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Used Vegetable Oil Fuel Blend Comparisons Using Injector Coking in a DI Diesel Engine.

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Summary. An imaging system was used to compare injector coking when used vegetable oil from local grocery store deli fryers was used as a diesel fuel replacement in small proportions. Fuel blends containing from 2.5% to 20% used vegetable oil were studied to determine which oil fuel blend would be optimal for future engine testing. The 2.5% oil fuel blend had injector coking levels slightly more than that of diesel fuel, while higher blends tended to have significantly higher injector coking levels.

Keywords. Alternative Fuels, Biodiesel, Engine Tests, Fuel oils, Injector Coking, Machine Vision, Vegetable Oils.

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Abstract

An injector imaging system was redesigned to evaluate the effects of using vegetable oil fuel blends in a 2.2L, direct injected, Kubota engine. The imaging system was retro fitted with a new injector holder to decrease imaging errors. The imaging system was also modified by altering the existing light filter to eliminate injector silhouette blurring. These modifications reduced the coked area measurement error to less than 0.44%, greatly increasing the reliability of the machine vision system.

The improved injector imaging system was then used to compare the effects of using used vegetable oil from local grocery store deli fryers was used as a diesel fuel replacement in small proportions. Fuel blends containing from 2.5% to 20% used vegetable oil were studied to determine which oil fuel blend would be optimal for future engine testing. Injector coking levels for the oil fuel blends in question were compared with injector coking levels for 100% diesel to assess the effects of combustion chamber carbonization. The 2.5% oil fuel blend had injector coking levels slightly more than that of diesel fuel, while higher blends tended to have significantly higher injector coking levels. The injector coking data was then used to select an appropriate oil fuel blend for future long term engine durability testing.

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Introduction

Since the invention of the diesel engine vegetable oils[2] have been considered as an alternative for diesel fuel. Since 1979 the University of Idaho has been involved with studying the use of vegetable oils as alternative fuel sources (Peterson, 1980). Short term tests have shown that raw vegetable oils can be used as diesel fuel substitutes while longer term tests indicate that injector coking, hard carbon deposits on cylinder components, ring sticking, and thickening of the lubricating oil results from the use of these oils. For most applications, these factors have led to modifying the raw oils into a fuel generally referred to as biodiesel through a chemical process called transesterification.

With heightened environmental concerns and the increasing cost of disposing of vegetable oils that have been used in the food preparation industry there is an increasing interest in using these waste oils as a fuel source. One source of vegetable oils of interest are those used by fast food chains and grocery stores. These stores are wide spread and produce varying but generally small amounts of waste vegetable oil which is usually collected by an oil renderer. To cut disposal costs, these businesses would like information concerning the feasibility of using these raw vegetable oils in the diesel engines of their food delivery fleets as a fuel additive. The intent of this project was to consider the feasibility of using Used Vegetable Oils (UVO)[3] in small amounts (5-10 percent) as a fuel for the small industrial engines used to power refrigeration units

[2]Unless otherwise stated the term vegetable oil refers to unmodified oil. When the esterified oil (biodiesel) is used, the word biodiesel will be used in the description to clearly delineate the oil.
[3]Used vegetable oil in this paper refers to oil that has been used in deep fat fryers such as the deli of a grocery store or restaurant.

on delivery trucks. The specific work reported in this paper refers to fuel injector coking tests with blends of UVO and diesel fuel.

Background

Many studies have been done at the University of Idaho and elsewhere involving the use of used oils as a primary source of energy. Particularly, during the early 1980's many studies were performed that tested the possibility of using vegetable oils as a fuel replacement for diesel fuel.

Engelman et al. (1978), presented data for 10 to 50% soybean oil fuel blends[4] used in diesel engines where the initial results were encouraging. They reported that at the conclusion of a 50-hour test that carbon build up in the combustion chamber was minimal. They concluded that waste soybean oil could be used as a diesel fuel extender with no engine modifications.

Studies done in New Zealand by Sims et al. (1981) indicated that vegetable oils, in particular rape seed oil, could be used as a replacement for diesel fuel. Their initial studies showed that a 50% vegetable oil fuel blend had no adverse effects in short term tests. While in longer term tests they encountered injector pump failure and cold starting problems. Carbon deposits on combustion chamber components was found to be approximately the same as that found in engines operated on 100% diesel fuel. These researchers concluded that rape seed oil had great potential as a fuel substitute, but that further testing was required.

[4]Vegetable oil fuel blends of varying percentages refer to fuels of which raw vegetable oils have been mixed at the indicated percentage with #2 diesel.

Caterpillar (Bartholomew, 1981) reported that vegetable oils could be mixed with diesel fuel at low percentages and not cause engine failure. Short term research showed that blends using 50/50 were successful, but that 20% vegetable oil fuel blends were better.

