Combustion analysis of pyrolysis end of life plastic fuel blended with ultra low sulfur diesel

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A B S T R A C T

The ever increasing energy demand along with fast depleting non-renewable fossil fuels and global climate change has led to a search for alternative energy resources. Waste plastic fuels have gained significant interest since they not only solve disposal problems but also provide an alternative energy resource. Combustion analysis of waste plastic derived fuels has shown conflicting findings with respect to fuel consumption and hazardous emissions. This is due to the conversion process employed (e.g., thermal vs. catalytic pyrolysis) and plastic type utilized resulting in a diverse range of fuel properties (i.e., viscosity and cetane Number). In this effort, a commercially-derived fuel (CynDiesel™) made from a blend of waste plastics through catalytic pyrolysis was tested as a blend with Ultra Low Sulfur Diesel (5%, 10%, 20%, and 100% by volume) to better understand the changes to pre-mixed and diffusion burn phases as a function of fuel properties. The significantly large cetane Number of this fuel combined with its relatively higher viscosity dramatically reduced the more efficient pre-mixed combustion phase; however, fuel consumption remained constant because of its greater energy content by mass. As a result, in-cylinder temperatures were found to be higher at high loads, but nitrogen oxide (NO_x) emissions went down with CynDiesel™ content. Furthermore, a theorized reduction in aromatic content and shift to saturated bonds with blend percentage resulted in lower hydrocarbon (HC) and carbon monoxide (CO) emissions even though particulate matter (PM) emissions increased because of the growth of the diffusion burn phase. At low blend contents, the waste plastic derived fuel did not adversely influence engine performance; however, there were apparent differences in the emissions profile.

1. Introduction

Waste plastics have created a significant environmental challenge because of their quantity and disposal issues. Within the United States alone, over 30 million tons of plastic waste is generated each year. Of this waste, nearly 50% is formed from polyethylene-based plastics, namely polyethylene terephthalate (PET) at 12.4%, and high- and low-density polyethylene (HDPE and LDPE) at 17.8% and 19.6%, respectively. Polypropylene (PP) and polystyrene (PS) compose 13.9% and 8.7%, respectively, while polyvinyl chloride (PVC) makes up 5.5%, and other unclassified plastic materials constituent the remaining 22% of total plastic waste [1]. Since these plastics are produced from refined crude oil, they can potentially be used to create liquid hydrocarbon fuels whose properties are close to that of existing fossil fuels. Thermal pyrolysis is one of the more promising processing options in order to recover the energy from this waste since only about 10% of the energy content of the waste plastic is used to create valuable hydrocarbon products and this technique is considered to be economical [2–4].

The composition and quantity of liquid fuels derived from pyrolysis depends on the type of waste plastic used, temperature, and reaction conditions [2,5–10]. Furthermore, pyrolysis processes encounter varying degrees of degradation of the plastic depending on the precise feedstock used and the specific pyrolysis process utilized [11]. Typically, PS has shown near total conversion into liquid and gaseous products through pyrolysis [12]; whereas, PP, PET, and PVC have displayed intermediate amounts of conversion with HDPE and LDPE generally the most resistant to conversion [13]. However, HDPE and LDPE also normally produce a higher liquid fraction under pyrolysis, and fuels from HDPE feedstocks often mimic ULSD more closely than the other feedstocks, with comparable values for flash point, energy content, density, and viscosity [14,15]. Hence, fuels derived from HDPE waste plastics have relatively little trouble meeting ASTM D975 and EN590 fuel standards [16]. In contrast, plastics such as PET, PS, and PVC have shown higher concentrations of aromatics and unsaturated chemical compounds, leading to potentially higher NO_x emissions, and lowered cetane number of the resulting fuel [13,17–19]. Within mixtures of feedstocks, PET, PS, and PVC mixtures have shown further increases in aromatic content beyond that encountered in pyrolysis of neat PET, PS, or PVC feedstocks [12,18], which may also be related to increased temperature used for those feedstocks during conversion. In addition, pyrolysis of PP

and PVC feedstocks produce fuels reminiscent of some neat polyethylene feedstocks [19], as interactions between the degraded feedstocks lead to the creation of longer hydrocarbon molecules typically produced from pyrolysis of LDPE or HDPE. Generally, pyrolysis of more varied mixtures (particularly in the cases of municipal solid waste) is less well understood, and differentiation between the effects of impurities (such as glass, metals, or paper products) and the mixture of the actual plastic feedstocks are not well defined at present [11].

Within the conversion process, proper reactor operation can yield fuels directly suited for internal combustion engine usage. The extent of conversion of the waste into usable engine fuels can be further increased through the application of stable hydro-cracking catalysts [6,9,20,21]. The inclusion of a catalyst lessens the process temperature while lowering both boiling temperatures and densities of the obtained liquid products, and also promotes selective degradation of waste plastics into a more useful product [6,20]. Furthermore, studies have shown that adding iron and calcium based catalysts helps remove bromine from the liquid fuel product, subsequently decreasing the nitrogen content by converting nitrile compounds into ammonia [2]. This can reduce NO_x and hydrogen cyanide (HCN) emissions when this liquid fuel is used as a blend with petroleum diesel in a compression ignition (CI) engine. Catalytic pyrolysis (particularly fluid catalytic cracking) has been shown to effectively break down various feedstocks, including PS and PE (when dissolved in BTX compounds) [22–24], or HDPE (when dissolved in phenol) [25], all successfully producing heavy fuel oils usable for CI combustion. Selective catalysis and sufficient washing may also be utilized to remove impurities from the waste plastic feedstocks, improving the general quality of the output fuels [26]. Impurities within the feedstocks themselves also form a concern; PVC has the potential to form hydrochloric acid during pyrolysis, harming both the reactor and its potential as a fuel unless the chlorine content in the feedstock can be lowered prior to or during pyrolysis [27].

In general, the diesel fractions of pyrolysis oil obtained from thermal cracking of waste plastics have been observed to have a higher viscosity, density, and lower calorific value as compared to that of conventional diesel fuel [6,7,10,28] as attributed to the larger aromatic content of the fuel derived through this process [29]. