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Combustion Characteristics of Waste Tyre Pyrolysis Fuel as Industrial Burner Fuel

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Abstract

This study examined the potential of using waste tyre pyrolysis fuel oil as an industrial burner fuel. The combustion characteristics of tyre-derived fuel (TDF) oil were evaluated using Cuenod NC4 forced draught oil burner equipped with a built-in fuel atomizer and an onboard control system. TDF oil obtained from a local waste tyre treatment facility was blended with petroleum diesel (DF) at TDF volumetric concentration of 40% (TDF_{40}), which was tested against pure petroleum diesel and refined modified tyre-derived fuel (TDF^*). Critical combustion parameters such as thermal power output, fuel consumption, flame stability, flue gas temperature, and emissions were investigated to evaluate the performance of the combustion equipment. Using DF as a reference fuel, it was observed that TDF_{40} required high air-to-fuel ratio (AFR) in order to produce a stable flame with high flame temperature and less emissions. TDF^* produced a reasonably stable flame with less sulphur dioxide emissions compared to TDF_{40} ; however, its specific fuel consumption (SFC) was higher than that of DF. It was also discovered that the burner's SFC was higher when fuelled with TDF_{40} . Total contamination and viscosity of TDF oil contribute significantly to the flow characteristics of the fuel, resulting in reduced pressure and subsequently poor fuel atomization. Rapid soot formation at atomizer nozzle was also observed when the burner was fuelled with TDF_{40} . TDF oil and its derivatives (TDF^*) produce SO_2 , NO_2 and CO emission levels higher than the acceptable limits as prescribed by the European Air quality standard (EU2015/2193). It was concluded that TDF oil could be used as a potential industrial burner fuel if diluted with petroleum diesel fuel at TDF volumetric concentration of <40% or any ratio that could adjust the viscosity level below 5.3 cSt. Fuel preheating and multistage filtration system are also recommended to reduce total contamination and water levels in the fuel mixture. Exhaust gas scrubbing is recommended due to significantly high sulphur oxide emission in the flue gas.

Keywords: atomization, boiler, emissions, energy, flame

1. Introduction

1.1. Background

An ongoing increased fuel demand continues to speed up depletion of fossil fuel resources such as crude oil and coal. The use of non-renewable fossil-derived fuels such as petroleum diesel for power and energy production contributes toward a large global carbon footprint compared to other cleaner renewable energy sources such as biogas, natural gas and biodiesel. Renewable energy sources and various waste-to-energy initiatives are being explored globally; however, most of these initiatives are inefficient and environmentally unfriendly. This continues to put a lot of pressure on emerging countries to find cost-effective use of sustainable alternative fuels in order to reduce dependency on fossil-derived fuels. It remains a challenge to develop economical and sustainable solutions to derive fuels from waste streams or renewable sources in order to supplement the traditional fossil-derived fuels. One of the methods is to produce low-cost alternative fuels from waste tyres and rubber products through pyrolysis technology and blend it with available commercial fuels.

There is an increasing interest in pyrolysis technology, especially for the treatment of waste automotive tyres with the aim of producing alternative liquid fuel and solid char. This fuel is traditionally used as heavy bunker fuel oil in environments where emissions control legislations are not very stringent [1]. Previous research has shown that tyre-derived fuel (TDF) oil has similar properties to petrochemical diesel fuel; hence, it has been tested in compression ignition engines [2, 3].

TDF oil is produced through the thermal decomposition of rubber-based material in an oxygen-depleted environment followed by a condensation of the vapors to yield a liquid fuel [4–6]. In a continuous pyrolysis technology, shredded tyre chips are continuously fed into an oxygen free reactor vessel, which is heated to temperatures of 570°C in a “continuous pyrolysis reactor” as shown in **Figure 1**. The produced gases are contained and condensed into liquid TDF oil (47 wt% of feed), and the remaining solid char (35 wt% of feed) is separated from steel (10 wt% of feed) using a magnetic separator. A stream of uncondensed pyrolysis gas (5 wt% of feed) is recycled into the process to heat up the pyrolysis reactor as shown in **Figure 1**. A flue gas scrubber system is incorporated to remove toxic emissions from the flue gas stream because the process uses TDF oil and excess pyrolysis gases to heat up the reactor vessel [7]. Waste tyre pyrolysis technology 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 TDF oil by various techniques. Rodriguez et al. [8] investigated pyrolysis of 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 18,000 ppm sulphur-containing compounds. It has also been reported that the main difference between the continuous and batch processes is in the yield of aromatics content, which is 43.5% in the continuous process described in **Figure 1** [9].

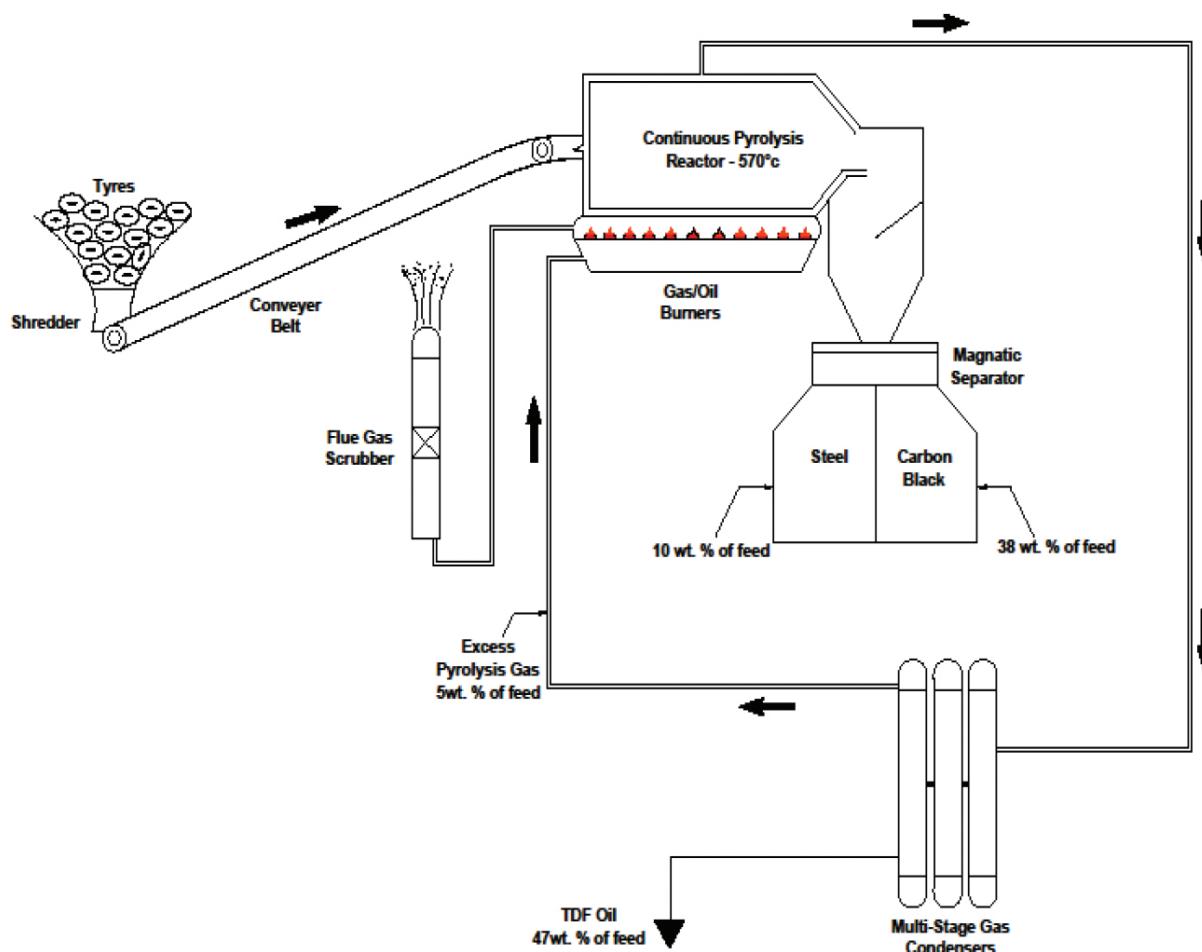


Figure 1. Continuous waste tyre pyrolysis plant.

1.2. Tyre-derived fuel oil

TDF oil has similar characteristics to diesel fuel; hence, it has been demonstrated for use in boilers, turbine and diesel engines; however, concerns with regard to its acidity, ignition characteristics, clogging tendency and gaseous emissions have limited its commercial application [10, 11]. Previous researchers have determined some properties of TDF oil such as ultimate analyses, flash point, moisture content, density and viscosity. The results showed that TDF oil had fuel properties similar to those of petroleum diesel fuel [12, 13]. Chromatographic and spectroscopic studies on TDF oil also show that it can be used as liquid fuel, with a calorific value of 43 MJ/kg [14].

TDF oil has generated significant interest as an alternative option to petroleum diesel. As a result, a number of studies compared internal combustion and emission as well as engine performance of various TDF–petroleum diesel blends [2, 9, 15–17]. External combustion characteristics of TDF oil are not fully understood because most of the research in TDF oil combustion has been demonstrative in nature. Therefore, the purpose of this research is to

develop a better understanding of TDF oil combustion with regard to the operating conditions used during combustion as well as its physical properties.

While TDF has high energy content, it requires some processing to ensure efficient use in combustion equipment. However, the results reported by [18] indicate that because of its high viscosity and low cetane number, TDF must be blended with petroleum diesel fuel or complemented by a cetane improver, such as diethyl ether, for application in most common combustion equipment. Consequently, many studies using TDF blended with petroleum diesel fuel or methyl esters for application in internal combustion engines are found in the literature [19, 20], but none of them were tested in external combustion fuel burners.

Certain properties of TDF oil such as cetane number, viscosity, and total sulphur contribute to burner performance and emission characteristics. Previous research performed some investigations on qualitative analysis of waste rubber-derived oil as an alternative diesel additive, whereby it was found that TDF oil has high viscosity, total sulphur, total contamination, water content, and flash point of 9 cSt, 9106 ppm, 143 mg/kg, 3.43 vol.% and 94°C, respectively [21].

A further study revealed that TDF oil could be refined through fractional distillation process to obtain cleaner fuel with reduced total sulphur of 1800 ppm, kinematic viscosity of 1.6 cSt, flash point of 26°C, total contamination of 29 mg/kg, water content of 0.03 vol.% and gross calorific value of 43 MJ/kg [22]. In addition, the use of refined TDF in combustion equipment results in reduction of unburned hydrocarbons, particulate matter and carbon monoxide [20]. In contrary, combustion of TDF oil results in an increased sulphur dioxide emissions, due to the presence of high sulphur levels in the fuel [23, 24].

1.3. Combustion emissions

In an ideal combustion process of a hydrocarbon liquid fuel occurring in excess oxygen, all fuel would be converted into heat, water, carbon dioxide and negligible equilibrium amounts of carbon monoxide. However, given the complexity of physiochemical interactions during the combustion process, there are other side reactions taking place, resulting in the formation of pollutants or emissions.

