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The use of modified tyre derived fuel for compression ignition engines

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ABSTRACT

This study investigated physical and chemical modification of tyre-derived fuel oil (TDFO) obtained from pyrolysis of waste tyres and rubber products for application as an alternative fuel for compression ignition engines (CIE's). TDFO collected from a local waste tyre treatment facility was refined via a novel "oxidative gas-phase fractional distillation over 13× molecular sieves" to recover the light to medium fractions of the TDFO while oxidising and capturing some sulphur compounds in a gas phase. This was followed by desulphurization and chemical modification to improve cetane number, kinematic viscosity and fuel stability. The resulting fuel was tested in an ADE407T truck engine to compare its performance with petroleum diesel fuel. It was discovered that gas phase oxidative fractional distillation reduces the low boiling point sulphur compounds in TDFO such as mercaptans. Using petroleum diesel fuel as a reference, it was observed that the produced fuel has a lower cetane number, flash point and viscosity. On storage the fuel tends to form fibrous microstructures as a result of auto-oxidation of asphaltenes present in the fuel. Mixtures of alkyl nitrate, vinyl acetate, methacrylic anhydride, methyl-*tert* butyl ether, *n*-hexane and *n*-heptane were used to chemically modify the fuel in accordance with the minimum fuel specifications as per SANS 342. The engine performance tests results did not show any sign of engine ceasing or knocking effect. The power-torque trend was very consistent and compared well with petroleum diesel fuelled engine. The levels of total sulphur are still considerably high compared to other cleaner fuel alternatives derived from zero sulphur sources.

1. Introduction

An increased fuel demand continues to accelerate depletion of fossil fuel resources such as crude oil and coal. The use of non-renewable fossil derived fuels such as petroleum diesel has larger carbon footprints compared to other cleaner renewable energy sources such as natural gas and biodiesel (Di et al., 2009; McNeil et al., 2012). This has put a lot of pressure on emerging countries to find sustainable alternative fuels and reduce dependency on fossil fuels. One of the solutions is to recover fuel from complex industrial waste material by various processes.

Crude oil obtained from pyrolysis of waste tyres is often referred to as tyre derived fuel oil (TDFO) or bunker fuel oil. This oil can be further refined by fractional distillation to produce diesel equivalent fuel derivative referred to as tyre derived fuel (TDF) (Murugan et al., 2008). The fuel properties of TDF including calorific values, ultimate analyses, flash point, moisture content, density and viscosity have been determined by previous researchers. The results showed that TDF had fuel properties similar to those of a light petroleum fuel oil (Lopez et al., 2009; Lah et al., 2013). Chromatographic and spectroscopic studies on the liquid obtained from pyrolysis of waste tyres show that TDFO can be used as liquid fuels and chemical feedstock, with a calorific value of 43 MJ/kg (Rofiqul et al., 2008). TDF has generated significant interest as an alternative option for petroleum diesel. As a result, a number of studies compared combustion and emission as well as engine performance of various TDFs with petroleum diesel i.e. Galvagno et al. (2002), Li et al. (2004), Onay (2007), Olazar et al., 2008, Murugan et al. (2008).

Waste tyre pyrolysis technology for production of liquid fuel has been considered as an alternative method for disposal of waste tyres while producing alternative fuel. Several studies have been carried out in the production of TDFO obtained from waste tyres and rubber products by various techniques (Sharma and Murugan, 2013). Rodríguez et al. (2001) investigated pyrolysis of waste tyres in a fixed-bed reactor at 500 °C and reported that product oils consisted of 62 wt% aromatic compounds, 31.6 wt% aliphatic compounds, 4 wt% nitrogen-containing compounds, and 18000 ppm sulphur containing compounds. Another study investigated pyrolysis of waste tyres in continuous conical spouted bed reactor, in the 425–600 °C range, by feeding two types of tyre

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materials with different contents of natural and synthetic rubber. It was observed that main differences between the continuous and batch processes are in the yield of aromatics content, which is higher in the continuous process, and in that of the heavy liquid fraction, which is higher in the batch process (Olazar et al., 2008).

Pyrolysis of waste vehicle tyres with the purpose of fuel production for the usage as a fuel in internal combustion engines may be an alternative disposal solution pending its environmental and economic viability. One of the experimental studies reported in literature has revealed that utilization of TDF as a fuel in diesel engine resulted in normal engine operation without modification when it is blended with commercial diesel fuel up to 70% of TDF-diesel blends. Thermal efficiencies were lower compared to pure diesel operation. Higher smoke, sulphur oxides and un-burnt hydrocarbon emissions were reported (Murugan et al., 2008). Another work was been carried out to evaluate the performance, emission, and combustion characteristics of a single cylinder direct injection diesel engine fuelled with up to 50% of TDF blended with diesel fuel. It was concluded that it is possible to use TDFO in diesel engines as an alternate fuel in the future (Martinez et al., 2013).

