The Bio-fuel Thermal Efficiency Analysis Using Statistical Method

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***Abstract* - Energy problem and the environmental problem are becoming hot issues globally. The deterioration of the environment and the rapid depletion of the petroleum fuel are no longer problems for specific countries or regions. Although fossil fuel is the initial power of the economic growth and the daily life, the environment is threatened by the use of fossil energies. Finding alternative energy is becoming a hot issue in world wide. It may become a strategic direction for the countries. Biodiesel is safe, biodegradable, and reduces serious air pollutants. Such as particulates, carbon monoxide, hydrocarbons, air toxics. The object of this study was to compare fuel thermal efficiency using two different blends biodiesel (B50, B100) and gasoline. Set the factor of fuel type and the air/fuel ratio as two factors and several tests were conducted under different condition and all data were analyzed using the statistical method and analysis of variance (ANOVA). The *P* value for the fuel type was 0.001 and the air/fuel ratio was 0.021. It means the factors of fuel type and air/fuel ratio both have significant effect on the exhaust temperature for the source of variation with 95% of confidence.**

Keywords The Analysis of Variance, ANOVA, Biodiesel, The Method of Least Squares, Combustion

BACKGROUND

With the growing global demand for crude oil, the lack of secure sources of oil due to regional and political instability in the producing regions, and the increasing cost of the use of crude oil have led to the search for alternative sources. The adverse impact on the environment and the increasing global climate change impacts have all combined to make the search an urgent national security issue. The search for secure sources of renewable energy has led to the innovative use of oil based agricultural products as feedstock for the production of biodiesel. The increased use of edible oil-based agricultural products resulted in high food prices as farmers redirected their crops from food to energy feedstock. Now the challenge is to produce biodiesel fuels using nonedible agricultural sources as feedstock. Biodiesel is manufactured from plant oils, animal fats, and recycled cooking oils. Biodiesel's advantages are as follows:

- It is renewable.
- It is energy efficient.
- It displaces petroleum-derived diesel fuel.
- It can be used as a 20% blend in most diesel equipment with no or only minor modifications.
- It can reduce global warming gas emissions.
- It can reduce tailpipe emissions, including air toxics.
- It is nontoxic, biodegradable, and suitable for sensitive environments.

Biodiesel contains 2.5 to 3.5 units of energy for every unit of fossil energy input in its production, and because very little petroleum is used in its production, its use replaces petroleum at nearly a 1-to-1 ratio on a life-cycle basis. This value includes energy used in diesel farm equipment and transportation equipment (trucks, locomotives); fossil fuels are used to produce fertilizers, pesticides, steam, and electricity; and methanol is used in the manufacturing process. Because biodiesel is an energy-efficient fuel, it can extend petroleum supplies. [1-3]

U.S. Biodiesel Production Status

Figure 1 shows estimated U.S. biodiesel production by fiscal year (Oct 1 – Sep 30). As can see from 2006 the amount of biodiesel production is increasing rapidly, and by 2007 the amount was approximately 450 million gallons, compare to 2006, it's 92% more. By 2008 the amount was about 700 million gallons, compare to 2007, it's 50% more.

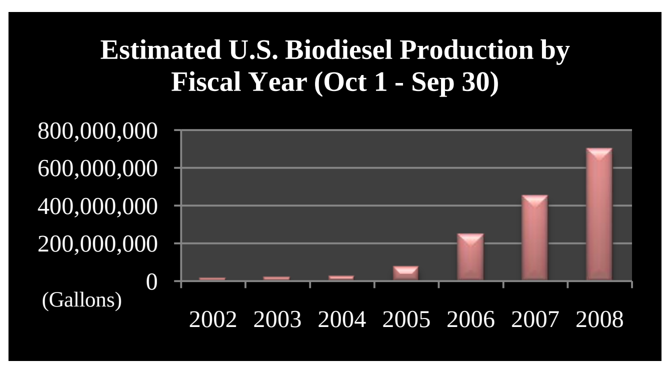

Figure 1 Estimated U.S. Biodiesel Production [www.biodiesel.org]

EXPERIMENTAL FACILITY AND PROCEDURE

The Combustion Laboratory Unit C491 is use to conduct the experiment.[4] Figure 2 shows the Combustion Laboratory Unit C491. Two kinds of biodiesel blends and a gasoline fuel will be used to do the test. Figure 3 shows the pictorial view of the biofuel testing facility Combustion Laboratory Unit C491.