Other studies done by Barsic et al. (1981), Bettis et al. (1982), Bruwer et al. (1980), Hofman et al. (1981), Peterson et al. (1981), Quick (1980), and Ryan et al. (1984) indicated that while vegetable oil fuel blends had encouraging results in short term testing, problems occurred in long term durability tests. They indicated that carbon build-up, ring sticking, and lubricating oil contamination was the cause of engine failure when vegetable oils are used in high percentages (50% or more) as diesel fuel substitutes.

Due to the problems reported by researchers using raw vegetable oils in the early 1980's, the use of raw vegetable oils was abandoned by most researchers in favor of chemically modified vegetable fuels more commonly known as biodiesel[5]. Thus, in recent years there is little literature concerning the feasibility of using raw vegetable oils as a fuel additive.

To study the effects of using small amounts of UVO in diesel engines it is proposed to use the facilities at the University of Idaho to measure fuel characteristics, perform injector coking tests, and long term engine durability tests. The injector coking test proposed by Korus et al. (1985) is a quick and easily performed test which has been shown to be an effective way of rapidly

[5]Biodiesel is defined as the mono alkyl esters of long chain fatty acids derived from vegetable oils or animal fats, for use in compression ignition (diesel) engines.

screening alternative fuels for potential negative effects on the internal components of diesel engines.

Peterson et al. (1983) observed a loss of power when 100% sunflower oil was used in a short term engine performance test which included operating the engine at maximum torque for fifteen minutes. This loss of power was attributed to hard carbon deposits in the combustion chamber and to stuck piston rings. This test caused the researchers to believe that short term tests could be used to predict long term effects. This led to further investigation of how short term tests could be used as a rapid screening test for the long term effects of using vegetable oils as a fuel.

Korus et al. (1985), suggest that an injector coking test be used to evaluate how different raw vegetable oils affected the combustion chamber. Using the 2-hour torque testing sequence suggested by Peterson et al. (1983), a procedure was developed to use injector coking as a rapid screening test for fuel substitutes such as raw vegetable oils. After the test engine had been submitted to the torque test sequence, the injectors were removed and photographed at 16x with a 35 mm camera. The photographs were then enlarged and the coked injector tips measured using an electronic graphics calculator and a Wang System 220 microcomputer. The results of the coked area measurements for alternative fuels were referenced to similar area measurements for a standard diesel fuel. The result was a coking index with diesel fuel as the base line.

This method was later used by Peterson et al. (1987) to measure injector coking with propane fumigation of raw vegetable oils in direct injected engines. The 2-hour torque test proposed by

Korus et al. (1985) was a suitable method to identify the best fuels for further longer term durability testing.

Reid et al. (1989), proposed that the technique used by Korus et al. (1985) and Peterson et al. (1987) be improved by using computer vision technology. Their proposed injector coking method used an engine testing sequence that differed both in set-up and duration from Peterson's torque test (Peterson et al., 1983). After being subjected to their revised rapid test procedure, the injectors were measured using video imaging technology. Just prior to measuring the coking of the injectors, the researchers would manually remove all soft carbon deposits from the injector tips. The injectors were then measured at several locations that lined up with injector tip orifices. Reid et al. (1989) also suggested that a clean reference injector be measured with each set of test injectors to correct for set-up errors. In their method, the area of the clean injector was subtracted from the dirty injector area, leaving only the coked area for the test fuel. The coked areas from the alternative fuels were compared to a diesel fuel reference area to create a coking index.

Goodrum et al. (1996) combined the Peterson et al. (1983), Korus et al. (1985) and the Reid et al. (1987) methods for analyzing injector coking. Goodrum et al. (1996) used Peterson's 2-hour torque test to maximize injector coking. They applied the methods for measuring the injector tips that Korus et al. (1985) suggested using the video technology that Reid et al. (1987) had proposed. By combining these methods, a 2-hour testing sequence was devised to measure injector coking using alternative fuels. Injector silhouette blurring was a problem when using the machine vision system to image the injector tips. Positioning and orientation of the injectors was

also found to be a potential cause of error. Over a four month period of time, the vision system had a standard deviation of 0.2% for a typical reference injector, and was used to compare injector coking of various fatty acids.

Geller et al. (1999) adopted Goodrum's method for their analysis of modified vegetable oils. Geller et al. (1999) stated that the experimental precision of the screening tests supported the validity of the methods established earlier by Korus et al. (1985) and Goodrum et al. (1996).

