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Full Length Article

An experimental investigation on the usage of waste frying oil-diesel fuel blends with low viscosity in a Common Rail DI-diesel engine

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ABSTRACT

In this study, waste frying oil (WFO) was blended with mineral diesel fuel (MDF) (without converting biodiesel) in the ratios of 2%, 7%, 15% and 25% (v/v) on the condition that the viscosities of all WFO-MDF blends were lower than viscosity upper limit given in European Biodiesel Standard, EN 14214. It was aimed to determine the influences of the direct usage of WFO-MDF blends with low viscosity on the performance, injection, combustion, and emission characteristics of a Common Rail Direct Injection (DI) diesel engine. Engine tests were performed at constant engine speed of 2000 rpm and five different engine loads (50 Nm, 75 Nm, 100 Nm, 125 Nm and 150 Nm). WFO blends' brake specific fuel consumption values were higher than those of MDF. The brake thermal efficiencies of MDF are better than WFO-MDF blends. Slightly higher cylinder gas pressures were attained with the neat MDF but the crank angles where the peak pressures obtained were close to each other. Injection timings did not show significant differences, but fuel quantities injected during pilot and main injection were higher for WFO blends. Excluding 50 Nm engine load, ignition delay and combustion durations were consistent with each other. Compared to MDF as the reference fuel, the use of WFO caused to increase in all exhaust emission types measured, especially THC emissions. The deterioration in performance and emission characteristics increased with increasing engine load and WFO content of the fuel blend.

1. Introduction

In road transport, the number of diesel engine vehicles has been increasing each passing year. For instance, in Turkey, between the years of 2006 and 2016, the share of diesel engine automobiles increased by 485% and became 32.1% of the total automobile amount. In this interval, the number of LPG automobiles increased by 182% while the number of gasoline engine vehicles decreased by 30.6%. When the other diesel engine vehicles such as medium duty and heavy duty are included, it is seen that about 58% of road vehicles in Turkey have diesel engine [1]. Together with this rapid dieselization, Turkey's annual diesel fuel consumption is about 10 times higher than that of gasoline [2]. This causes steadily increasing import bill for the country which does not have fossil energy sources. Taking these issues into consideration, it is obviously seen that using alternative diesel fuel which is renewable, domestically producible and having better exhaust emission profiles is very significant.

Powering diesel engines with vegetable oils is not a new concept and dates back to Rudolph Diesel who was the inventor of diesel engine. However, since vegetable oils have physico-chemical fuel properties different from those of mineral diesel fuel (MDF), severe engine failures were observed with extended engine tests. When the relevant literature is reviewed, it is seen that there are lots of studies reporting that the usage of vegetable oils as fuel in diesel engines resulted in the clogged feeding channels and fuel filter [3–13], carbon deposition on the combustion chamber walls, piston rings, piston head and valve seats due to incomplete combustion [14–19], injector tips coking with gel formation caused by polymerization of vegetable oil resulting in much worse fuel atomization, deterioration of lubricating oil by partially burnt vegetable oil and consequent piston ring sticking, and solidification at unacceptably high temperatures [20–25]. This should be pointed out that the usage of vegetable oils in in-direct (IDI) diesel engines gave relatively better results compared to direct injection (DI) diesel engines [26–31]. The main reasons for these severe engine problems especially observed with DI diesel engines are the low in-cylinder temperatures of this type engines: The average combustion chamber temperature is about 200 °C while average temperature in pre-combustion chamber is about 500–600 °C, resulting in improper evaporation of vegetable oil droplets having very high distillation temperatures and the susceptibility to fuel atomization quality due to relatively less

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effective air turbulence (swirl) encountered in these engines [32,33].

Vegetable oils' extremely high viscosity (about 15 times higher than that of MDF), resulting from the high molecular weight and chemical structure, is the biggest technical obstacle against their direct use as fuel in diesel engines [34–36]. The high viscosity negatively influences the fuel injection process and deteriorates the fuel atomization quality. Poorly atomized larger size vegetable oil droplets, along with the lower volatility of vegetable oils, lead to slower evaporation and inefficient fuel-air mixture formation, resulting in incomplete combustion and consequent serious engine problems mentioned above. In order to eliminate these atomization-related problems, it is crucial to bring down the viscosity of vegetable oils in close to that of MDF. There are four methods used for reducing the high viscosity of vegetable oils: thermal cracking (pyrolysis), microemulsification, dilution (blending with MDF) and transesterification [37–39]. Among these techniques, transesterification is unquestionably the most preferred one. Biodiesel fuel, which is produced via transesterification, is one of the most important and promising alternative energy sources. It has some technical advantages and better exhaust emissions in comparison with MDF [40–45]. Despite these superiorities, it cannot economically compete with MDF due to decrease in crude petroleum price and increase in vegetable oil price [46–48]. In addition to the feedstock cost, transesterification reaction adds extra cost (including chemicals, labor and time) and inevitably increases the biodiesel unit price. As an expected result of this high cost problem, biodiesel usage rate could not be increased as much as the desired amount all across the globe. Because of this, the direct usage of waste frying oil (WFO)-MDF blends having acceptable fuel properties in diesel engines may also be considered. In addition to its cost benefit, the usage of WFO as a diesel fuel may be useful in lowering serious environmental problems caused by disposal of this waste material.

