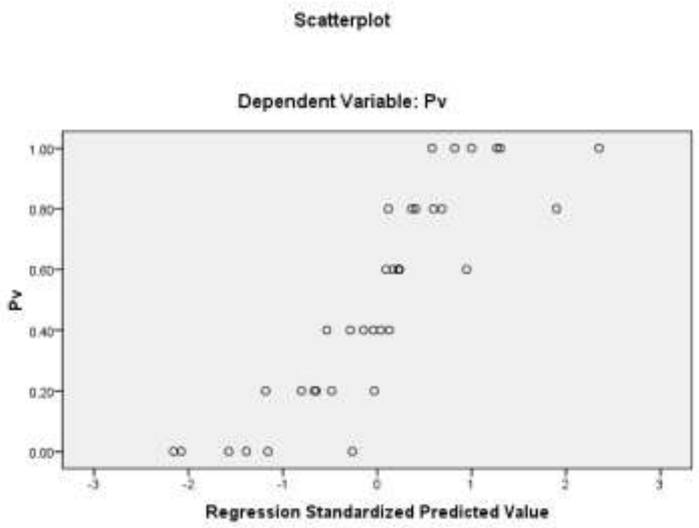

Figure 5: Regression scatter plot

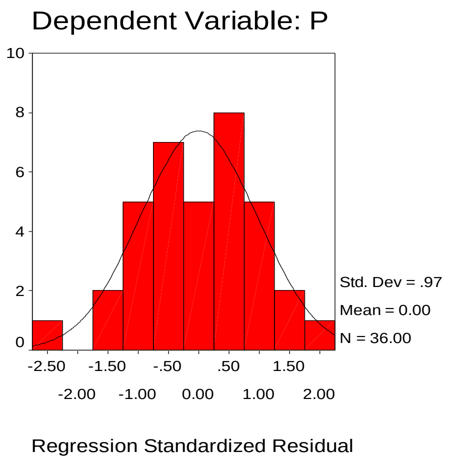

Figure 6. Regressive residual validated curve.

7.0 CONCLUSION

Model was formulated to establish the relationship between vessel pressure variations and flame temperature and height respectively. The results established a significant relationship between vessel pressure and flame temperature and height thus, call for additional efforts for integrating energy management systems inside the quality control facility of the product regulatory arm of NNPC. The model will enable energy managers to significantly monitor and reduce adulterated kerosene consumption rate and thereby reduce the risk it poses to the consumers.

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