EXPERIMENTAL INVESTIGATION AND PERFORMANCE EVALUATION OF DI DIESEL ENGINE FUELED BY WASTE OIL-DIESEL MIXTURE IN EMULSION WITH WATER

by

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Exploitation of the natural reserves of petroleum products has put a tremendous onus on the automotive industry. Increasing pollution levels and the depletion of the petroleum reserves have lead to the search for alternate fuel sources for internal combustion engines. Usage of vegetable oils poses some challenges like poor spray penetration, valve sticking and clogging of injector nozzles. Most of these problems may be solved by partial substitution of diesel with vegetable oil. In this work, the performance and emission characteristics of a direct injection diesel engine fueled by waste cooking oil-diesel emulsion with different water contents are evaluated. The use of waste cooking oil-diesel emulsion lowers the peak temperature, which reduces the formation of NO_x*. Moreover the phenomenon of micro explosion that results during the combustion of an emulsified fuel finely atomizes the fuel droplets and thus enhances combustion. Experiments show that CO concentration is reduced as the water content is increased and it is seen that 20% water content gives optimum results. Also, there is a significant reduction in* NO_x *emissions.*

Key words: *waste cooking oil, DI diesel engine, micro explosion, emulsification*

Introduction

Invention of the internal combustion engine has tremendously increased our day-to-day energy demand. This has resulted in the widespread exploitation of the petroleum reserves, which are getting depleted at a rapid rate. Moreover, the combustion of these fuels has polluted the environment to alarming levels. In search of the alternate fuels, people have used various fuels like LPG, CNG, H_2, alcohols, vegetable oils, *etc*. Due to its wide availability, high cetane values, edible and non-edible oils have been proved as an effective alternative for diesel. Vegetable oils are not a new grade of fuels to be researched in a diesel engine. Even in 1893 Rudolf Diesel operated his engine on peanut oil. Hotels and restaurants use vegetable oils for frying and cooking purposes. After the usage as well all the properties of the raw oil are retained in these oils except that they are contaminated. By proper filtration, these impurities could be removed and the filtered oil can be used as a fuel in a CI engine. This filtered oil has less viscosity and low fire point when compared to the raw vegetable oil and therefore turns out to be an excellent substitute for the raw vegetable oil as an alternate fuel for diesel engines.

Yoshimoto *et. al* [1] investigated the engine performance with a stable emulsified fuel including frying oil, composed of vegetable oils discarded from restaurants and households. It had been further reported that NO_x concentration and smoke density were reduced without worsening BSFC with water to fuel volume ratios of 15-30% at a rated power output. Also, emulsified biodiesel with 30% (by volume) showed a significant reduction in NO_x while maintaining the minimum BSFC value achieved with gas oil. Brown *et al.* [2] summarized the results of experimental work carried out in the area of diesel emission reductions using advanced catalyst water blend fuel. They reviewed the impact and potential benefits of combining catalyst and water blend diesel to reduce exhaust emissions from engines.

Tests on DI diesel engine with water diesel emulsion by Subramanian *et al*. [3] indicated a considerable reduction in smoke and NO levels. This was accompanied by an increase in brake thermal efficiency at high outputs. When the oxygen concentration in the intake air was enhanced in steps up to 25% along with the use of water diesel emulsion, the brake thermal efficiency was improved and there was a further reduction in the smoke, HC, and CO levels. Tajima *et al.* [4] obtained better combustion rate and lower smoke using the waste vegetable oil methyl ester in a high-speed DI test engine when compared to gas oil. Bertola *et al.* [5] found the effect of the introduction of water in the combustion chamber of a DI diesel engine on combustion characteristics and pollutant formation by using water-diesel emulsions with three distinct water amounts (13, 21 and 30%). Analysis of the measured and computed data shows clear and favorable trends. Also, at constant injection pressure, the reduction of NO_x and particulate matter was achieved with 30% water emulsion compared to diesel fuel. These reductions were in all cases proportional to the water content in the fuel. This was measured in all engine load conditions.

Kee *et al.* [6] have summarized the effects of water-emulsified fuel on diesel combustion and emission reduction under various ambient temperatures, equivalence ratios and water addition ratios using a rapid compression machine and a total gas sampling device. It has been indicated that promoted diffusion combustion of emulsified fuels offers shorter combustion duration and an increment in the amount of heat release when compared with those of gas oil. It has been found that this reduction is due to low NO_x formation rate. Senda *et al*. [7] investigated the flame structure and combustion characteristics for two waste cooking oils and found that spray tip penetration got increased and the spray angle was decreased. Particulate matter emissions were lowered with pure biodiesel compared to other fuels in the whole engine operating range. Rosca *et al*. [8] indicated that transesterification process has significantly decreased the viscosity of the methylester, which is very close to the one of diesel fuel. The use of methylester led to changes in the injection characteristics like increased injection pressure, lower average injection rate, and earlier start of combustion. Macian *et al*. [9] used a specific transient cycle to show real emission differences between conventional diesel fuel and biodiesel. In the present work, the performance and emission characteristics of a direct injection diesel engine fueled by used cooking oil-diesel emulsion with different water contents are evaluated. Also, the scenario of peak temperatures, formation of NO_x and enhancement of combustion are studied.

Vegetable oils in CI engines

Properties of sunflower oil, waste-cooking oil obtained from sunflower oil are compared with diesel as shown in tab. 1. Diesel engines use these fuels obtained from various methods like trans-esterification, blending with diesel, and prepared as emulsion with water.

Benefits of emulsifying the fuel

Emulsified fuel burns at a low combustion temperature. This low temperature is not an ideal environment for nitrogen to react with oxygen to form NO_x. Because of this, NO_x emission from a CI engine is greatly reduced. The phenomenon of micro explosion takes place when the

Table 1. Comparison of properties of waste-cooking oil with diesel

No.	Properties	Sunflower oil	Waste cooking oil	High speed diesel
1	C [w/w%]	78.3	76.8	86.6
2	H_2 [w/w%]	12.8	11.6	13.4
3	O_2 [w/w%]	8.75	10.6	–
4	Flash point in °C at 1 atm.	232	210	65
5	Density [kgm^{-3}]	910	920	830
6	Kinematic viscosity at 40 °C [cs]	30.6	33.4	2.8
7	Lower heating value at 25 °C [MJkg^{-1}]	37	36.47	42.7
8	Stoichiometric air/fuel ratio	12.98	12.98	14.55
9	Cetane number	35.5	33.4	45

emulsified fuel is injected at high pressure into the combustion chamber. The fine droplets sprayed at the early part of combustion will be heated up during the pre-flame reaction period. Therefore the larger droplets that follow during the later stage of combustion will be subjected to very high temperature. At this temperature, the droplets will be subjected to an environment conductive for rapid heat transfer. Water will be superheated and becomes extremely unstable. This results in the destruction of the fuel droplets explosively resulting in ultra fine droplets, which mixes well with the incoming air and thus enhances the combustion reaction. Therefore, the products of incomplete combustion are reduced.

Experimentation

Preparation of waste cooking oil diesel emulsion

The waste cooking oil (WCO) diesel emulsion is prepared in a separately powered high-speed stirrer. Emulsions are prepared with varying water content from 10 to 30%. First, equal quantities of diesel and WCO are added into the high-speed stirrer. To this mixture, a pre calculated amount of water is added along with an optimum amount of surfactant. This mixture is now stirred for a period of 20 minutes by switching it off after every 5 minutes. The emulsion is thus prepared and filled in to the fuel tank. From the tank, it is sent to the engine.

Test setup

Investigations are carried out on a four--stroke water-cooled DI diesel engine with the setup as shown in fig. 1. Engine is started with diesel (taken in a separate fuel tank) and after the steady-state is reached, the WCO-diesel emulsion is allowed to flow through a 3-way cock into the engine. Engine is tested from no-load condition to full-load condition and the emissions like NO_x, CO, and HC are measured using exhaust gas analyzer. Smoke intensity is measured using a smoke meter.

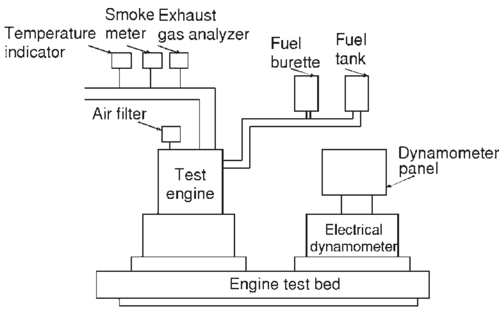

Figure 1. Schematic diagram of the experimental setup

Micro-explosion test

Micro-explosion and vaporizing behavior of the emulsified fuel droplets determines the influence of emulsified fuel properties such as water content, water particles size and viscosity of base fuel on combustion in a diesel engine. An experiment is conducted in this regard to find the evaporation rate of the droplet of the emulsified fuel for various water contents.

The evaporation time of the emulsified fuel was tested on a hot plate and investigated at atmospheric pressure. The hot plate is a circular one of 170 mm diameter and 15 mm thick with 2 mm deep and 30 mm diameter depression at the center to prevent the droplets from flying out. This hot plate is heated to a constant high temperature of 130 °C and the fuel is injected on to the plate. Using a syringe, 10 droplets are injected and the time taken for the fuel to evaporate is determined using a stopwatch.