The most significant combustion emissions are sulphur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), unburned hydrocarbons (HC) and particulate matter (PM) [25]. These are among emissions regulated by the National Air quality Act No. 39 of 2004, which is in line with the European Air quality standards published under the European Union directive No 2015/2193 as summarized in **Table 1**. Some of these emissions are promoted by inefficient operation of the combustion equipment due to the quality of fuel used, for example, when large numbers of inert particles are passing through the combustion equipment pump and atomizer nozzle, cavitation occurs causing erosive wear and increasing nozzle size. This leads to larger fuel drop sizes and particles becoming trapped in the mating surfaces of the sealing areas of the injector tips, keeping them apart. Leaking and dribbling subsequently occur at injector nozzle resulting in reduced injection pressure and poor atomization. The effects of these various problems are the main cause of inefficient combustion and subsequent increased emissions levels. Pilusa et al. [26] reported that sufficient filtration of fuel ensures uniform fuel

flow through the precision components of the combustion equipment, resulting in efficient combustion and reduced emissions.

Pollutant	Pollutant limit	Exposure period	Test method
SO ₂	300 µg/m ³ (134 ppb)	1 h	ISO 6767
NO ₂	200 µg/m ³ (106 ppb)	1 h	ISO 7996
CO	30 mg/m ³ (26 ppm)	1 h	ISO 4224
	10 mg/m ³ (8.7 ppm)	8 h	
PM ₁₀	120 µg/m ³ (134 ppb)	24 h	EN 12341

Table 1. Selected regulated pollutants limits as per national ambient air quality standards [27].

1.4. TDF combustion

Previous research investigated the use of oils for the operation of medium industrial boilers, whereby several atomization techniques have been employed, including pressure atomization, air atomization, steam atomization and fuel preheating in order to reduce viscosity [28]. A higher air-to-fuel (AFR) equivalent was recorded for efficient combustion of high-viscosity fuel oils. Particulate matter has arisen as one of the most challenging aspects of TDF oil combustion given its consistently high readings, particulates have been observed to collect on burner surfaces [29]. The aim of this research was to assess the combustion characteristic of TDF oil as an alternative low-cost industrial burner fuel.

2. Material and experimental procedures

2.1. Material

A sample of TDF oil produced from a continuous waste tyre pyrolysis process was obtained from a local waste tyre treatment technology. As reported in literature, TDF oil produced from a continuous pyrolysis process at temperature above 500°C has superior characteristics in terms of aromatic content as compared to the one produced from a lower temperature batch process [8, 9]. Petroleum diesel (500 ppm) was purchased from a nearby fuel filling station, and it was used as a reference test fuel and also to prepare TDF oil–diesel mixtures. An illustration of the combustion experimental setup is shown in **Figure 2**. In order to produce a chemically modified TDF (TDF*), TDF oil was distilled using an experimental setup illustrated in **Figure 3** and all chemical reagents used were purchased from Sigma Aldrich South Africa. Vinyl acetate, n-heptane, n-hexane, methacrylic anhydride, n-butanone and amyl alcohol and nitric acid were used as reagents to chemically modify some properties of

TDF*. **Tables 2** and **3** present the technical specifications of the burner and emissions analyzers used for these research.

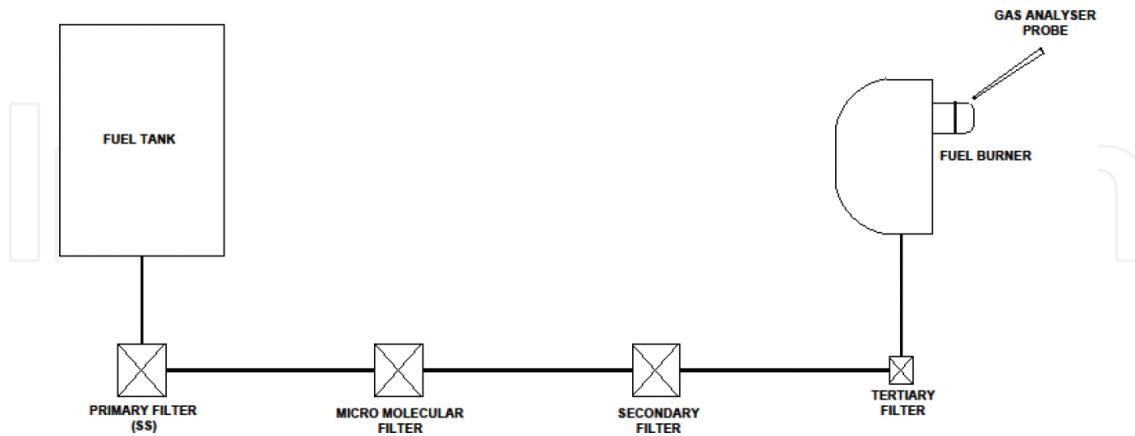


Figure 2. Experimental setup for external fuel combustion.