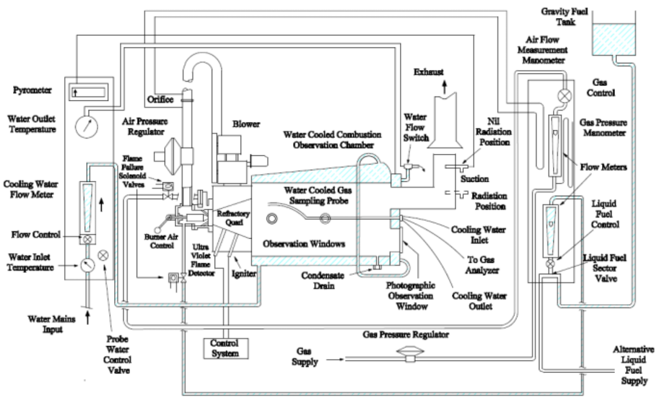

Figure 2 The Proposed Equipment Diagram of for Biomass Sample Testing (P.A.Hilton)

Figure 3 The Pictorial View of the Biofuel Testing Facility C491

SCIENTIFIC METHODOLOGY

I. Some Combustion Chemistry

A generic oxygenated hydrocarbon fuel ($C_nH_mO_r$) with idealized air (O_2 + kN_2) to major products (CO_2, H_2O, O_2, and N_2) is:

$$C_nH_mO_r + (n + \frac{m}{4} - \frac{r}{2})(O_2 + kN_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + k(n + \frac{m}{4} - \frac{r}{2})N_2 \quad (1)$$

$$C_nH_mO_r + \lambda(n + \frac{m}{4} - \frac{r}{2})(O_2 + kN_2) \rightarrow nCO_2 + \frac{m}{2}H_2O + (\lambda - 1)(n + \frac{m}{4} - \frac{r}{2})O_2 + \lambda k(n + \frac{m}{4} - \frac{r}{2})N_2 \quad (2)$$

Where n, m, and r are the number of carbon, hydrogen, and oxygen atoms in the fuel molecule, respectively. λ is the excess air factor which is equal to the reciprocal of equivalence ratio. *K* is the mole ratio of nitrogen to oxygen in air, normally *K* is 3.76. [5] Petroleum diesel fuel molecule represented as $C_{10}H_{22}$.[6, 7] Chemically correct air/fuel ratio assumes all fuel burnt to CO_2 and H_2O:

$$C_{10}H_{22} + 15.5(O_2 + 3.76N_2) \rightarrow 10CO_2 + 11H_2O + 58N_2 \quad (3)$$

Chemically correct air to fuel ratio based on mass is

$$\frac{C_{10}H_{22}}{15.5(O_2 + 3.76N_2)} = \frac{10 \times 12 + 22 \times 1}{15.5(2 \times 16 + 3.76 \times 2 \times 14)} = \frac{1}{15} \quad (4)$$

The canola biodiesel fuel molecule represented as $C_{59}H_{94}O_5$. Chemically correct air/fuel ratio assumes all fuel burnt to CO_2 and H_2O:

$$C_{59}H_{94}O_5 + 80(O_2 + 3.76N_2) \rightarrow 59CO_2 + 47H_2O + 301N_2 \quad (5)$$

Chemically correct air to fuel ratio based on mass is

$$\frac{C_{59}H_{94}O_5}{27(O_2 + 3.76N_2)} = \frac{59 \times 12 + 94 \times 1 + 5 \times 16}{27(2 \times 16 + 3.76 \times 2 \times 14)} = \frac{1}{12.5} \quad (6)$$

