

Performance of an IDI Engine Fueled with Fatty Acid Methyl Esters Formulated from Cotton Seeds Oils

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ABSTRACT

This study evaluates the performance of an indirect injection (IDI) diesel engine fueled with cotton seed biodiesel while assessing the engine's multi-fuel capability. Millions of tons of cotton seeds are available in the south of the US every year and approximately 10% of oil contained in the seeds can be extracted and transesterified. An investigation of combustion, emissions, and efficiency was performed using mass ratios of 20-50% cotton seed biodiesel (CS20 and CS50) in ultra-low sulfur diesel #2 (ULSD#2). Each investigation was run at 2400 rpm with loads of 4.2 - 6.3 IMEP and compared to the reference fuel ULSD#2. The ignition delay ranged in a narrow interval of 0.8-0.97ms across the blends and the heat release rate showed comparable values and trends for all fuel blends. The maximum volume averaged cylinder temperature increased by approximately 100K with each increase in 1 bar IMEP load but the maximum remained constants across the blends. The gas to cylinder walls radiation and convection heat fluxes for both ULSD#2 and CS50 were 1.8 MW/m² and 2.5MW/m² respectively. The energy specific fuel consumption (ESFC) for CS50 was 4.4% less than ULSD#2 at 6.3 bar IMEP. The indicated thermal efficiency of the engine ranged from approximately 45-50% while the mechanical efficiency ranged from 70-80%. The nitrogen oxide (NO_x) and soot showed minimum values with the CS20 fuel blend. Overall, the study confirmed that concentrations of up to 50% cotton seed biodiesel in ULSD are effective at maintaining performance and efficiency of a small bore IDI engine and the high tolerance of such an engine to biodiesel.

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INTRODUCTION

Currently in the United States the transportation sector consumes 68% of the total liquid energy demand. This demand is expected to rise to 73% by the year 2030 [1]. The possibility of alternative liquid fuels and fuel blends push researchers to explore biological based alternatives, specifically fatty acid methyl esters (FAME). FAME is being evaluated due to its high calorific value, ease of processing, and relatively low cost. As revised by the 2005 Energy Policy Act [2], renewable fuels are required to be blended into existing fuels for transportation and that volume is to increase from 9 billion gallons to 36 billion gallons from 2008 to 2022. Biofuels present a convenient, and easy to implement solution especially if they recycle crop's waste. It has been observed that dependent on engine design, biodiesel-fueled engines produce less carbon monoxide, unburned hydrocarbons (UHC), and particulate emissions compared to engines fueled with ULSD#2 [3]. The EPA states that the combustion of liquid fuel is the 4th leading cause of particulates PM10 and PM2.5,

and carbon monoxide emissions, according to a study performed in 2011[1]. Our study focused on the IDI engine because scarcity of published work and of its potential multi-fuel capability, as well as the investigation of the performance and emission characteristics of CS versus ULSD#2 ran as a base line for all experimental trials.

LITERATURE REVIEW

Environmental concern and the easy availability at the farm's level, renewable fuels still have appeal even when the oil prices drop. Many concerns with moving toward new sources of energy include meeting infrastructure and land requirements while maintaining economic recovery, efficiency, and reduction of environmental impact. Diverse renewable liquid fuel sources can provide the economies self-reliant and self-sufficient no matter the continent and less vulnerable fluctuations in the liquid petroleum market. Diesel alternatives formulated from biomass waste present an immediate and sustainable solution over current fuels. Biodiesel formulated from vegetable

oil or animal fats [4]. Food based biofuels may create food market competition that may increase the price of food and result in a shortage of land used to grow food products [5]. Other associated problems relate to the chemical composition of the compounds with impact on performance [6].

Many biofuels show unfavorably low temperature properties. Cloud point increases with an increasing chain length and increasing saturation, while cetane number also increases as a result of this [7]. During cold weather conditions an increased cloud and pour point causes fuel to thicken and consequently affects the performance of critical engine components such as the filters, fuel pump, fuel lines, and injectors and sprays [8]. Methods to improve the chemical properties have been evaluated extensively. Georgogianni [9] investigated modifications to the formulation process and Knothe [10], investigated the impact of additives on the fuel's performance.