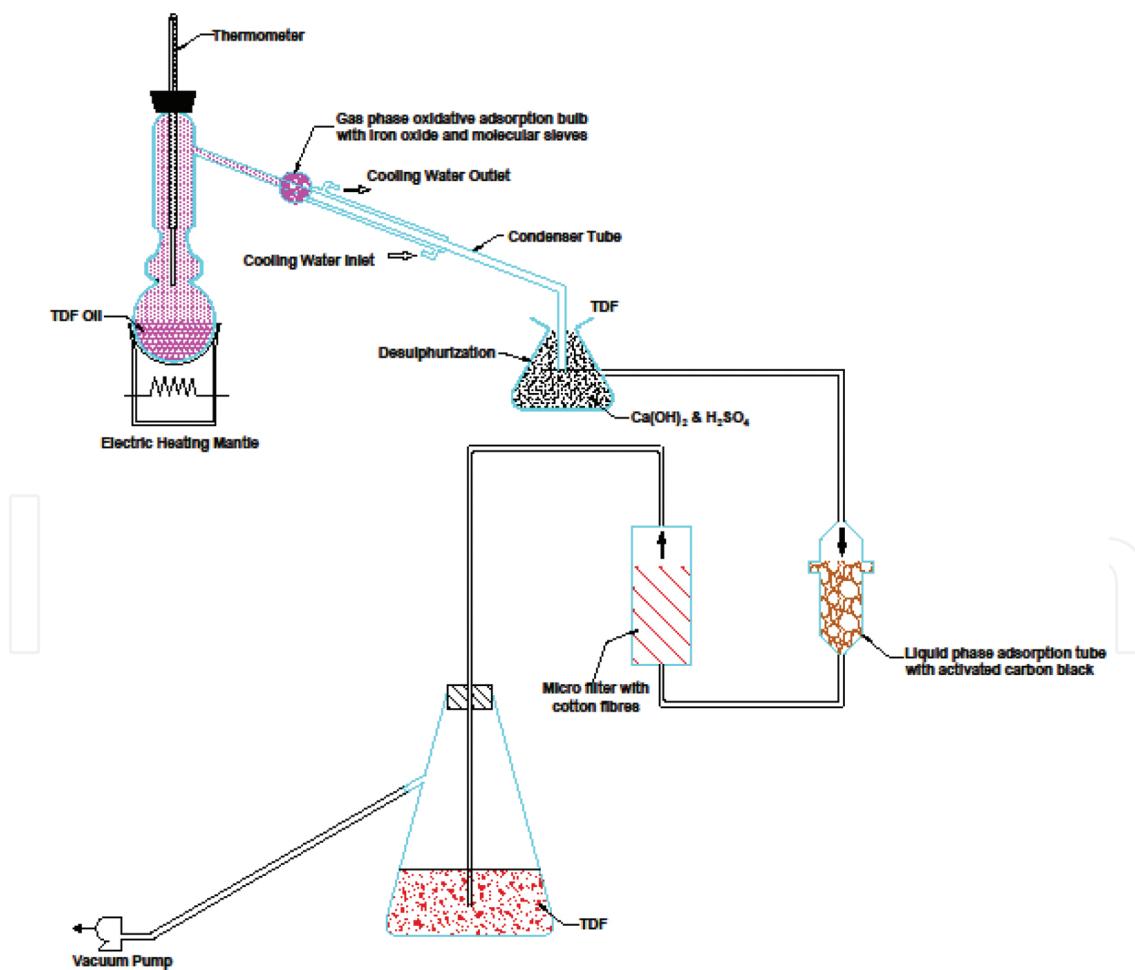


Figure 3. Experimental setup for TDF* production from TDF oil [22].

Fuel flow (kg/h)	1.5–3.4
Flame power (kW)	18–40
Nozzle (US gal/h)	0.5–0.85
Preheated nozzle line	Yes
Pump and fan motor	Single phase, 230 V, 50 Hz, 2800 min ⁻¹ , 4 µF/400 V capacitor
Electronic igniter	EBI
Blower turbine	Ø133 × 42
Air flap control	Manual
Control panel	Yes
Blast tube	Ø63/80 × 177
Fuel pump	11 bar discharge precision gear pump with solenoid valve AS47D

Table 2. Technical specification NC4 fuel burner [30].

Parameter	Sensors	Range	Resolution
Carbon monoxide	Electrochemical cell	0–10000 ppm	1 ppm
Nitrogen dioxide	Electrochemical cell	0–500 ppm	0.1 ppm
Sulphur dioxide	Electrochemical cell	0–5000 ppm	1 ppm

Table 3. Testo 350 gas analyzer technical specifications [31].

2.2. Experimental procedures

2.2.1. Fuel preparation

An experimental setup consisting of a fuel tank, in-line filtration system, and a forced draught external combustion system with emissions analyzer was developed as shown in **Figure 2**. Mixtures of TDF oil and petroleum diesel (DF) were prepared at TDF oil volumetric concentration in each sample of; 10, 20, 30, 40, 50 and 70%. To ensure that the problem of total contamination and water content is eliminated, all fuel bends were processed through a multi-stage filtration illustrated in **Figure 2** and random confirmation tests were performed to verify that the water content and total contamination were within acceptable limits. The most economical fuel blend was determined by the highest possible TDF oil volumetric concentration yielding the acceptable viscosity and flash point of the fuel mixture. Various TDF oil-

petroleum diesel blends were assessed by measuring their viscosities and flash points as per ASTM D445/D93 test methods, and the most economical mixture was selected and undergone full analysis as per test results presented in **Table 4**.

Parameter	Unit	Test method	TDF oil	DF	TDF ₄₀	TDF*	SANS342
Kinematic viscosity	(cSt at 40°C)	ASTM D445	9.23	2.25	4.9	3.41	2.2–5.3
Density	(kg/m ³ at 20°C)	ASTM D4052	942	828	846	848	800–950
Flash point	(°C)	ASTM D93	96	67	63	42	>50
Cetane index		ASTM D4737	22.3	53.9	41.7	51.8	
Calorific value	(MJ/kg)	ASTM D3338	39.9	45.9	42.7	43.8	
Total sulphur	(mg/kg)	ASTM 4294	11,450	443	4,516	1,100	<500
Aromatics	(wt%)	Calculated	43.5	26.1	36.3	27.2	
Lubricity	(µm WS1.4)	CEC-F06-A-96	939	489	678	471	>460
Oxidation stability	(g/m ³)	ASTM D2274	15	20	13	17	23
Total contamination	(mg/kg)	IP440	589	12	8	14	20
Water content	(mg/kg)	ASTM 6304	33,540	160	56	98	85

Table 4. Physical properties of TDF oil, DF, TDF₄₀ and TDF*.

A sample of TDF* was produced by flash distillation of TDF oil using the experimental setup shown in **Figure 3**. Other samples of TDF oil, DF and TDF* were also prepared for testing. Each sample was characterised in accordance with SANS 342 as per results presented in **Table 4**.