The gasoline fuel molecule represented as C_8H_{18}.[8] Chemically correct air/fuel ratio assumes all fuel burnt to CO_2 and H_2O:

$$2C_8H_{18} + 25(O_2 + 3.76N_2) \rightarrow 16CO_2 + 18H_2O + 94N_2 \quad (7)$$

Chemically correct air to fuel ratio based on mass is

$$\frac{2C_8H_{18}}{25(O_2 + 3.76N_2)} = \frac{16 \times 12 + 36 \times 1}{25(2 \times 16 + 3.76 \times 2 \times 14)} = \frac{1}{50.47} \quad (8)$$

For petroleum diesel fuel the chemically correct air to fuel ratio based on mass is 15:1 refer to (4). For canola biodiesel are 12.5:1 Refer to (6). For gasoline fuel is 50.47:1 Refer to (8). Biodiesel is an oxygenated fuel so contains some oxygen atoms in fuel so theoretically it requires less air than petroleum diesel and gasoline fuel.

II. The Method of Least Squares

Field data is often accompanied by noise. Even though all control parameters (independent variables) remain constant, the resultant outcomes (dependent variables) vary. A process of quantitatively estimating the trend of the outcomes, also known as regression or curve fitting, therefore becomes necessary. [9] The curve fitting process fits equations of approximating curves to the raw field data. Nevertheless, for a given set of data, the fitting curves of a given type are generally NOT unique. Thus, a curve with a minimal deviation from all data points is desired. This best-fitting curve can be obtained by the method of least squares. [10] This paper will apply the 5th degree order polynomial to fit data values using Matlab Curve Fitting Toolbox. When using an 5th degree polynomial (9) to approximate the given set of data $(x_1, y_1), (x_2, y_2), ..., (x_5, y_5)$, the best fitting curve f(x) has the least square error. Please note that $p_0, p_1, p_2, ..., p_5$ are unknown coefficients while all x_i and y_i are given.

$$y = p1 \cdot x^5 + p2 \cdot x^4 + p3 \cdot x^3 + p4 \cdot x^2 + p5 \cdot x + p6 \quad (9)$$

$$\Pi = \sum_{i=1}^{n} [y_i - f(x_i)]^2 = \sum_{i=1}^{n} [y_i - (p1 \cdot x^5 + p2 \cdot x^4 + p3 \cdot x^3 + p4 \cdot x^2 + p5 \cdot x + p6)]^2 = \min \quad (10)$$

The Matlab Curve Fitting Toolbox provides graphical user interfaces (GUIs) and command-line functions for fitting curves and surfaces to data. The toolbox performs exploratory data analysis, preprocess and post-process data, compare candidate models, and remove outliers. Also can conduct regression analysis using the library of linear and nonlinear models provided or specify custom equations. The toolbox also supports nonparametric modeling techniques, such as interpolation and smoothing.

III. The Analysis of Variance

There are two different factor levels including a levels of factor A, b levels of factor B, and assuming that A and B are fixed, the analysis of variance table is shown in Table 1.

Table 1 The Analysis of Variance Table for Two-Factor Fixed Effects Model

Source of Variation	*Sum of Squares*	*Degrees of Freedom*	*Mean Square*	*F_0*
A	SS_A	a - 1	$MS_A=SS_A/(a-1)$	MS_A/MS_E
B	SS_B	b - 1	$MS_B=SS_B/(b-1)$	MS_B/MS_E
Error	SS_E	(a-1)(b-1)	$MS_E= SS_E/((a-1)(b-1))$	
Total	SS_T	N-1		

The sums of squares are found from the following equations. [11, 12]

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij}^2 - \frac{y_{..}^2}{N} \quad (11) \qquad SS_A = \frac{1}{b}\sum_{i=1}^{a} y_{i.}^2 - \frac{y_{..}^2}{N} \quad (12)$$

$$SS_B = \frac{1}{a}\sum_{j=1}^{b} y_{.j}^2 - \frac{y_{..}^2}{N} \quad (13) \qquad SS_E = SS_T - SS_A - SS_B \, (14)$$

In this experiment, two factors were considered as the affecting factors. They were the factor of fuel type and the factor of air/fuel ratio. The factor of fuel type B100, B50 and gasoline were compared. The factor of air/fuel ratio was 5:1, 6:1, and 7:1.