Georgogianni et al [9] investigated the effect of ultrasonic versus mechanical stirring on the transesterification reactions. The results obtained show that the ultrasonic method coupled with higher concentrations of catalyst, specifically 2% NaOH, increase the yield of the process to 94% after just 20 minute reaction time.

Knothe [10] investigated aspects of oxidative stability of biofuels. Approaches to improving the stability of biodiesel include adding anti-oxidants, but this will only delay oxidation. It was concluded that the structure of the compound had the greatest influence on auto-oxidation.

Soloiu et al [6] investigated the combustion parameters of poultry fat FAME blends in an indirect injection diesel engine (IDI). It was concluded that the introduction of up to 50% FAME in ULSD#2 had minimal effect on the engine performance. It was observed that maximum combustion pressure and heat release rates were similar with a negative apparent heat release occurring at the start of injection (SOI). The IDI engine in the study compounded the premixed phase and diffusion phase at 10 degrees ATDC. The NO_x emissions were similar to ULSD#2. The soot emissions decreased by 30% for the B50 fuel blend the CO decreased by 17% and unburned hydrocarbon emissions decreased by up to 63% for increasing FAME concentrations.

Canakci et al [11] investigated an IDI engine fueled with preheated crude sunflower oil (PCSO). The study showed that PCSO decreased brake torque by 1.4% while the BSFC and thermal efficiency increased by 5% and 1% respectively. The ignition delays for the PCSO were longer and the start of injection with the injection event occurring 1 CAD before ULSD. The combustion duration was also lengthened by 2 degrees for the PCSO. Emissions investigations showed that UHC, CO_2 , and smoke opacity decreased while CO emissions increased.

Soloiu et al [12] investigated the combustion parameters of peanut FAME blends in an IDI diesel engine. The study found that the ignition delay for peanut FAME and ULSD#2 were relatively similar. The maximum combustion pressure was slightly higher for the FAME at 2400rpm. The volume averaged maximum gas temperature was slightly lower for the FAME. The heat flux was nearly the same

while the heat loss decreased slightly from ULSD#2 to the FAME blend. The mechanical efficiency for each of the tested fuels was constant at 77% while the brake thermal efficiency for the P20-P50 ranged from 30-35% at 6.2 bar IMEP. Favorable characteristics for soot, NO_x , and CO_2 were seen for the FAME.

Ozsezen et al [13] investigated the performance and emission characteristics of palm oil in an IDI diesel engine. The brake specific fuel consumption (BSFC) increased for the palm oil with respect to ULSD#2. The heating value of the palm oil was 9.8% lower than ULSD#2 and therefore the torque output was lower for palm oil. The CO emissions decreased with an increase of biodiesel concentration.

Soloiu et al [14] investigated the exhaust emissions in a direct injection diesel engine for cotton seed biodiesel. The cetane number for cotton seed FAME was calculated using an equation developed by Bamgboye and Hansen to be 52. The study found that NO_x , CO, and CO_2 emissions were slightly higher while Soot and UHC emissions were slightly lower with respect to ULSD#2. Cotton seed biodiesel has been also investigated by Nabi et al [15]. The results showed that CO, PM, and smoke emissions decreased while NO_x emissions displayed higher values. The thermal efficiency of the biofuel blends was slightly lower than that of ULSD#2 due to lower heating values.

FUEL PROPERTIES AND CHEMICAL COMPOSITION

Technical functionality and performance of a fuel are prevalent concerns when determining a fuel's quality. Both the physical and chemical properties influence the ignition and combustion of the fuel, which in turn influences the performance and emissions characteristics. The properties of the fuel will also affect the longevity of the engine and of its critical components. Due to this, standards for biodiesel have been developed to ensure consistent quality.

The ASTM D6751 standards [16] have been established for the United States to control the quality of biodiesel. In order to verify the quality of the biofuel, experimental determination of lower heating value, calorific value, stability, and values of dynamic viscosity were performed.