A bench-scale distillation setup consisting of 1 L round bottom flask, heating mantle, glass water-cooled condenser and a collecting flask as shown in **Figure 3** was used for flash distillation of TDF oil. The glass condenser was fitted with steel wool in order for the water vapour from the oil to promote oxidation of steel wool into ferric oxide, which will act as a catalyst for oxidation of sulphur compounds in gaseous phase. The temperature of the feed crude oil was monitored and initially maintained at 100°C to allow for evaporation and recovery of water, low boiling point mercaptans, sulphides and disulphides in the crude oil. The condenser bulb was filled with 13× molecular sieves supported over oxidized 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 crude oil was raised to 350°C for extraction of light and heavy fuel fractions from the crude oil, while oxidizing and capturing the sulphur compounds over the active layer of molecular sieves in the condenser bulb as shown in **Figure 3**. The system was properly sealed at each connection point to ensure that all vapours pass through the ferric oxide and molecular sieves before they are condensed into light fraction fuel. The condensed fuel was desulphurized by adding 25 wt% Ca(OH)₂ and 10 wt% H₂SO₄ as per treatment method reported [24]. This was followed by filtration through a series of activated carbon and micro-molecular filtration system presented in **Figure 3** for the removal of suspended and dissolved contaminants. The distillate was further chemically modified to adjust its viscosity and cetane index by adding recommended amounts of vinyl acetate and methacrylic anhydride as per IARC guideline for liquid fuel additives [32]. Chemical modifiers including 1400 ppm of vinyl acetate as viscosity modifier and 0.4 wt% methacrylic anhydride as fuel stabilizer were dosed into the distillate. A mixture of 30 vol.% n-heptane, 50 vol.% n-hexane and 20 vol.% methyl tert-butyl ether was added to the distillate at 5 vol.% to homogenize the fuel with the reagents to form modified tyre-derived fuel (TDF*).

2.2.2. Combustion tests

An NC4 Cuenod forced draught fuel burner was connected to a fuel tank through fuel piping consisting of 100 µm stainless steel mesh primary filter followed by a two-stage micro-molecular filter with packed cotton fibers and 13× molecular sieves, 5 µm paper-based secondary filter media and a 1 µm cellulose-based polishing filter. All joints and connection points were lined with thread tape to prevent leakages. The fuel tank was placed at elevated position, 1.5 m above the burner pump suction point in order to create enough net positive suction head for the pump. The burner head was mounted on a stationary frame facing an open area with sufficient ventilation.

The emission gas analyzer was also mounted on a stationary frame next to the burner head, such that its probe is in line with the burner head. The burner was switched on allowing the nozzle line to be preheated to optimum operating temperature. The test fuel was added into the tank and allowed to accumulate into the filters before firing the burner. The burner was fired, and the flame intensity was adjusted using manual air flap to select the optimum combustion air setting (CAS), while monitoring flue gas temperature using an infrared thermometer.

The burner was run for 60 min for each test fuel, and performance parameters such thermal power output, fuel consumption, flame stability, flue gas temperature and emissions were recorded. Flue gas emission was measured using Testo 350 emissions analyzer equipped with built-in electrochemical cells with an auto dilution system capable of measuring gaseous emissions of SO₂, CO and NO₂. The analyzer probe was positioned at the burner head to automatically sample the gases and measure the emissions. The tests results were stored into the analyzer memory and exported into Microsoft excel spreadsheet for analysis.

3. Results and discussions

3.1. Fuel characterisation

Based on the test results presented in **Table 4**, it was evident that pure TDF oil has some properties that do not comply with the minimum SANS 342 requirements to be used as combustion fuel in precision combustion equipment. Amongst these properties, TDF oil has significantly high concentrations of total sulphur and high viscosity compared to petroleum diesel. Its high total contamination and water content are the main reasons for its low calorific value and possibly high flash point. Although water and total contamination can be easily separated from the fuel by physical separation processes such as evaporation and filtration, some properties require distillation and chemical modification to be adjusted.

It has been reported that fractional distillation of TDF oil at temperatures of 350°C reduces total sulphur and that further chemical desulphurization and filtration produces a cleaner fuel [2, 22, 24]. However, the fuel's viscosity and flash point drops below the acceptable limits prescribed in SANS 342 standards due to some TDF oil constituent components being stripped away during distillation and chemical desulphurization process. It is believed that some of these constituent components solidify and removed from the fuel during filtration.

Addition of recommended amounts of 1400 ppm vinyl acetate (viscosity modifier) and 0.4 wt % methacrylic anhydride (fuel stabilizer) as per IARC guideline for liquid fuel additives has shown a significant improvement of the fuel's viscosity and flash point [32]. However, the flash point was found to be lower than the specified minimum limit for safe handling. Lower flash point is often associated with elevated fuel consumption and potential risks of auto-ignition during handling and storage; hence, it is expected for TDF* to be consumed faster than diesel fuel during combustion with higher flame temperature as a result of auto-ignition. A mixture of 30 vol.% n-heptane, 50 vol.% n-hexane and 20 vol.% methyl tert-butyl ether, which was added to the TDF* at 5 vol.% to homogenize the fuel, is believed to have contributed to the fuel's improvement in calorific value as well as the cetane index as reported in **Table 4**.

Ignition properties of TDF oil are typically poor as represented by a low cetane index of 22.3. This is associated with the presence of high concentrations of non-flammable components such as water and total contaminants of 3.54 vol.% and 586 mg/kg, respectively. Nonetheless, the cetane number improved to 44.8 as the TDF oil was converted to TDF* by gas phase oxidative fractional distillation process described in **Figure 3**. This number was further improved by the addition of chemical modifier. Alkyl nitrate is commonly used as ignition improvers due to their affinity for hydrocarbon chain clouding in oils and hydrocarbon liquid fuels [33]. It was observed that the addition of 800 mg/L of alkyl nitrate into TDF could effectively increase the cetane index of the fuel by 12–16%.

