Exhaust Temperature Analysis of Biodiesel Fuels Using MATLAB

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Abstract

The primary goal of the engineering curriculum is to provide the student with necessary skills to perform effective problem solving. Another goal is to teach undergraduate & graduate students how to transition from textbook problems to realistic engineering problems and processes. Students in the Industrial Engineering Department at Morgan State University, participate in ongoing projects at the laboratories of Center for Advanced Energy Systems & Environmental Control Technologies (CAESECT). The biodiesel experiments were designed to study combustion of B50 and B100 fuels using different air/fuel ratio. Students monitor exhaust temperatures of combustion gases and analyze them using MATLAB and statistical method.

Introduction

The engineering experimental design class was offered in industrial engineering department. In the class, the analysis of variance (ANOVA) and design of experiments were introduced to the students. At the end of the semester, all the students were required to do a project, and this project is one of the projects. In this project, the combustion laboratory unit C491 was used to test the canola biodiesel, and the test results were analyzed using the analysis of variance (ANOVA) method and MATLAB.

Biodiesel is a domestic, renewable fuel for diesel engines derived from natural oils like soybean oil, and which meets the specifications of ASTM D 6751. Biodiesel can be used in any concentration with petroleum based diesel fuel in existing diesel engines with little or no modification. Biodiesel is not the same thing as raw vegetable oil. It is produced by a chemical process which removes the glycerin from the oil. Biodiesel is a fuel comprised of mono-alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, designated B100, and meeting the requirements of ASTM D 6751.[1, 2] Biodiesel Blend is a blend of biodiesel fuel meeting ASTM D 6751 with petroleum-based diesel fuel, designated BXX, where XX represents the volume percentage of biodiesel fuel in the blend.[3] Biodiesel, as defined in D 6751, is registered with the US EPA as a fuel and a fuel additive under Section 211(b) of the Clean Air Act. Biodiesel is typically produced by a reaction of a vegetable oil or animal fat with an alcohol such as methanol or ethanol in the presence of a catalyst to yield mono-alkyl esters and glycerin, which is removed. [4, 5]

The biodiesel used in the experiment was canola oil. B100 is 100% canola oil, and B50 is 50% canola oil and 50% petroleum diesel. The canola biodiesel and the petroleum diesel shows in Figure 1.

Figure 1. Picture view of the Canola Biodiesel and the Petroleum Diesel

Experimental Facility

The Combustion Laboratory Unit C491 is use to conduct the experiment.[6] Figure 2 shows the Solidworks model of the combustion part for the biofuel testing facility Combustion Laboratory Unit C491. Two kinds of biodiesel blends will be used to do the test.