Researchers have investigated the vegetable oil and WFO usage in diesel engines, as neat or blended with MDF. D'Alessandro et al. [49] fueled a DI diesel engine with MDF, biodiesel, linseed oil, palm oil, corn oil, soybean oil, peanuts oil, sunflower oil, refined palm oil, waste frying sunflower oil and waste frying palm oil at three different engine loads. Vegetable oils were directly used without blending with MDF or biodiesel. They observed the change of fuel consumption and exhaust emissions. Vegetable oil fuels and biodiesel had higher fuel consumption than MDF. CO and NO emissions of vegetable oils were higher than those of MDF. Fuel consumption and exhaust emissions of WFO fuels were comparable to those of other vegetable oils. Emberger et al. [50] examined the exhaust emissions of pure vegetable oils (coconut oil, palm oil, high-oleic sunflower oil, rapeseed oil, sunflower oil, soybean oil, corn oil, and jatropha oil) in two tractors which were equipped with common rail and pump-line injection systems. They reported that both tractors can be operated with vegetable oils and MDF at the same level of efficiency. Vegetable oils had higher NO_x, HC and PM emissions compared to MDF. They have also found that exhaust emissions increased with increasing unsaturation, indicating deteriorated combustion with increasing unsaturation of the vegetable oils. Rakopoulos et al. [51] conducted engine tests to evaluate the performance and exhaust emission characteristics of a heavy-duty, DI, turbo-charged diesel engine fueled with pure MDF and blends of sunflower oil, cotton seed oil, corn oil and olive oil with MDF in the ratios of 10% and 20%. They determined that fuel consumption values of all vegetable oils were slightly higher than that of MDF while their thermal efficiencies were practically the same. The NO_x, HC and CO emissions of all the vegetable oil fuels were slightly higher compared to those of MDF. Jiotade and Agarwal [52] implemented the endoscopic visualization technique in a single-cylinder, air-cooled diesel engine which was operated with pure jatropha oil and MDF. They investigated the combustion characteristics of test fuels. They revealed that both of jatropha oil and MDF had similar in-cylinder pressures at all loads. Heat release rate peak for jatropha oil occurred relatively earlier than for MDF and higher amount of heat was released in the diffusion combustion phase. Jatropha oil showed earlier start of combustion compared to MDF at all engine loads. With increasing engine load, combustion duration increased for both test fuels and was relatively higher for jatropha oil. Flame temperature of MDF increased with increasing engine load; however, jatropha oil showed comparatively lower flame temperatures at higher engine loads.

Although there are many studies regarding direct usage of vegetable oils in diesel engines, as neat or blended with MDF, the viscosity values of oils and even blends are still too high to be used in today's modern diesel engines which are very susceptible to fuel quality, especially to fuel viscosity. In most of these studies, prior to injection, the researchers preheated the vegetable oils or blends to reduce their viscosities. This means more complex fuel injection system and, of course, cost increase. In European Biodiesel Standard (EN 14214), the viscosity upper limit is $5.00\,mm^2\,s^{-1}$ (at 40 °C). This is one of the biggest indicators of biodiesel fuel quality. The main purpose of transesterification reaction converting triesters to monoesters is to reduce the high viscosities of triglycerides below this value [53,54]. In the literature, there is no information about the technical feasibility of direct use of WFO-MDF blends having viscosities less than $5.00\,mm^2\,s^{-1}$ (without preheating) in a commercially available modern diesel engine equipped with electronically-controlled high pressure fuel injection system which requires extremely high fuel quality. Therefore, in this study, WFO was blended with MDF in different ratios without exceeding the viscosity upper limit and their effects on the performance, injection, combustion and emission characteristics of a Common Rail Direct Injection (CR-DI) diesel engine were determined. According to the author's knowledge, this is the first study performed with this aim.

2. Materials and methodology

WFO used in the engine tests was obtained from a catering facility. It was sunflower oil origin. Its some physico-chemical properties and fatty acid composition can be seen in Table 1. It was filtered and heated at 110 °C for 1 h to remove any food impurities and moisture. MDF was purchased from a local gas station. WFO was blended with MDF in the ratios of 2%, 7%, 15% and 25% (on volume basis, v/v) without exceeding the $5.00\,mm^2\,s^{-1}$. Test fuels were coded as following: Mineral

Table 1
Some physico-chemical properties and fatty acid composition (%) of WFO.

Property	Unit	Test Method	Value
Viscosity (40 °C)	$mm^2\,s^{-1}$	ASTM D445	38.15
Density (15 °C)	$kg.m^{-3}$	ASTM D4052	923.8
Acid Value	$mg\,KOH.g^{-1}$	AOCS Cd 3d-63	0.76
Higher Heating Value	$kJ.kg^{-1}$	ASTM D240	39,604
Iodine Value	$g\,I_2.100\,g^{-1}$	EN 14111	124.33
Saponification Value	$mg\,KOH.g^{-1}$	EN ISO 3657	192.38
Peroxide Value	$meq.kg^{-1}$	AOCS Cd 8b-90	40.49

C 14:0	C 16:0	C 16:1	C 18:0	C 18:1	C 18:2	C 18:3	C 20:0	C 22:0	Total Saturation
0.09	6.67	0.14	4.17	34.10	53.54	0.29	0.18	0.83	11.63

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