Previous research has shown that TDF oil is distillable at temperature range of 193–359°C, up to 10, 50 and 90 vol.% of this fuel can be recovered at distillation temperatures of 218, 289 and 335°C, respectively [22]. At this temperature range, sulphur is more easily removed because lower boiling oil fractions primarily contain sulphurous compounds that are in the form of mercaptans, sulphides, disulphides or lower member ring compounds, which are relatively

easier to desulphurize [34]. Typical sulphur compounds such as mercaptans, sulphides and disulphides boils below 193°C and can be easily evaporated for effective gas phase desulphurization over an active surface layer of adsorbent such as molecular sieves or activated carbon [35].

There were few TDF oil parameters not complying with SANS 342 specifications for use in precision combustion equipment. These included viscosity, total sulphur, total contamination and water content. Adequate filtration can easily eliminate the concerns associated with total contamination and water content. Parameters such as viscosity and total sulphur may be adjusted by blending TDF oil with other cleaner petroleum fuels. A blend containing 40 vol. % TDF (TDF_{40}) was found to be the optimum test mixture with an acceptable kinematic viscosity of 4.9 cSt and flash point of 63°C. This sample was taken for full analysis and was tested against TDF* and pure petroleum diesel to evaluate its combustion characteristics.

TDF oil was obtained with relatively high viscosity of 9.23 cSt; however, the viscosity dropped to 1.88 cSt after distillation. Although viscosity of liquid fuels decreases temporarily as its temperature is increased, the specifications for precision combustion equipment require the kinematic viscosity of the fuel measured at 40°C to range between 2.2 and 5.3 cSt for normal fuel flow and operation of the equipment with less emissions. The test results presented in **Table 4** show that the kinematic viscosity of TDF could be improved by the addition of 1400 ppm vinyl acetate. Additives such as vinyl acetate can reduce the thinning effect of the fuel caused by operation at high temperatures [36]. This viscosity improver has long chains and high molecular weights. Its function is to increase the relative viscosity of the fuel more at high temperatures than at low temperatures. It coils at low temperatures and uncoils as the temperature increases. Uncoiling makes the molecules larger, which increases internal resistance within the thinning oil [37].

The test data presented in **Table 4** show a 90.3% overall reduction in total sulphur from conversion of TDF oil into TDF*. This was achieved by multiple processing methods as described in **Figure 3**. Previous research has revealed that sulphur reduction in TDF oil can be achieved by chemical treatment followed by blending it with low sulphur commercial diesel fuel [38, 39]. Pilusa et al. [22] has presented that most mercaptans boils at below 100°C, explaining why they could be removed from the TDF oil via gas-phase desulphurization distillation over an adsorbent with a pore size large enough to capture all molecular size ranges.

Desulfurization remains a key driver with increasing trends to shift towards cleaner fuels. As the sulphur level in diesel fuel is reduced, the inherent lubricity characteristics of the fuel are also reduced. Sulphur level of the petroleum diesel fuel is reduced by the application of hydro-treating processes which remove sulphur- and nitrogen-containing compounds, and these compounds have good natural lubricity [35]. The process of producing low-sulphur diesel fuel also leads to a reduction in aromatic compounds, and these compounds are known to have better lubricity than aliphatic compounds [40]. Combustion fuels with poor lubricity characteristics can lead to atomizer pump wear and eventually failure, so the lubrication properties of the fuel have become an important parameter. Lubricity improvers such as 0.03 wt% phosphate ester amide restore the natural lubricity properties of the fuel [41]. There was no

need to add any lubricity modifier as the test value for TDF* was found to be within the acceptable limits after the fuel was treated with other chemicals.

3.2. Combustion tests

Uniform fuel droplets are consistently generated by the atomizer at the combustion zone allowing mixing with incoming forced air. An electric-generated spark initially ignites the mixture, while the stable flame at the burner core continues to ignite the incoming fuel air mixture as demonstrated in **Figure 4**.

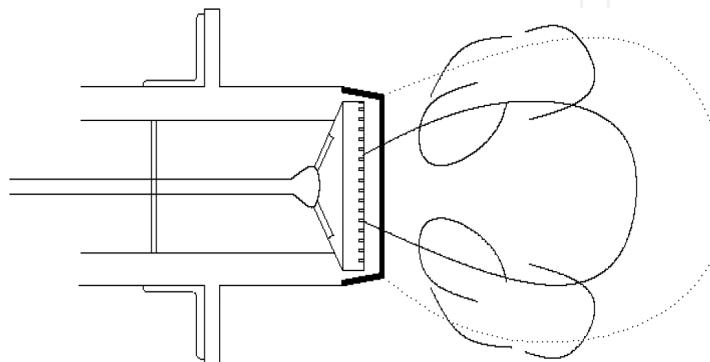


Figure 4. Cross section of the fuel burner.

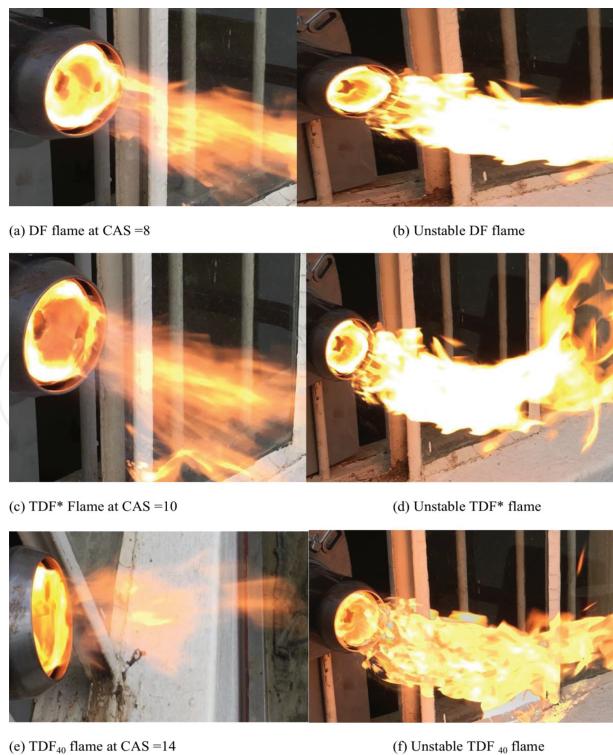


Figure 5. Images of stable and unstable burner flames produced by various fuels tested.