McDonnell et al. (1998) used a slightly different method to quantify injector coking. They used an accelerated engine testing procedure developed by Virk et al. (1991). This test used fuel injectors modified by decreasing the injector needle opening pressure by 20%. The testing procedure used was a steady state test where the engine was operated at 75% speed and 75% power for twenty-five minutes. The injectors were removed and inspected by measuring the carbon "trumpets" around each of the injector orifices. The injectors were first disassembled and then with a light placed in the injectors, the individual orifices were measured using a machine vision system. This method was reported to be an accurate and repeatable means of measuring injector fouling, as they were able to analyze each injector orifice. Although the method is accurate at measuring injector coking, it requires that the injectors be modified prior to use, and it requires that the injectors be disassembled after each test unlike the previous methods discussed.

Objectives

1. Improve methods for analyzing injector coking in direct injected diesel engines using short term engine tests.
2. Study the effects of used vegetable oil fuel blends as a replacement for diesel fuel in a 2.2 liter four cylinder, DI, Kubota engine.
3. Use short term testing results to find an optimal vegetable oil blending percentage based upon injector coking for future long term durability testing and verification of short term results.

Methods and Procedure

The process developed to quantify injector coking was a compilation of approaches that were discussed earlier. The coked injectors were measured with a machine vision system consisting of a light box and attachments (see Figure 1), a solid state CCD camera, and a Pentium II class computer with an image grabber card. The silhouettes of the coked injector tips were created and quantified using a light box and a CCD camera. The injector tips were imaged while clean

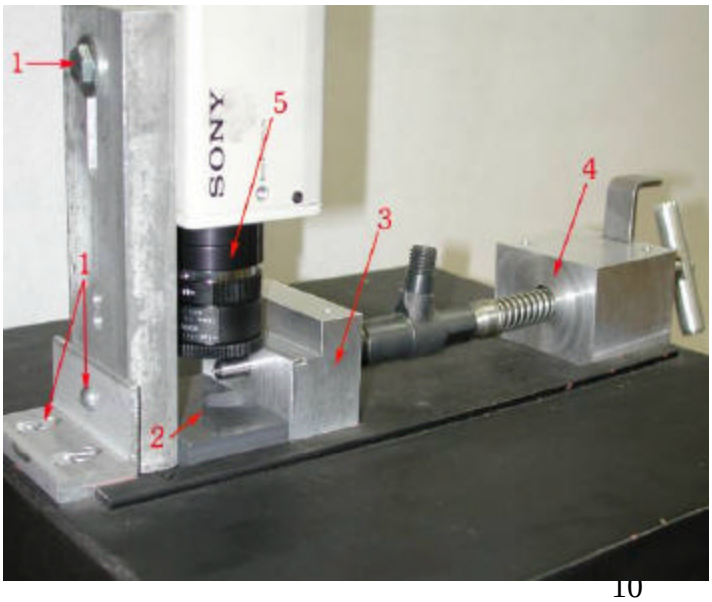


Figure 1 Machine Vision System for measuring injector tips. The major components of the system consist of:

1. Camera mounting and 3-dimensional adjusting screws.
2. Viewing area with plastic cover used to reduce silhouette edge blurring.
3. Injector Cradle.
4. Spring loaded plunger.
5. Sony CCD Camera with 16 mm extension tube and F1.4 lens.

prior to testing, and again after use in the engine. The injectors were cleaned between tests using a soft brass brush. The images, with and without carbon deposits, were compared to get a coked area measurement for each injector.

To create the injector silhouettes a 30.5x30.5x20.3 cm light box was constructed. This box contained a 15-Watt white fluorescent light bulb which was positioned directly underneath the viewing area. The viewing area consisted of a light filter approximately 5 cm in diameter. The filter was made using multiple layers of vellum placed between two pieces of clear plastic. The CCD camera was placed directly above the viewing area using a mounting bracket that was adjustable in the x, y, and z planes, see Figure 1. The camera, thus mounted, could be positioned directly over the tip of the injector. A Sony CCD black and white camera, with a F1.4 (16 mm) lens and a 16 mm extension tube, was used for imaging the injectors.

The light filter did not completely eliminate the scattered light rays from the fluorescent bulb which caused the edges of the injector silhouettes to be blurred, a problem also noted by Ried et al. (1989). The light filter was modified by placing a covering made of a 1.3 cm thick piece of gray opaque plastic from which a section in the shape of an injector tip had been removed. The cut out portion of the cover was directly beneath and approximately twice the size of the injector tip. See Figure 1, component number 2 to see the plastic cover on the viewing area. The plastic cover blocked the refracted light rays and eliminated the edge blurring due to the backlighting.