While TDFO has high energy content, it requires some processing to assure efficient use in internal combustion engines. Some of these oils have already been evaluated as alternative for diesel and gasoline fuels. Compression ignition (CI) engines stand out as being potential power plants for the use of TDFO without requiring major engine modifications. In fact distillation properties of TDFO are very similar to conventional diesel fuel as presented in Table 1. However the results reported by Hariharan et al. (2013) indicate that because of its low cetane number, TDFO must be blended with diesel fuel or complemented by a cetane improver, such as diethyl ether, for application in diesel engines. Consequently, many studies using TDFO blended with diesel fuel or methyl esters are found in the literature. Thus only limited number of studies is performed in commercial multi-cylinder turbocharged engines Martinez et al. (2014), Koc and Abdullah (2014), but none of them with pure TDFO.

Certain properties of TDF such as cetane number, viscosity, and total sulphur contribute to engine performance and emission characteristics. Refined TDFO often contains around 1800 ppm total sulphur, with kinematic viscosity of 1.6 cSt, flash point of 26 °C and gross calorific value of 43 MJ/kg (Pilusa et al., 2014). In addition, the use of TDF in internal combustion engines results in reduction of unburned hydrocarbons, particulate matter and carbon monoxide (Koc and Abdullah, 2014). In contrary, internal combustion of TDF results in an increased sulphur dioxide emissions, due to the presence of high sulphur levels in the fuel (Martínez et al., 2013; Frigo et al., 2014; Argawal, 2014). Previous research has also shown that TDF properties partially satisfy SANS 342, and the use of this fuel should be comparable with petroleum diesel (Hüseyin and Cumali, 2015).

This research investigates possible chemical modification of TDF such that its viscosity, flash point, cetane number, calorific value and lubricity are within EN 590 and SANS 342 specification for internal combustion application.

Table 1
Test operating points for the ECE R49 13-mode test (UNECE, 1993).

Mode	% Load	Engine speed	Factor
1	0	Idle	0.083
2	10	Intermediate	0.08
3	25	Intermediate	0.08
4	50	Intermediate	0.08
5	75	Intermediate	0.08
6	100	Intermediate	0.25
7	0	Idle	0.0833
8	100	Rated	0.1
9	75	Rated	0.02
10	50	Rated	0.02
11	25	Rated	0.02
12	10	Rated	0.02
13	10	Idle	0.0833

Rated speed: The speed at which the engine achieves maximum power with full rack setting on the fuel pump. **Intermediate speed:** The speed corresponding to the maximum torque value if such a speed is within the range of 60–75% of rated speed. In other cases it means a speed equal to 60% of rated speed. % Load: The fraction of maximum available torque at a given engine speed. **Factor:** The regulation 49 procedure derives a cumulative result from steady state operation at 13 operating points at a range of speeds and percentages of full load. The quantity of emissions measured at each operating point or mode is given a weighting factor.

2. Material and experimental procedures

2.1. Material

A sample of TDFO was obtained from a continuous waste tyre pyrolysis owned by International Rubber Recycling (Pty) Ltd in South Africa. A specific focus for this research was to investigate modification of low aromatic TDFO obtained from a continuous pyrolysis system similar to the one shown in Fig. 1 as opposed to high aromatic TDFO obtained from batch processes. Vinyl acetate, *n*-heptane, *n*-hexane, methacrylic anhydride, *n*-butanote and amyl alcohol and nitric acid were used as reagents to chemically modify some properties of the refined TDFO. All these reagents were purchased from Sigma Adrich South Africa.

2.2. Experimental procedures

2.2.1. Fuel preparation

A schematic block diagram of the extraction system used in this study is presented in Fig. 2. The process consists of various stages whereby TDFO is converted into modified tyre derived fuel (TDF*). A sample of TDFO was characterized as an alternative fuel for compression ignition engines as per test results presented in Table 1. A distillation curve of TDFO was generated in comparison with its derivatives and standard diesel fuel.

A bench scale distillation set-up consisting of 1000 ml round bottom flask, heating mantle, glass water cooled condenser and a collecting flask as shown in Fig. 3 which was used for flash distillation of the TDFO. The glass condenser was fitted with 16 g of steel wool which will act as catalyst when oxidised into ferric oxide. The temperature of the feed TDFO was monitored and initially maintained at 100 °C to allow for evaporation and recovery of water, low boiling point mercaptans, sulphides and disiphides in the TDFO. The condenser bulb was filled with 26 g of 13× molecular sieves supported over oxidised steel wool. This will ensure oxidation of high boiling point sulphur compound and adsorption over the active layer of micro-porous sieves in a gas phase prior to condensation. The function of 13× molecular sieve pellets is to enhance adsorption of low boiling points sulphur compounds as well as water removal from the fuel.

The distillation temperature of the TDFO was raised to 350 °C for extraction of light and heavy fuel fractions while oxidising and capturing the sulphur compounds over the active layer of molecular sieves in the condenser bulb as shown in Fig. 3. The system was properly sealed at each connection point to ensure that all vapours passes through the ferric oxide and molecular sieves before they are condensed into light fraction fuel. The condensed TDFO was desulphurized using Ca (OH) and H_2SO_4 as per treatment method reported Hüseyin and Cumali (2015). This was followed by filtration through a series of activated carbon and micro-molecular filtration system presented in Fig. 3 for the removal of suspended and dissolved contaminants. This TDF was characterized as an

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