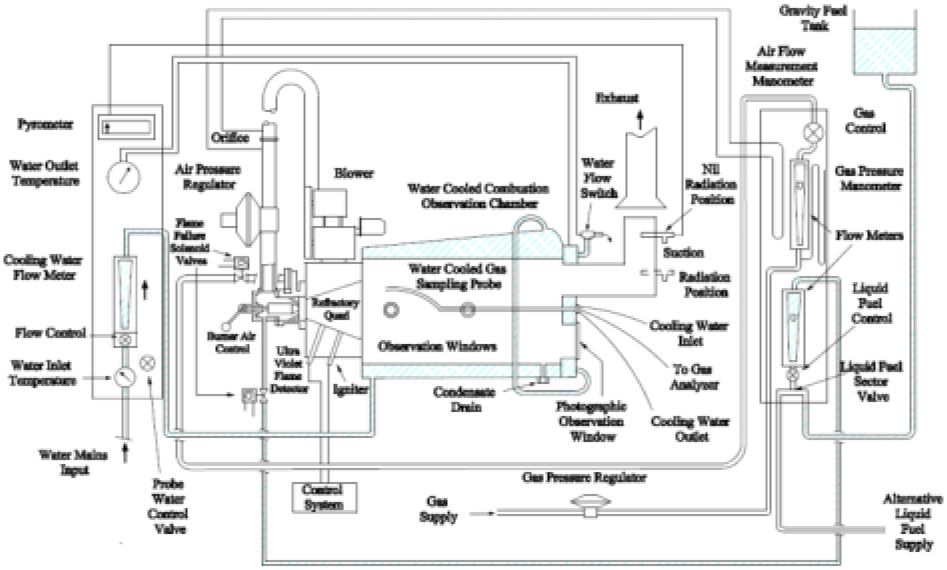


Figure 2. The Proposed Equipment Diagram of for Biomass Sample Testing

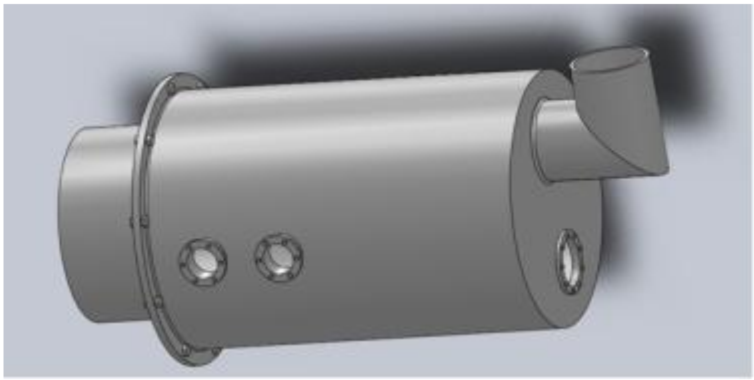


Figure 3. The 3D Solidworks Model of Combustion part for the C491

Scientific Methodology

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. [7]

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. [8]

This paper will apply the 5th degree order polynomial to fit data values using Matlab Curve Fitting Toolbox. When using an 5th degree polynomial equation 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.

$$y = p1 * x^5 + p2 * x^4 + p3 * x^3 + p4 * x^2 + p5 * x + p6 \qquad \text{(Equation 1)}$$

$$\Pi = \sum_{i=1}^{n} \left[y_i - f(x_i) \right]^2 = \sum_{i=1}^{n} \left[y_i - (p1 * x^5 + p2 * x^4 + p3 * x^3 + p4 * x^2 + p5 * x + p6) \right]^2 = \min \qquad \text{(Equation 2)}$$

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.

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. [9, 10]

$$SS_T = \sum_{i=1}^{a}\sum_{j=1}^{b} y_{ij}^2 - \frac{y_{..}^2}{N} \qquad \text{(Equation 3)}$$

$$SS_A = \frac{1}{b}\sum_{i=1}^{a} y_{i.}^2 - \frac{y_{..}^2}{N} \qquad \text{(Equation 4)}$$

$$SS_B = \frac{1}{a}\sum_{j=1}^{b} y_{.j}^2 - \frac{y_{..}^2}{N} \qquad \text{(Equation 5)}$$

$$SS_E = SS_T - SS_A - SS_B \qquad \text{(Equation 6)}$$

In this experiment, two factors were considered as the affecting factors. They were fuel type and the air/fuel ratio. Two fuel types, B100 and B50, were compared. The air/fuel ratios examined were 5:1, 6:1, and 7:1

Results and Discussion

This paper focuses on the thermal efficiency aspects of the two fuels. The two fuels are B100, B50 biodiesel 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 parameters to see which parameter has the most significant effect on the exhaust temperature.[11] Table 2 shows the experiment result.

Table 2. Summary of the Test Result

Item	Exhaust Temp (℃)	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

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 (℃) and the y-axis is the air/fuel ratio.