An injector cradle was developed that allowed for precise positioning of the injector each time it was measured. This holder was milled out of a 3.2x6.4x4.5 cm aluminum block. A series of

holes were milled in the center of the block, which were the same dimensions as that of the injector. The holes were then enlarged 0.051 mm so that the injector would turn freely in the cradle without any side to side motion. To allow the camera to be positioned directly over the injector, the block had a notch cut in it. Thus allowing the camera to be positioned 9.5 mm above and centered directly over the tip of the nozzle. The finished injector cradle is shown in Figure 1 as component 3. The cradle was attached to the light box by using screws and mounting rails. This was done so that cradles for different injector styles could be installed on the same light box with ease. After milling the cradle, it was scribed with three indicator marks to locate the measuring points, see Figure 2. To ensure that the injector remained snug in the cradle, a spring-loaded plunger was mounted behind the injector cradle, see Figure 1, component 4. The plunger held the injectors firmly in place with a force of 17.8 N.

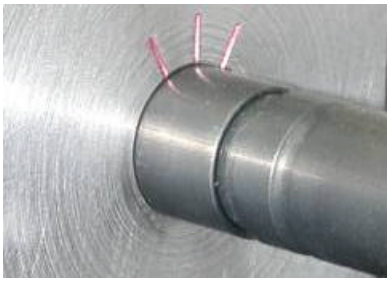


Figure 2 Close-up of the injector cradle showing the orientation marks use to position the injectors for measurement.

The Imaging System consisted of a DIAS Image Grabber Card, and an Ag Vision Imaging Software Package (Decagon Corp, Pullman, Washington). The PCI card was installed on a Pentium II class computer and connected to a video monitor. The Ag Vision software allowed the operator to select the gray scale cutoff level that would provide the sharpest image. Based upon the camera and lighting system that were used, a 170 grayscale threshold was selected. With the grayscale set, the software was used to capture, save, and measure the area of the injector silhouettes.

Injectors were placed in the cradle and measured, as described, at three orientations. The locations of the measurements were dependant upon a mark that had been randomly scribed on each injector prior to testing, and the marks on the cradle. The injectors were measured nine times, with three readings being taken at each of the 30 degree locations on the cradle. The injector images were simultaneously photographed with a digital camera for visual inspection and comparison as the particular machine vision software used did not allow for saving viewable digital images.

To correct for instrumentation drift, the method suggested by Goodrum et al. (1996) was adopted. Their method allows for direct comparison of test results over a several month time period. The approach was to measure a reference injector just prior to and after measuring each set of test injectors. The reference injector measurements were then used to adjust the test injector measurements for changes in the imaging system due to drifting and set-up error. A given test injector area, INJ_i, was corrected by comparing the averages of reference injector value, INJ_r, to the original reference injector value, INJ_o as follows:

$$INJ_c = INJ_i \frac{INJ_o}{INJ_r} \quad \textbf{(0)}$$

The test injectors were measured before testing and then again after use with a specific fuel type. The measurements taken were averaged, corrected for drifting, and then converted to a coking index number (CI) which was based upon the average diesel coked area. With the measurements averaged and corrected for drifting, the clean injector area was subtracted from the dirty injector

area, leaving only the coked area. The coked area was then converted to the coking index as follows:

$$CI_i = \frac{cokedarea_i}{cokedarea_{D2}} \quad \textbf{(0)}$$

Where CI_i is the coking index number for the given injector, and $cokedarea_i$ is the injector area being compared to the reference diesel coked area, $cokedarea_{D2}$. This measuring system was then used to measure and compare coked areas for several fuel types.

The tests were run on a 2.2 L, Kubota four cylinder, industrial V2203, direct injected, diesel engine with a Rockford Power Take Off. The load cell used was a 40 hp hydraulic dynamometer. The dynamometer and engine were controlled using a Pentium class computer that had been programmed with the engine testing routine. The engine testing routine used was one very similar to the 2-hour torque test suggested by Peterson et al. (1983) where the test engine was run for ten minutes at 2500, 2300, 2100, 1900, 1700, and 1500 rpm on the test fuel at max torque with a ten minute warm-up and cool-down interval on diesel fuel at low idle.

The fuels tested were blends of used hydrogenated canola and soybean oils (UVO) collected from an Albertsons, Inc. deli fryer. The canola and soybean oils were blended with diesel fuel on a volumetric basis at the following percentages: 0% oil, 2.5% oil, 5% oil, 10% oil, 15% oil, and 20% oil. Also tested were two fuels consisting respectively of 10% Hydrogenated Canola Methyl Ester(HyCME) and 10% Hydrogenated Soybean Methyl Ester(HySME). The coking tests were run for each of the 14 different blends as well as again for the six soybean oil fuel

blends and the 10% HySME fuel blend which were tested a second time at an elevated fuel temperature of 35EC. This design resulted in a total of 21 different coking tests.