RESULTS AND DISCUSSION

This paper focuses on the thermal efficient aspects of the three fuels. The three fuels are B100, B50, and Gasoline fuels. The biodiesel used in the experiment was canola oil. B100 is 100% canola oil, and B50 is 50% canola oil and 50% petroleum diesel. Several experiments were conducted under different conditions. After these experiments all the collected data were put together and analyzed using the method of least squares and the statistical method. The different fuel types and the different air/fuel ratios were set as the factors to see which factor has the most significant effect on the exhaust temperature. Table 2 shows the experiment result.

Table 2 Summary of the Test Result

Item	Exhaust Temp (°C)	Air Mass Flow (g/s)	Fuel Flow (g/s)	Air/Fuel Ratio
B100	550	19.44	3.675	5.2910
	565	22.22	3.538	6.2810
	574	25.00	3.524	7.0935
	589	27.78	3.470	8.0054
	604	30.56	3.449	8.8580
	618	33.33	3.402	9.7982
B50	468	19.44	3.538	5.4959
	462	22.22	3.524	6.3053
	490	25.00	3.470	7.2049
	554	27.78	3.449	8.0527
	590	30.56	3.402	8.9816
	612	33.33	3.402	9.7982
Gasoline Fuel	427	19.444	4.900	3.9683
	431	22.222	4.800	4.6296
	435	25.000	4.760	5.2521
	446	27.778	4.600	6.0386
	472	30.556	4.600	6.6425
	475	33.333	4.601	7.2448

The Figure 4 show a bar-chart represents the relationship between air/fuel ratio and the exhaust temperature. The x-axis is the exhaust temperature (°C) and the y-axis is the air/fuel ratio.

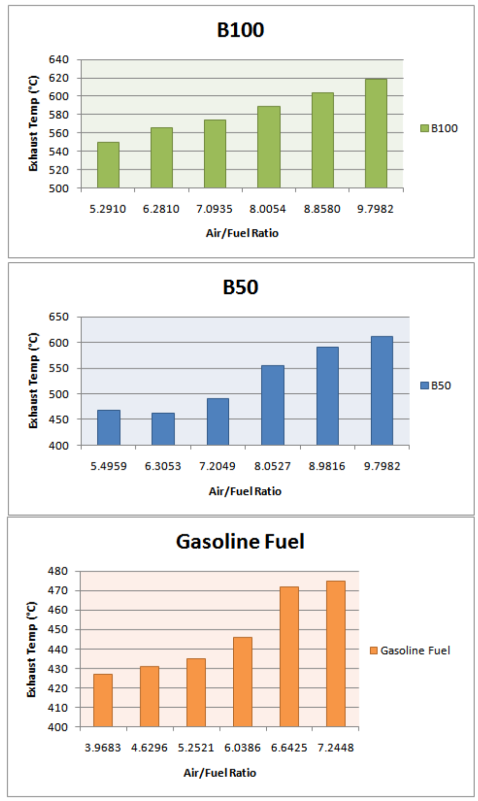

Figure 4 the Relationship between Air/Fuel Ratio and the Exhaust Temperature

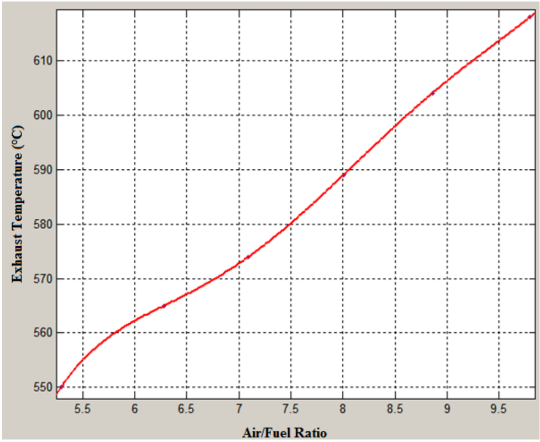

Figure 5 the 5th degree Polynomial Fit to Actual Data for B100

Figure 5 shows a best fitting curve based on the 5th degree polynomial using the Matlab Curve Fitting Toolbox. The equation shows in (15) and also evaluated the exhaust temperature at the different air/fuel ratio. At the air/fuel ratio 5:1, 6:1, and 7:1 the exhaust temperature (°C) was 539.527, 562.225, and 572.752.