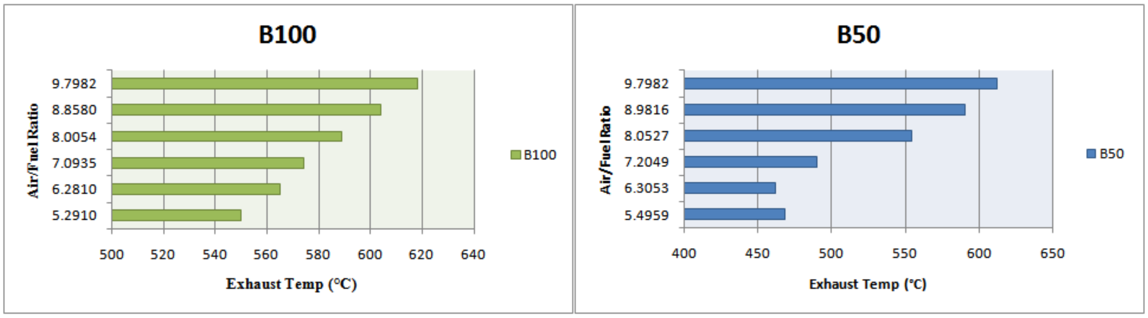


Figure 4. the Relationship between Air/Fuel Ratio and the Exhaust Temperature

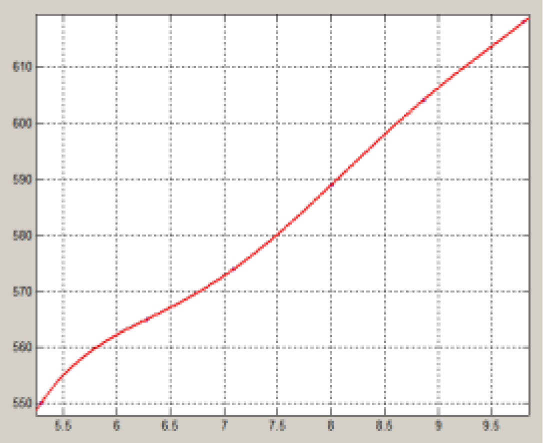
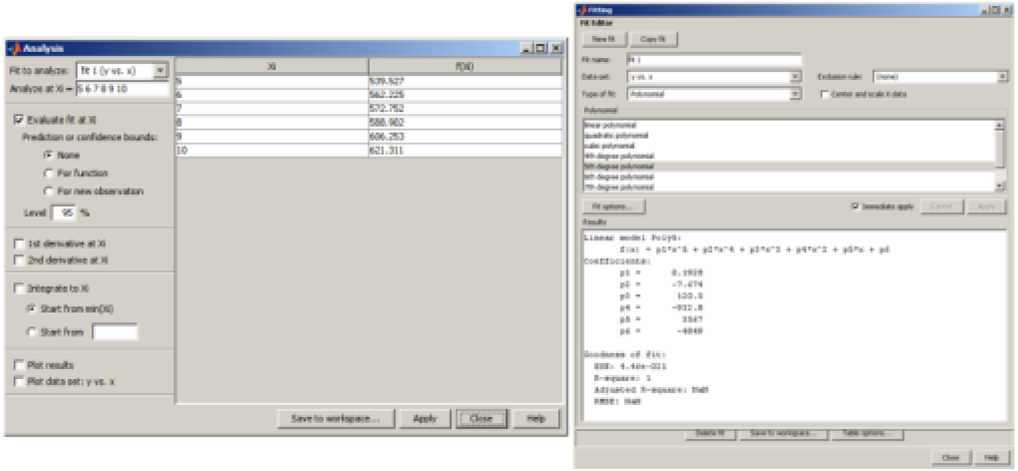


Figure 5. the 5th degree Polynomial Fit to Actual Data for B100

Figure 5 shows a best fitting curve based on the 5^{th} degree polynomial using the Matlab Curve Fitting Toolbox.



Fit to analyze: fit 1 (y vs. x)
Analyze at Xi = 5 6 7 8 9 10

☑ Evaluate fit at Xi
Prediction or confidence bounds:
● None
○ For function
○ For new observation
Level 95 %
☐ 1st derivative at Xi
☐ 2nd derivative at Xi
☐ Integrate to Xi
● Start from min(Xi)
○ Start from
☐ Plot results
☐ Plot data set: y vs. x

Xi	f(Xi)
5	539.527
6	562.225
7	572.752
8	588.902
9	606.253
10	621.311

Fit name: fit 1
Data set: y vs. x
Exclusion rule: (none)
Type of fit: Polynomial
☐ Center and scale X data

linear polynomial
quadratic polynomial
cubic polynomial
4th degree polynomial
5th degree polynomial
6th degree polynomial
7th degree polynomial

```
Linear model Poly5:
     f(x) = p1*x^5 + p2*x^4 + p3*x^3 + p4*x^2 + p5*x + p6
Coefficients:
```

Figure 6. Polynomial Function of the Fifth Degree in Matlab for B100

Figure 6 shows the 5^{th} degree polynomial for B100. And the equation shows blow 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 (℃) was 539.527, 562.225, and 572.752.