It was discovered that fuels with different physical properties attained stable flames under different AFR, which was controlled by CAS in this instance. DF flame stabilized quite quickly at CAS of 8, whereas TDF* and TDF₄₀ stabilized at CAS of 10 and 14, respectively, as shown in **Figure 5**. This implies that stoichiometric air requirement for TDF* and TDF₄₀ is much higher than that of diesel fuel. This could be as a result of high viscosities and flash points of both TDF* and TDF₄₀. As reported in literature, high viscosity results in restricted fuel flow and poor atomization whereas low flash point is associated with auto ignition and higher fuel consumption [9]. **Figure 5(a, c and e)** show the different stable flame intensities for DF, TDF* and TDF₄₀ with a decrease from white to dark orange core flame colors, respectively. This is also justified by the decrease in flue gas temperatures measured for each fuel.

All fuel tested were able to produce peak flame power output similar to the ones specified by the burner manufacture as stipulated in **Table 2**. The test results presented in **Figure 6** show that burner operated more efficiently with diesel fuel as it was able to reach the highest flame power output at CAS of 6 with actual fuel consumption of 2.84 kg/h. TDF* and TDF₄₀ has lower fuel consumption and consequently unstable flames and low flame power as a result of high viscosity, low flash point and low calorific value.

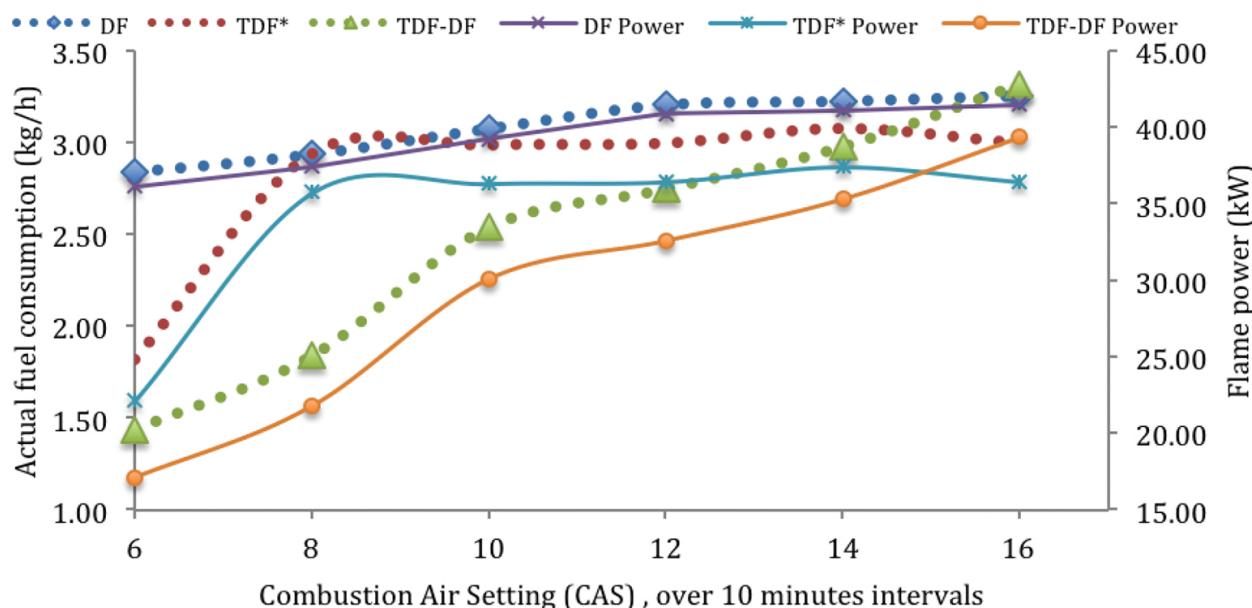


Figure 6. Performance test data of NC4 fuel burner using DF, TDF* and TDF₄₀.

The burner reached a stable flame at CAS 8 when operated with diesel fuel whereas TDF* and TDF₄₀ reached their stable flames at CAS of 10 and 14, respectively. The burner specific fuel consumption (SFC), which is defined as a ratio of the actual fuel consumed and power delivered, was found to be 78.43, 82.19 and 84.37 g/kWh when operated with DF, TDF* and TDF₄₀, respectively. This implies that more efficient heat was produced by diesel fuel due to its high calorific value and good flow characteristics.

3.3. Flue gas emissions

Combustion tests were carried out for 60 min for each test fuel. Average emission data were recorded every 10 min as the combustion air setting (CAS) was adjusted to the next value. The data reported in **Figure 7** display the average test data taken at the optimum CAS value for each fuel. CAS is a measure of air-fuel ratio (AFR); selection of higher CAS value on the burner allows more air to be introduced into the combustion zone for enhanced combustion. The optimum CAS was attained when a more stable flame with highest flue gas temperature was recorded. These values were obtained as 8, 10 and 14 for DF, TDF* and TDF₄₀, respectively.