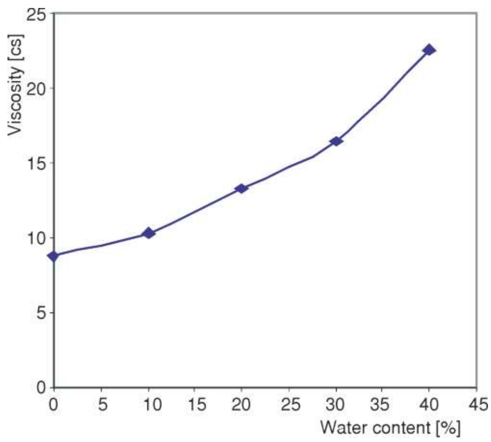

Figure 2. Viscosity at 40 °C with varying water content

Results and discussion

Experiments are initially carried out on the engine at peak output using diesel as fuel and with various concentrations of water in WCO--diesel. Viscosity, stability of WCO and emulsions were examined prior to experiments on the engine. Figure 2 shows changes in viscosity at different water contents (10, 20, and 30%). It could be observed that viscosity increases exponentially with increase in water content. The variation of brake thermal efficiency with load is as shown in fig. 3. This efficiency is lower when pure diesel is used. Also, it is found that η_{BTHU} is more when WCO-diesel blend is used. As water content is increased, efficiency is found decreasing. This is due to poor mixture formation as a result of high viscosity and stability. Similarly, variation of BSFC with load is as shown in fig. 4.

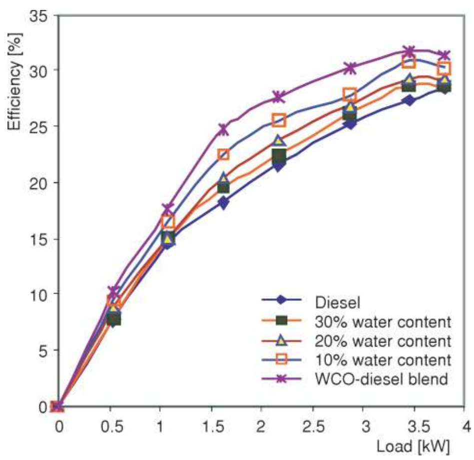

Figure 3. Variation of brake thermal efficiency with load (color image see on our web site)

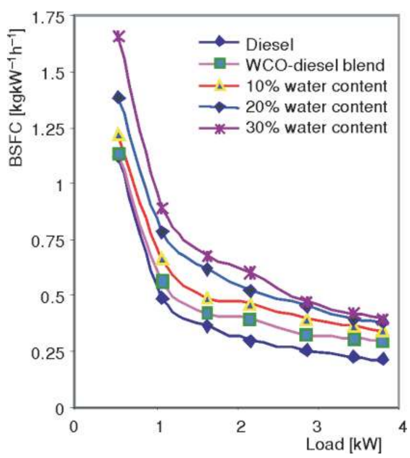

Figure 4. Variation of BSFC with load (color image see on our web site)

It shows that BSFC is less when pure diesel is used and is more when 30% of water is added. This could be explained by the lower heating value of the emulsified fuel.

Figure 5 shows the variation of load with NO_x. It is seen that WCO-diesel blend has more emission of NO_x when compared to 30% of water content. This is mainly due to the lower burning rate of emulsified oil, which leads to lower peak temperature. The rate of heat release during the pre-mix burning phase is lower with increasing content of water. Also, when compared to