$$f(x) = p1*x^5 + p2*x^4 + p3*x^3 + p4*x^2 + p5*x + p6 \qquad \text{(Equation 7)}$$

Coefficients:		Goodness of fit:
p1 =	0.1928	SSE: 4.46e-021
p2 =	-7.674	R-square: 1
p3 =	120.5	
p4 =	-932.8	
p5 =	3567	
p6 =	-4849	

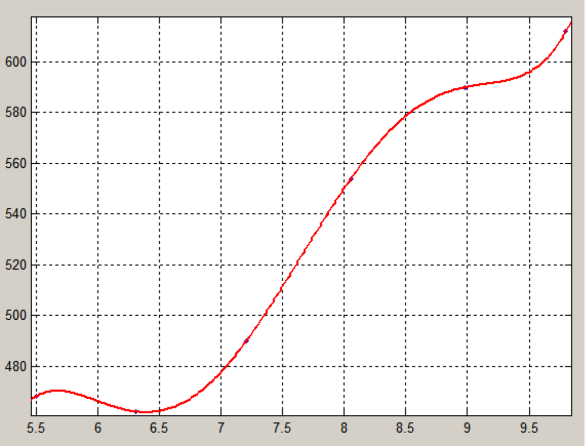


Figure 7. the 5th degree Polynomial Fit to Actual Data for B50

It is same way with B50. Figure 7 shows the 5th degree polynomial for B50. And the equation shows below 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 (℃) was 414.552, 466.089, and 477.776.

$$f(x) = p1*x^5 + p2*x^4 + p3*x^3 + p4*x^2 + p5*x + p6 \qquad \text{(Equation 8)}$$

Coefficients:		Goodness of fit:
p1 =	2.723	SSE: 1.876e-019
p2 =	-103.4	R-square: 1
p3 =	1548	
p4 =	-1.141e+004	
p5 =	4.139e+004	
p6 =	-5.873e+004	

Table 3. Evaluate Exhaust Temperature at different Air/Fuel Ratio

Fuel Type	**Air/Fuel Ratio**		
	5:1	**6:1**	**7:1**
B100	539.527 ℃	562.225 ℃	572.752 ℃
B50	414.552 ℃	466.089 ℃	477.776 ℃

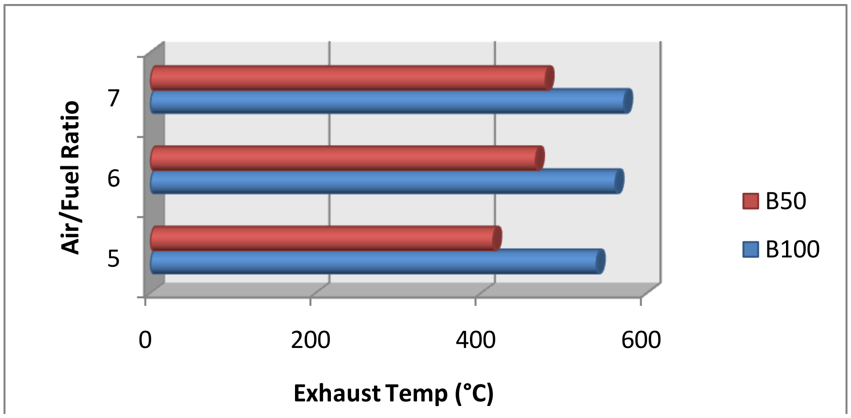


Figure 8. Bar-chart for the Evaluated Exhaust Temperature at different Air/fuel Ratio

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 shows the bar-chart for the evaluated exhaust temperature at different air/fuel ratio. Based on the figure, the exhaust temperature between B100 and B50 has a significant difference.