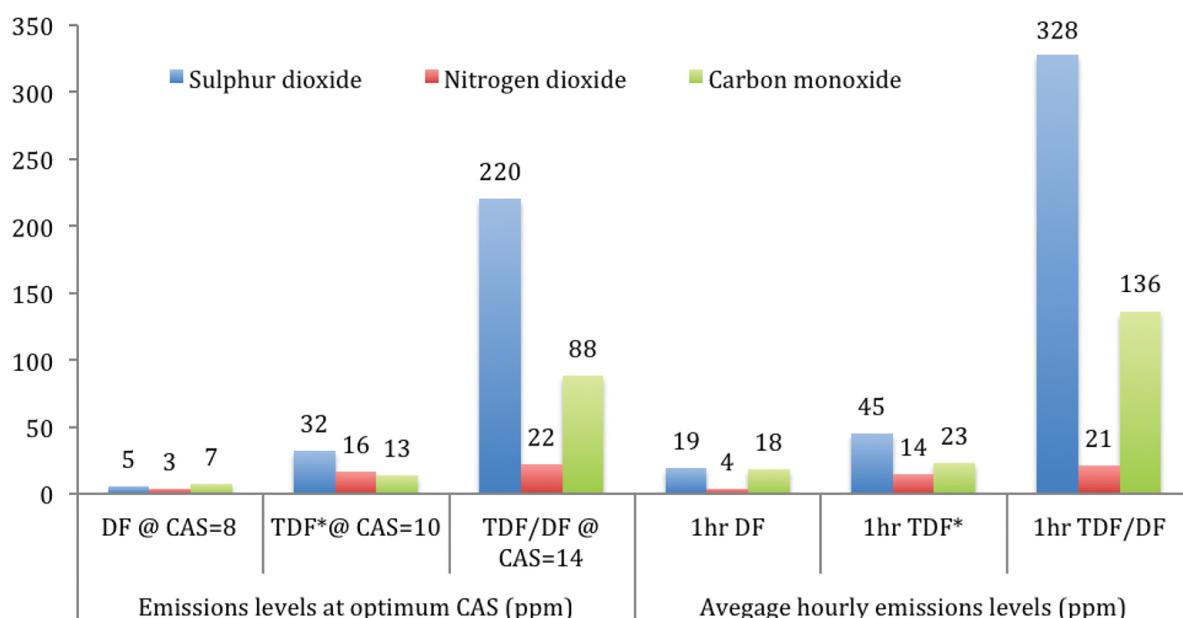


Figure 7. Selected flue gas emissions from a burner operated with various fuels.

The results show that TDF₄₀ produces high emission levels compared to TDF* and DF. High sulphur emissions are attributed by the concentrations of sulphur in the fuel; TDF₄₀ contains 4516 ppm total sulphur, while TDF* contains 1100 ppm total sulphur which is significantly higher than the sulphur levels in DF (443 ppm). The maximum flue gas temperatures for each fuel at optimum CAS were recorded as 546, 489 and 420°C for DF, TDF*, and TDF₄₀, respectively. Hence, the flame core color changed from white to dark orange as seen in **Figure 5** (a, c and e).

In practice, there are a number of reasons why this temperature will be lower than the adiabatic flame temperature, which has been reported to be 2102°C [42]. One of the reasons is that combustion products dissociate back into reactants or other higher reactive species accompanied by absorption of energy, hence reducing the actual flame temperature. Any excess air will increase the mass of flue gas relative to the mass of fuel, with a corresponding reduction in

temperature; hence, the flue gas temperature of highest CAS value (TDF_{40}) was reported to be the lowest. With sub-stoichiometric air supply, the flame temperature will also fall, as though the mass of flue gas is reduced. The effective calorific value of the fuel is also reduced by an amount equivalent to the calorific value of the CO, which is present in the flue gas.

CO emissions was found to be reasonably low and within the ambient air quality standards presented in **Table 1**, except for TDF_{40} blend which was higher. However, the formed CO molecules are oxidized if there is enough oxygen in the combustion environment. This may be as a result of high-volume fuel being introduced to the atomizer at high viscosity resulting in poor fuel atomization [43]. Larger fuel droplets are introduced into the combustion zone. These droplets are not fully oxidized due to their larger surface area and the flue gas product and also tend to contain high HC, CO and high flame temperatures promoting NO_2 formation. Under these conditions, more fuel is used due to inefficient fuel oxidation as it was observed with rapid soot formation on the burner nozzle when the TDF_{40} was tested.

4. Conclusions

TDF oil from continuous tyre pyrolysis plant has been refined by gas-phase oxidative fractional distillation including desulphurization, adsorption, filtration and chemical modification of certain physical properties in accordance with SANS 342 for use in precision combustion equipment. TDF* was produced as a test fuel to be compared with standard diesel fuel in a Cuenod NC4 fuel burner. It was concluded that TDF oil could be refined into TDF* exhibiting similar properties to standard diesel fuel. Vinyl acetate, alkyl nitrate and some combination of organic polar solvents can effectively adjust the fuel's viscosity, cetane index and calorific value. It was also concluded that TDF oil is not recommended for use in precision combustion equipment in its raw form. Pretreatment processes, such as multistage filtration, are essential for the removal of total contamination and residual moisture. Modification of the fuel's properties such as viscosity, flash point and total sulphur is essential. Purification of TDF oil through a process of oxidative desulphurization fractional distillation with chemical desulphurization and filtration has shown a great potential of using the fuel derivative (TDF*) directly in precision combustion equipment. TDF can also be blended with petroleum diesel fuel at TDF oil volumetric concentration of <40% (TDF_{40}), and the fuel mixture must undergo multistage filtration. TDF oil and its derivatives produce SO_2 , NO_2 and CO emission levels higher than acceptable limits as prescribed by the European Air quality standard (EU2015/2193). It was concluded that TDF oil is a potential industrial burner fuel if diluted with petroleum diesel fuel at TDF volumetric concentration of <40% or any ratio that could adjust the viscosity level below 5.3 cSt. Multistage filtration system is highly recommended to reduce total contamination and water levels in the fuel mixture. Exhaust gas scrubbing is also recommended due to significantly high sulphur oxide emission in the flue gas.

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