The fuel blends used in this testing procedure were each prepared from one of two UVO samples taken from a chicken fryer at a local grocery store. Prior to mixing, the UVO was filtered with a 2 micron fuel filter to remove remaining particulate matter. The UVO was then mixed with a Phillips certified 0.05 LS type 2 diesel to obtain the required blends. The waste hydrogenated canola oil was liquid at room temperature which allowed for mixing at room temperature. The waste hydrogenated soybean oil was about 70% solid at room temperature, requiring that it be heated before blending with diesel. The UVO was also converted into a methyl ester using the recipe outlined by Peterson, C. L. (1998). The methyl esters, HyCME and HySME, were then mixed with the same certified diesel to create a 10% biodiesel-diesel blends.

The engine test procedure began by warming the engine for 10 minutes at low idle (1100 rpm) on the test fuel. A common torque test was used to produce injector coking where the engine speed ranged from 2400 to 1500 rpm at 100 rpm increments. The engine was held at each increment for 10 minutes. The engine was returned to low idle for ten minutes for a cool down cycle. The engine was run at full throttle for the duration of the test with the speed being controlled by increasing the load on the hydraulic dynamometer. The computer, using a program written in C++, completely controlled the torque test using a speed sensor, a load sensor, and throttle controls. The program was designed and used to remove human error and variability in testing by making the torque tests identical for each test fuel. Temperature sensors were used to monitor the engine water, oil, air intake, and exhaust temperatures. All parameters were

measured and recorded at two minute intervals. The computer control screen allowed for user input and displayed runtime results as shown in Figure 3. After the 2-hour test procedure was completed, the engine was shut down and allowed to cool before the injectors were removed and measured. The fuel lines were drained and the fuel filters replaced prior to testing each fuel to eliminate fuel contamination. The test was repeated for each of the fuels under consideration with a clean set of injectors.

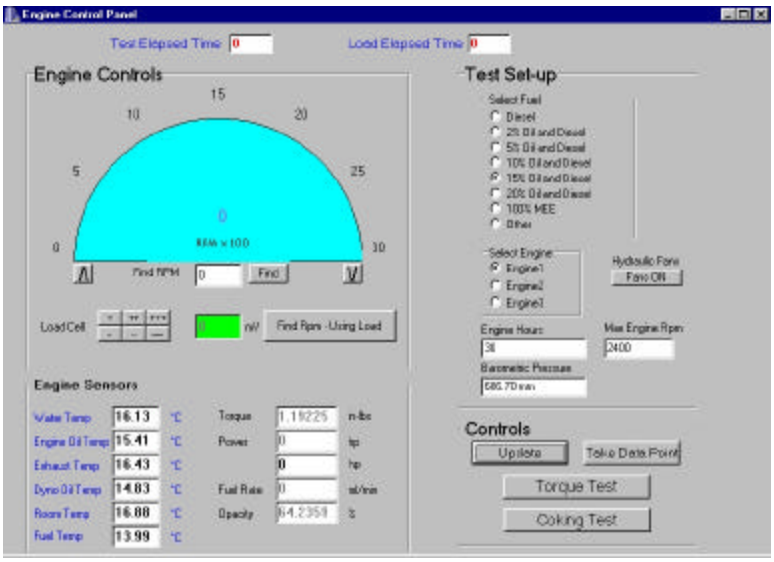


Figure 3 Custom computer control panel for running torque and coking tests on direct injected diesel engines.

Results

The injector holder and camera provided precise measurements of the test injectors using the Ag-Vision software. It was possible to measure each injector three times at three locations in approximately five minutes. A typical clean injector tip is shown in Figure 4. Note the very crisp injector silhouette and the distinct difference in the pixel gray scale along the edge of the injector tip. One injector was designated as the reference injector prior to fuel testing and was measured repeatedly to determine the stability of the vision system. The reference injector was

measured at the start and finish of every test session providing data for analyzing the performance of the new injector measuring equipment. The precision of the new injector holder and imaging software is shown in Table 1. The data shows how the area of the calibration injector varied over time. The area was averaged for each session and used to calculate the standard deviation over time for the imaging apparatus. It can be seen from the data that the system drifted less than ±175 pixels for the month under consideration. The resulting standard error for the system was # 0.44%.

Figure 4 A Clean injector silhouette from the new Injector Imaging System.

Figure 5 shows a typical coked injector tip. Note the difference in the shape and size of the injector tip from that of the injector shown in Figure 4. The difference in the silhouette area can be seen by the naked eye at this level of magnification. The shape and size differences are attributed to both soft and hard carbon deposits which resulted from the 2-hour torque procedure. These clean and coked injector tip silhouettes were compared to find the net coked areas.