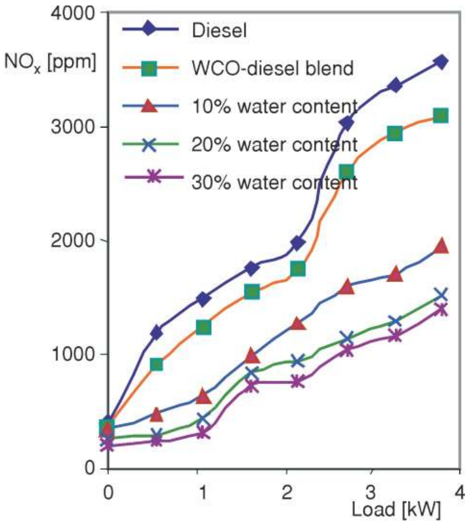

Figure 5. Variation of load with NO_x

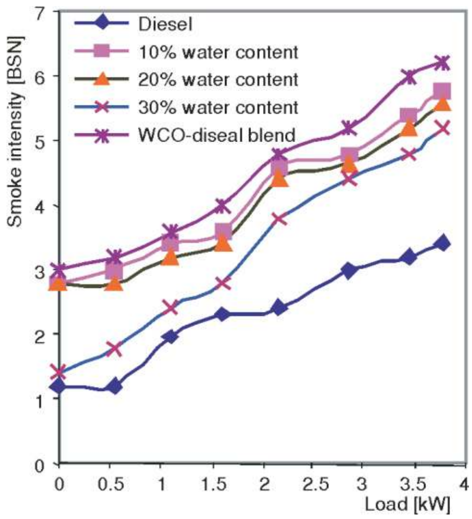

Figure 6. Variation of smoke intensity

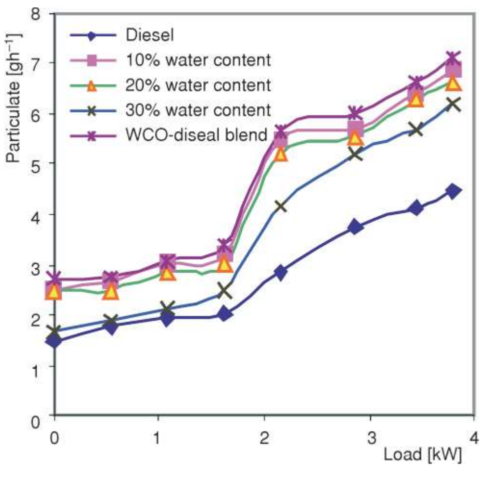

Figure 7. Variation of particulate matter with load

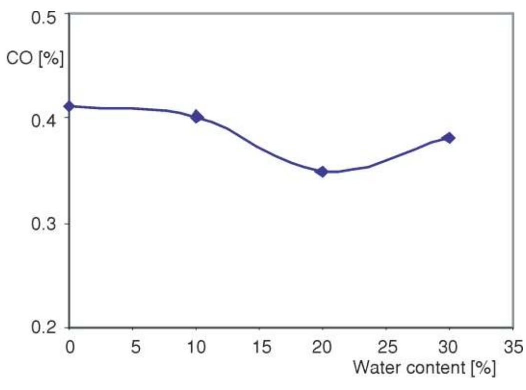

Figure 8. Variation of CO with water content

pure diesel, the smoke intensity is higher about 13.13% for 20% water content at full load (fig. 6). This may be due to poor mixing with air and quenching of flame. It is found that particulate emission for emulsified fuel is higher when compared with pure diesel (fig. 7). The variation of CO with water content is shown in fig. 8. The CO concentration is reduced as the water concentration

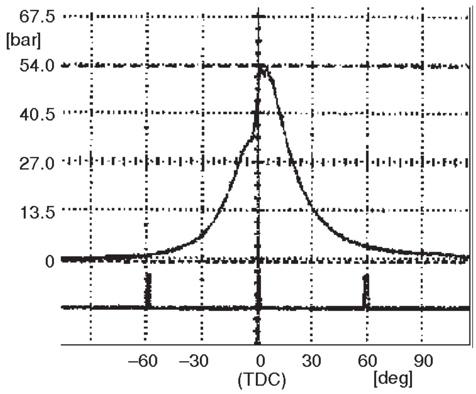

Figure 9. Pressure *vs.* crank angle diagram for diesel waste cooking oil blend at 75% load

is increased. But, if water is added above 20%, the CO concentration shoots up. This is due to the increase in the viscosity that affects the combustion. The pressure-crank angle diagram for WCO-diesel at 75% of load is presented in fig. 9.

Conclusions

Experiments are conducted using pure diesel and various concentrations of water (10, 20, 30%) in WCO-diesel emulsion. Based on the experimental results, the following conclusions are drawn:

– The NO_x concentration decreases with increase in water content in the WCO-diesel emulsion.
– A significant reduction in specific energy consumption (3.31%) is obtained with emulsified fuel containing 20% water.
– When compared to pure diesel, the smoke intensity is higher by about 13.13% for 20% water content at full load.
– Emission of the particulate matter for diesel is 4.8 g/h and for 20% water content is 6.3 g/h. So, there is an increment of about 23.8% at full load.
– CO concentration gets reduced as the water concentration is increased.
– There is a marginal increment of about 2.78% in brake thermal efficiency for 20% water content when compared to diesel.

From the experiments conducted it is found that 20% water content gives optimum results. As seen from the conclusions, there is a significant reduction in NO_x, while the smoke and particulate emissions are high. So, by properly controlling the emissions of smoke and particulate, this fuel can be viewed as an effective alternate to the raw vegetable oil as a fuel in diesel engines.

Nomenclature

BSFC – brake specific fuel consumption [$kgkW^{-1}h^{-1}$]
BSN – Bosch smoke number
CI – compression ignition
CNG – compressed natural gas
DI – direct injection
LPG – liquefied petroleum gas
WCO – waste cooking oil
η_{BHTU} – brake thermal efficiency

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