$$f(x) = p1 \cdot x^5 + p2 \cdot x^4 + p3 \cdot x^3 + p4 \cdot x^2 + p5 \cdot x + p6 \quad (15)$$

Coefficients:
- p1 = 0.1928
- p2 = -7.674
- p3 = 120.5
- p4 = -932.8
- p5 = 3567
- p6 = -4849

Goodness of fit:
- SSE: 4.46e-021
- R-square: 1

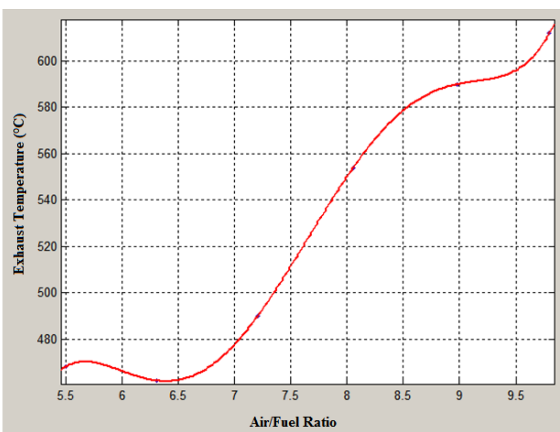

Figure 6 the 5th degree Polynomial Fit to Actual Data for B50

It is same way with B50. Figure 6 shows the 5th degree polynomial for B50. And the equation shows in (16) and also evaluated the exhaust temperature at the different air/fuel ratio. At the air/fuel ratio 5:1, 6:1, and 7:1 the exhaust temperature (°C) was 414.552, 466.089, and 477.776.

$$f(x) = p1 \cdot x^5 + p2 \cdot x^4 + p3 \cdot x^3 + p4 \cdot x^2 + p5 \cdot x + p6 \quad (16)$$

Coefficients:
- p1 = 2.723
- p2 = -103.4
- p3 = 1548
- p4 = -1.141e+004
- p5 = 4.139e+004
- p6 = -5.873e+004

Goodness of fit:
- SSE: 1.876e-019
- R-square: 1

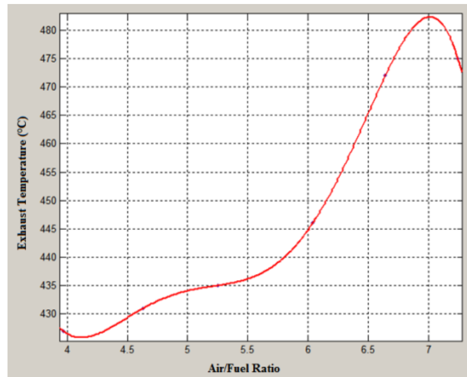

Figure 7 the 5th degree Polynomial Fit to Actual Data for Gasoline

It is same way with gasoline fuel. Figure 7 shows the 5th degree polynomial for gasoline fuel. And the equation shows in (17) and also evaluated the exhaust temperature at the different air/fuel ratio. At the air/fuel ratio 5:1, 6:1, and 7:1 the exhaust temperature (°C) was 434.006, 444.812, and 482.269.

$$f(x) = p1 \cdot x^5 + p2 \cdot x^4 + p3 \cdot x^3 + p4 \cdot x^2 + p5 \cdot x + p6 \quad (17)$$

Coefficients:
- p1 = -4.576
- p2 = 123.4
- p3 = -1315
- p4 = 6927
- p5 = -1.805e+004
- p6 = 1.903e+004

Goodness of fit:
- SSE: 1.609e-020
- R-square: 1

Table 3 Evaluate Exhaust Temperature at different Air/Fuel Ratio

Fuel Type	Air/Fuel Ratio		
	5:1	6:1	7:1
B100	539.527 °C	562.225 °C	572.752 °C
B50	414.552 °C	466.089 °C	477.776 °C
Gasoline	434.066 °C	444.812 °C	482.269 °C

Table 3 shows the evaluate exhaust temperature at different air/fuel ratio based on the method of least squares for the exhaust temperatures.