Cotton seed oil was selected as the source of crude oil for the biofuel formulation due to its ease of processing and high availability in the southern region of the United States [15]. 5.5 million tons of cotton seed crop were produced in 2012 for all of the U.S. [17]. The cotton seed biodiesel was produced by transesterifying crude oil utilizing solid base catalysis where sodium hydroxide (NaOH) was dissolved in methanol, then added to the reaction mixture.

The values that were determined experimentally were comparable to values found in the literature [14]. Table 1 below presents the fuel properties of ULSD#2 and 100% cotton seed FAME (CS100). Supplementary, total glycerin content, methanol content, and acid number were measured a Paradigm sensor and were within the standard.

Table 1. Fuel Properties

Property	ULSD No. 2	Cotton Seed
Cetane Number	47 [14]	50
Fuel Density (g/cm ³)	0.85 [14]	0.87 [14]
Viscosity at 40°C (cP)	3.32	5.2
Copper Strip Corrosion	No. 3 Max [14]	No. 3 max [14]
Flash Point °C min	100 [14]	176 [14]
Cloud Point	-16.1 [14]	17 [14]
LHV (MJ/kg)	42.65	36
MW	200 [14]	292 [14]

The chemical composition of the FAME was determined using a Gas chromatography - flame ionization detector (GC-FID). Table 2 below presents the chemical composition of CS100 FAME. The concentrations of the basic fatty acids were analyzed in order to determine the cetane number of the biodiesel, which is discussed in a later section.

Table 2. Fuel Properties of Cotton Seed Fatty Acid Methyl Ester

		Carbon #	FAME	CS100*
Saturated	x2	C14:0	Mystiric	0.86
	x3	C16:0	Palmitic	23.76
	x4	C18:0	Stearate	0.05
Total Saturated				24.67
Unsaturated	x5	C16:1	Palmitoleic	0.56
	x6	C18:1	Oleate	13.35
	x7	C18:2	Linoleate	57.11
	x8	C18:3	Linolenate	
Total Unsaturated				71.02

“*”The other 5% are not of detectable signal by GC-FID methods. The future work includes resolving the C18:1 Z and C18:3 peaks, and altering the method/ parameters to better characterize our fuels.

DYNAMIC VISCOSITY

Viscosity is one of many important factors that go into determining if a fuel is applicable for commercial use. A high viscosity can cause fuel lines to clog and deposits to form on the injector. The viscosity of the test fuels was determined using a Brookfield Viscometer DV-II Pro Type. The viscosity was determined over a temperature range of 26-60°C. Figure 1 below presents the viscosity vs. temperature diagram for each of the tested fuels. The viscosity of the fuel blends increased as the concentration of the biodiesel increased as the concentration of the biodiesel increased nevertheless being within the standard.

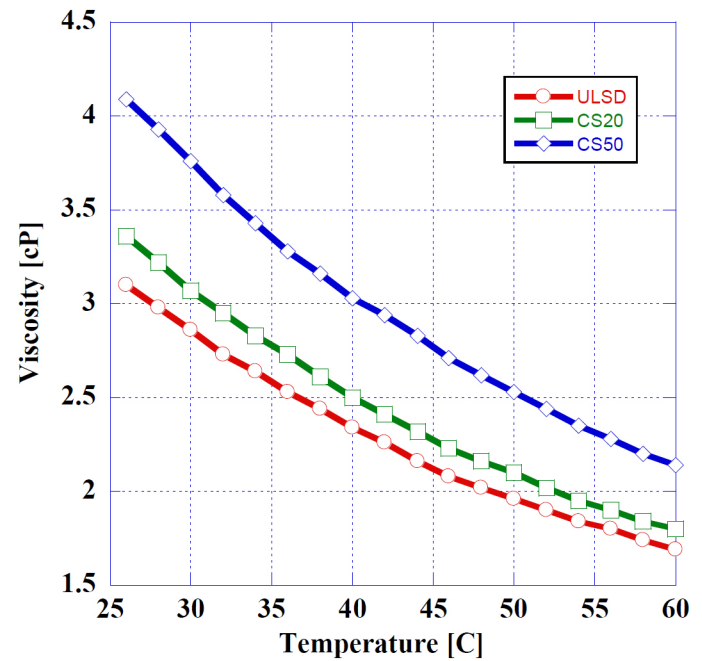


Figure 1. Temperature vs. Viscosity of all fuels tested

LOWER HEATING VALUE

Investigation of heating values was determined using a Parr 6772 Digital Calorimeter. The lower heating value is an indication of energy content and can be directly measured. The lower heating value (LHV) gives the energy content without recovering the latent heat of vaporization for water formed during the reaction [18]. Figure 2 below presents the LHV trend for all fuel blends.