TABLE #1

Reference Injector Areas using the New Injector Imaging System. Measurements taken over a span of a month.

Test #	Start	Finish	Daily Avg.
1	39742	39763	39753
2	39790	39828	39809
3	40229	40118	40174
4	40234	40118	40176
5	40103	39880	39991
6	40274	39873	40073
7	40197	40043	40120
8	40037	40083	40060
9	39950	40022	39986
10	39790	39828	39809
11	40191	40188	40190
12	39992	39971	39981
13	39977	39665	39821
14	40716	39971	40344
Test Average			**40021**
Std deviation			**175**
Error			**0.44%**

The injector areas reported in this table are in pixels, the unit of measure for digital photography.

Figure 5 A Coked injector silhouette. Note the highly visible carbon deposits.

The coked injector silhouettes were measured using the Ag-Vision software. The gross coked injector areas were adjusted for equipment drift prior to subtracting the clean injector areas using Equation #1. Table 2 shows the individual injector and average injector coked areas for the fuel combinations tested. The values reported are the net coked areas as the clean injector areas have already been subtracted. Note that the 100% diesel, 10% HyCME and 10% HySME have nearly the same coked area. It can also be seen that the coked area increases as the percentage of raw oil added to the fuel increases. The average coked injector areas were converted to a coking index for ease of comparison using Equation 2. The coking index numbers can been seen in the last column of Table 2.

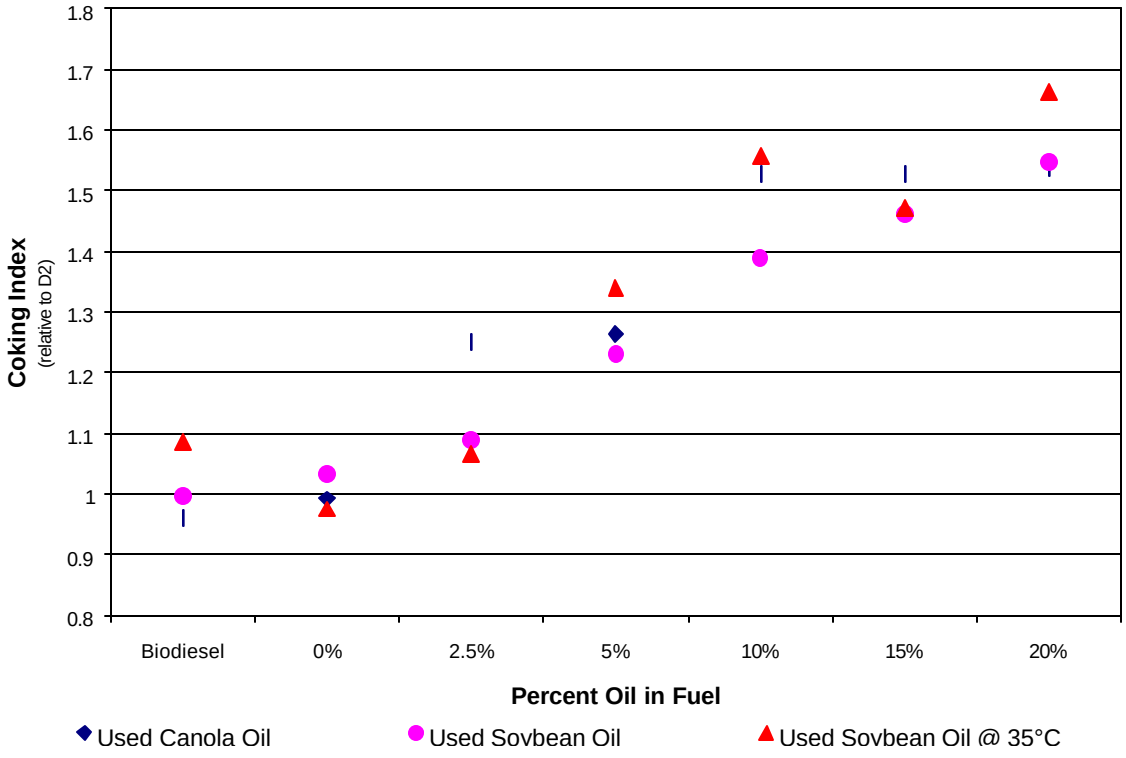
TABLE #2

Total Coked Injector Areas for all fuel combinations evaluated. Areas have been adjusted for equipment errors and the clean area has been subtract. Areas reported in pixels.