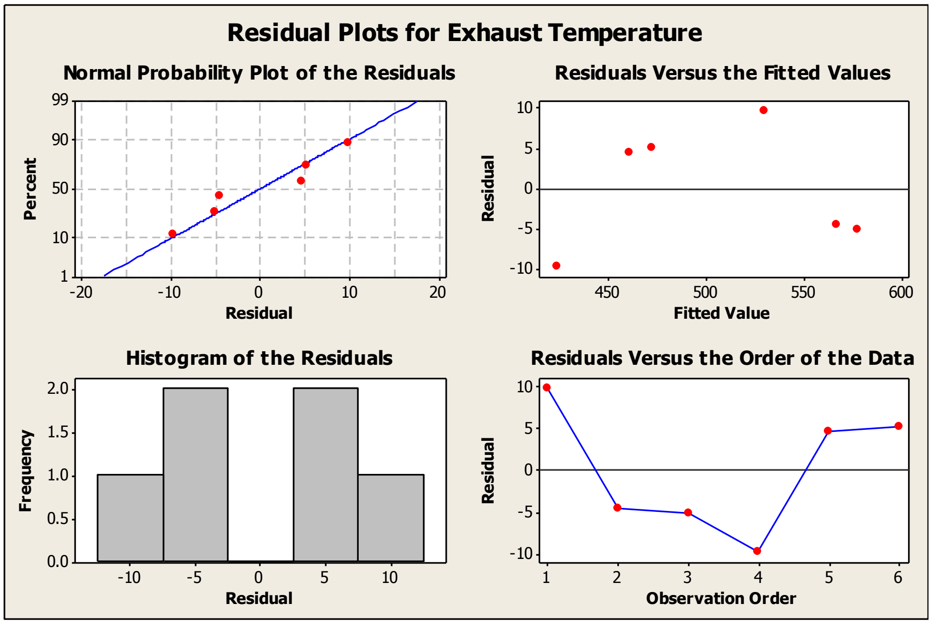


Figure 9. Residual Plots for Exhaust Temperature

Figure 9 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.

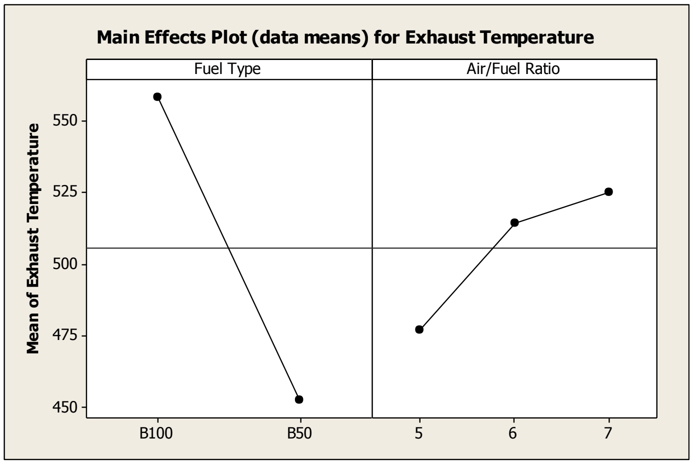


Figure 10. Main Effects Plot (data means) for Exhaust Temperature

Figure 10 shows the main effects plot for exhaust temperature. The parameter of fuel type and the parameter of air/fuel ratio have a significant effect on the exhaust temperature. And the parameter of fuel type has more significant affects on the exhaust temperature than the parameter of air/fuel ratio.

Table 4. ANOVA Table for the Exhaust Temperature

Source	*DF*	*SS*	*MS*	*F*	*P*
Fuel Type	1	16651.8	16651.8	115.31 > 18.51	0.009
Air/Fuel Ratio	2	2551.1	1275.6	8.83 < 19.00	0.102
Error	2	288.8	144.4		
Total	5	19491.8			

Table 4 shows the analysis of variance (ANOVA) for the exhaust temperature. If $\alpha = 0.05$. Because $F_{0.05,1,2} = 18.5128$ and $F_{0.05,2,2} = 19.00$, so we conclude that the parameter of fuel type has a significant effect on the exhaust temperature for the source of variation with 95% of confidence.

Conclusion

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

1. Two different type of biodiesel fuel, B100 and B50, 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 parameter and the data was statistically analyzed using analysis of variance (ANOVA).

4. Based on the main effect plot for exhaust temperature, the parameter of fuel type has more significant affects on the exhaust temperature than the parameter of air/fuel ratio.
5. The p-value of fuel type was 0.009 and air/fuel ratio was 0.102.
6. Based on the p-value the parameter of fuel type had a more significant effect on the exhaust temperature.
7. The parameter of fuel type has a significant effect on the exhaust temperature for the source of variation with 95% of confidence.

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