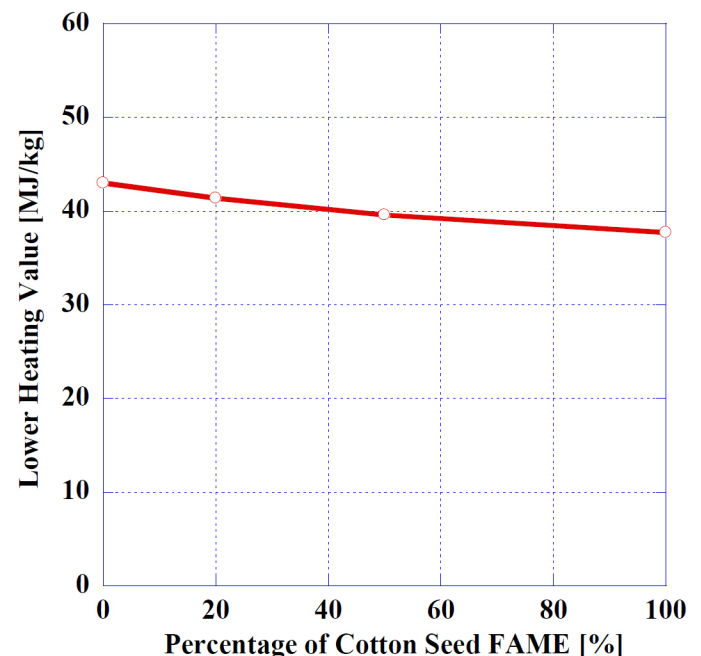


Figure 2. Lower Heating Value of Various Fuel Blends

CETANE NUMBER

Cetane number (CN) is the major indicator of the ignition quality of a diesel fuel. CN can be determined experimentally or analytically using the biodiesels FAME content as an indication of cetane number. Determination of the concentration of compounds in the fuel was performed using a GC-FID chromatograph. The regression model proposed by Bamgboye and Hansen [19] and calibrated by Soloiu [14] as seen in Equation 1 below was used to calculate the cetane number of cotton seed biodiesel.

$$CN = 61.1 + 0.088x_2 + 0.133x_3 + 0.152x_4 - 0.101x_5 - \dots \\ \dots - 0.039x_6 - 0.243x_7 - 0.395x_8 \quad (1)$$

The cetane number for the cotton seed biodiesel as determined by equation 1 above, is 50. Figure 3 below shows the cetane number of the tested fuels based on the mass ratios of the component fatty acids. Experimental determination of cetane number was performed using a constant volume combustion apparatus known as an Ignition Quality Tester (IQT_{TM} Advanced Engineering Technology, Ltd.). The CN of ULSD#2 by IQT was established as 47.