	Injector #1	Injector #2	Injector #3	Injector #4	Average	Coking Index
Test Set #1 --- Used Hydrogenated Canola Oil						
100% Diesel	3679	3772	3122	3480	3513	**0.99**
10% HyCME	2658	3679	2954	4316	3401	**0.96**
2.5% Oil	4565	4492	4274	4403	4433	**1.25**
5% Oil	4229	4554	4976	4171	4482	**1.26**
10% Oil	4666	4882	6206	5901	5414	**1.53**
15% Oil	4772	5588	5571	5730	5415	**1.53**
20% Oil	5296	5096	5331	6063	5446	**1.54**
Test Set #2 --- Used Hydrogenated Soybean Oil						
100% Diesel	3296	3862	3820	3674	3663	**1.03**
10% HySME	3348	3407	3916	3445	3529	**1.00**
2.5% Oil	3666	3805	4029	3938	3859	**1.09**
5% Oil	3921	4028	4705	4804	4365	**1.23**
10% Oil	5202	5219	4602	4681	4926	**1.39**
15% Oil	5145	4568	5328	5692	5183	**1.46**
20% Oil	5687	6068	4529	5659	5486	**1.55**
Test Set #3 --- Used Hydrogenated Soybean Oil Heated to 35°C						
100% Diesel	3566	3407	3283	3565	3455	**0.98**
10% HySME	3794	3681	3744	4160	3845	**1.09**
2.5% Oil	4099	3588	3908	3488	3771	**1.06**
5% Oil	4857	4451	4686	4988	4745	**1.34**
10% Oil	5553	5348	5879	5303	5521	**1.56**
15% Oil	5212	4936	5215	5477	5210	**1.47**
20% Oil	6079	5690	5468	6339	5894	**1.66**

Figure 6 is a plot of the Coking Index Values. The plot of the coking index numbers shows that there is not a significant difference in the amount of injector coking based upon the type of oil added to the diesel fuel, thus indicating that canola and soybean oils have similar effects upon the combustion chamber deposits. It is also evident from the plot that there is a relationship between the amount of oil added to the fuel and the amount of coking that forms on the injector tips.

Figure 6 Plot of the coking Index Numbers for all the fuel blends. Note that the 0% oil is equivalent to 100% diesel.



Using the statistical software package SAS, an evaluation of the coking data was done. A model was fit to the data to determine if a significant difference in injector coking existed based upon either the oil type added to the fuel or the amount of oil added. Figure 7 shows the model used to analyze the average injector coked areas from Table 2 based upon oil type. Where the null hypothesis was $\$_1=\$_2=\$_3=0$, and the alternative hypothesis being that some of the $\$$'s were not equal. The results of this analysis based upon a 0.05% confidence level failed to reject the null hypothesis showing no significant difference in the coking areas based upon the oil type. Therefore it could be said that there is no difference in the amount of coking dependant upon the type of oil used in this study.

Figure 7 General Linear Model used for oil type comparison. Where $\$_o$ is the x-axis intercept and $\$_1$, $\$_2$, and $\$_3$ correspond to the three oils used in the test fuel blends.

$$\hat{Y} = \hat{b_0} + \hat{b_1} X_1 + \hat{b_2} X_2 + \hat{b_3} X_3 + E$$

After showing that the oil type had no effect upon injector coking, SAS was once again used to determine the relationship between injector coking and the amount of oil added to the fuel. The Least Squares Difference (LSD) method was used to assess the significant differences in the level of injector coking dependent upon the percent oil in the fuel mixture. The results of the LSD analysis using a confidence level of 95% are given in Table 3 which shows that the 100% diesel, 10% biodiesel, and the 2.5% oil diesel fuel blends are very similar. Although the 2.5% oil fuel blend was found to be statistically different than the 100% diesel fuel. The 10%, 15%, and 20% oil diesel fuel blends are statistically different from the lower percent oil fuel blends. While the 5% blend is statistically different from all the oil fuel blends tested.

TABLE #3

Coked Injector Area Means for the seven fuel combinations evaluated. Means reported in pixels.