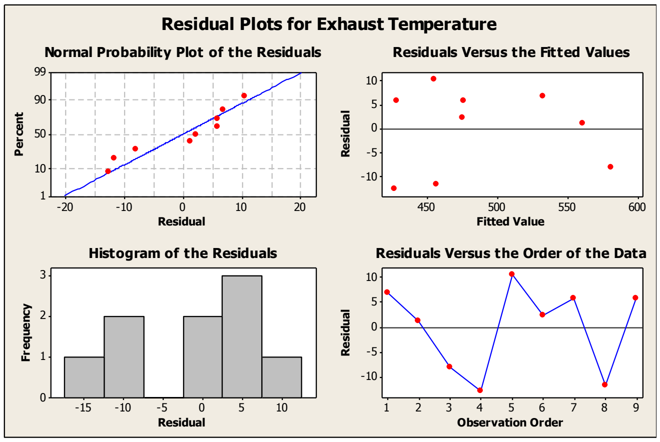

Figure 8 Residual Plots for Exhaust Temperature

Figure 8 shows a residual plot for exhaust temperature. At the first figure shows a normal probability plot of the residuals, there is no severe indication of non-normality, nor is there any evidence pointing to possible outliers.

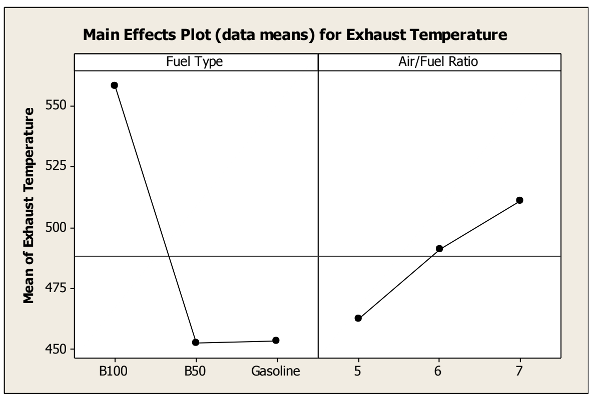

Figure 9 Main Effects Plot (data means) for Exhaust Temperature

Figure 9 shows the main effects plot for exhaust temperature. On the factor of fuel type, the B50 and Gasoline fuel are similar. The factor of fuel type and the factor of air/fuel ratio have a significant effect on the exhaust temperature for the source of variation with 95% of confidence.

Table 4 ANOVA Table for the Exhaust Temperature

Source	*DF*	*SS*	*MS*	*F*	*P*
Fuel Type	2	22012.3	11006.2	73.66 > 6.94	0.001
Air/Fuel Ratio	2	3523.0	1761.5	11.79 > 6.94	0.021
Error	4	597.7	149.4		
Total	8	26133.0			

Table 4 shows the analysis of variance (ANOVA) for the exhaust temperature. The null hypothesis for this study is that all the exhaust temperatures are equal, does not affected by fuel type and air/fuel ratio.

If $P \leq \alpha$ or $F > F_{0.05,2,4} = 6.94$, reject the null hypothesis. Set $\alpha = 0.05$, because $F_{0.05,2,4} = 6.94$, so we conclude that the factor of fuel type and the factor of air/fuel ratio have a significant effect on the exhaust temperature for the source of variation with 95% of confidence. Based on the *P* value the factor of fuel type had more significant effect on the exhaust temperature.

CONCLUSION

Based on the analysis of particle characteristics, design of experiment, and analysis of variance (ANOVA), the major accomplishments of the research can be concluded as follows:

1. Three different types of fuel, B100, B50, and gasoline fuel were successfully tested using advanced instrumentation Combustion Laboratory Unit C491.
2. Use the method of least squares to reduce the noises and based on the 5^{th} degree order polynomial to evaluate the exhaust temperature at the different air/fuel ratio 5:1, 6:1 and 7:1.
3. Set the type of the fuel and the air/fuel ratio as factor and the data was statistically analyzed using analysis of variance (ANOVA).
4. The *P* value for the fuel type was 0.001 and the air/fuel ratio was 0.021.
5. Based on the *P* value the factor of fuel type had more significant effect on the exhaust temperature.
6. The factors of fuel type and air/fuel ratio both have significant effect on the exhaust temperature for the source of variation with 95% of confidence.

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