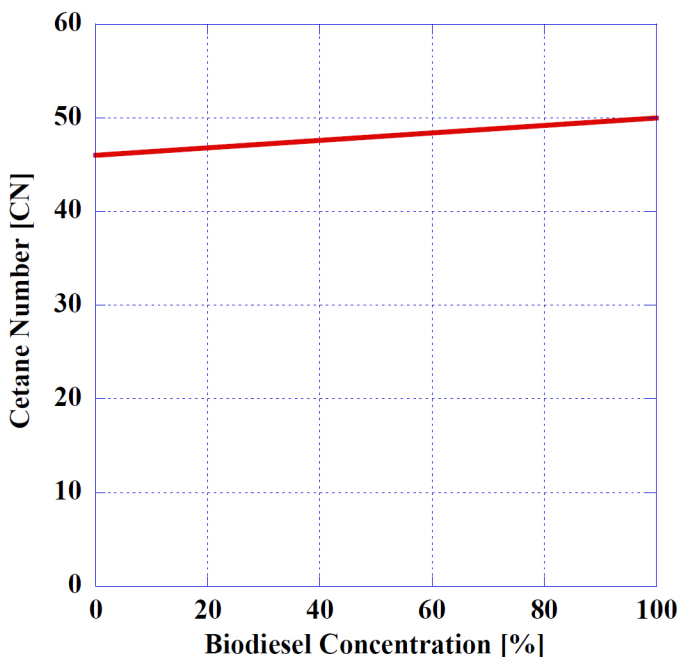


Figure 3. Analytical Cetane Number for Test Fuels

THERMO-GRAVIMETRIC AND DIFFERENTIAL-THERMAL ANALYSIS

The thermal gravimetric analysis (TGA) and differential thermal analysis (DTA) was performed on a Shimadzu DTG-60. An analysis of 100% ULSD#2 and 100% cotton seed biodiesel was performed. Vaporization characteristics are determined from the TGA curve and endothermic and exothermic reactions are determined from the DTA curve. The TGA curve indicates the fuel's vaporization temperature and speed of vaporization. An increase in vaporization temperature

indicates an increase in the droplets' momentum and an increase in the duration of travel time inside of the combustion chamber and the higher possibility of wall impact.

The results of the experiment are displayed in Figure 4 and Table 3 below. The TGA showed an increase in vaporization temperature for the CS100 when compared to ULSD#2. The ULSD began to vaporize at 110°C and the CS100 maintained stability until 200°C. The CS100 fuel then vaporized rapidly with TA50 and TA90 occurring at 200°C and 235°C respectively. The differential thermal analysis results show that ULSD#2 reaches its maximum endothermic reaction around 165°C (absorbing the lower heat of vaporization). The maximum exothermic reaction (heat release) for ULSD#2 occurred around 260°C. The DTA of the CS100 fuel showed a maximum endothermic reaction around 240°C (much higher than that of ULSD). The CS100 fuel displayed exothermic reaction from 275°C to 310°C with multiple peaks corresponding to various fatty acids. A final exothermic reaction from a heavy fatty acid was undergone shortly over 500°C.

Table 3. Thermal Gravimetric Analysis

	TA10 (°C)	TA50 (°C)	TA90 (°C)
ULSD	110	180	225
CS100	200	235	260

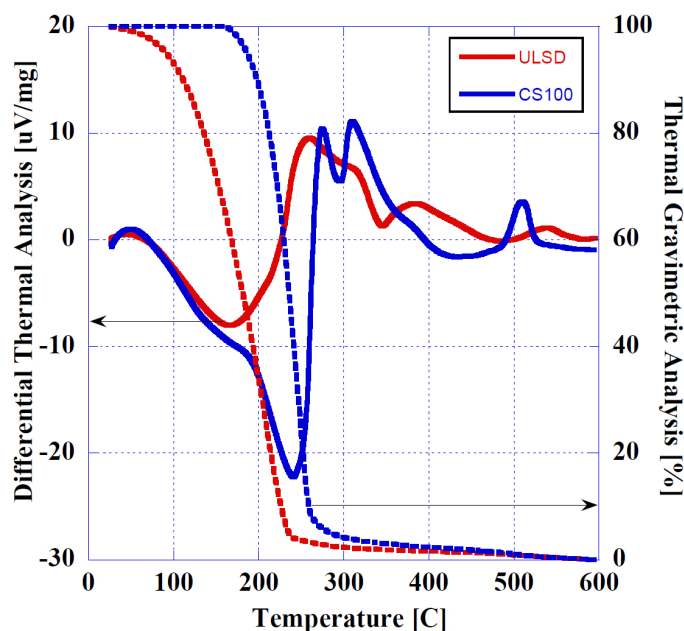


Figure 4. TGA DTA for ULSD and CS100

OXIDATIVE STABILITY

This section presents the results from investigations of the oxidative stability of cotton seed FAME. The unsaturated fatty compounds leave the fuel susceptible to oxidation when exposed to air, light, and elevated temperature [8].