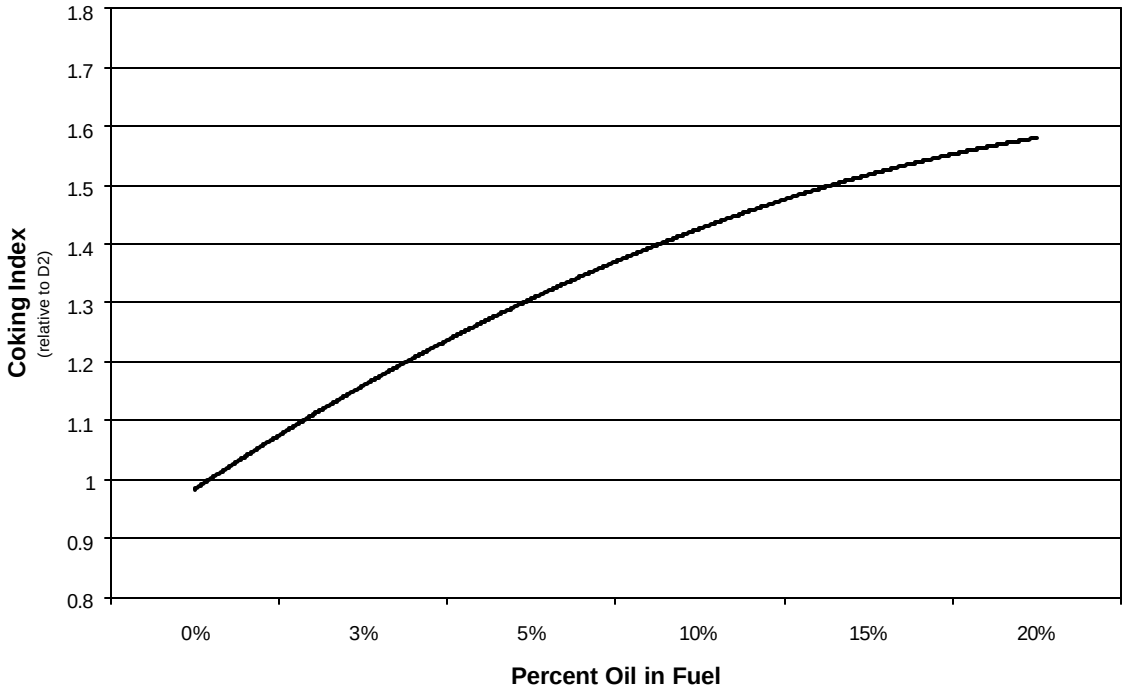
Fuel Blends	Mean Coked Area*
100% Diesel	3544.0a
10% HyCME	3592.0ab
2.5% Oil	4012.3b
5% Oil	4531.0c
10% Oil	5183.3d
15% Oil	5287.3d
20% Oil	5609.0d

*Means followed by the same letter are not significantly different according to the LSD method(P 0.05).

To further study the relationship between the percent UVO used in the oil fuel blends and injector coking, a regression analysis was used. The results of which can be seen in Equation 3. Where Y-hat is the predicted coking index number and X is the percent UVO added to the fuel blend. For the second order relationship shown in Equation 3 the resulting R-squared value is 0.97 indicating that the regression equation is sufficient in predicting coked injector areas. Figure 8 shows the predicted injector coking index values vs. the percent oil in the fuel.

$$\hat{Y} = 0.0141X^2 + 0.2183X + 0.7791 \quad \textbf{(0)}$$

Figure 8 Plot of the predicted coking index vs. percent oil using equation 3.



Discussion

The 2.5% oil fuel blend had injector coking levels very similar to diesel and to the 10% biodiesel fuel blends. The 5% oil fuel blend had injector coking levels slightly higher then the 2.5%, but lower than the 10% and higher oil fuel blends. Injector coking levels for the 10%, 15%, and 20% oil fuel blends were not significantly different. Based on this data 2.5% oil fuel blends would be the best candidate fuel for further durability testing. Oil fuel blends of 5% would be potentially more risky than the 2.5%, but less risky than the higher group of fuels. Oil fuel blends of 10% and higher would be the riskiest fuels to test and would potentially result in some durability problems.

The original project goals were to use 10% oil fuel blends if possible. A test engine was run on a 12% oil fuel blend and based on that test, it has been decided to risk a 10% oil fuel blend test in a

new 2.2L, direct injected, Kubota engine. Results of that test will be the subject of a future paper.

Conclusions

The following are specific conclusions of this test:

1. The injector area measurement error for the machine vision system was reduced to 0.44% by using improved light methods and a new injector holder.
2. Oil fuel blends of 2.5% had injector coking levels similar to diesel and to 10% biodiesel blends.
3. Canola, soybean, and heated soybean oils showed no significant difference in injector coking levels.
4. Oil fuel blends of 5% had injector coking levels between 2.5% and 10% oil fuel blends.
5. Oil fuel blends of 10% and higher had injector coking levels that were not significantly different.
6. A second order regression equation was developed for predicting injector coking in a 2.2L, direct injected, Kubota engine.
7. The injector coking data for 2.5% oil fuel blends indicates that this fuel would be least likely to cause problems in extended engine durability testing.
8. Based upon the results of the injector coking data and initial results from a 12% oil fuel blend durability engine test, a 10% oil fuel blend will be used for future engine durability testing even though the injector coking test indicated significant risk of unacceptable combustion chamber deposits.

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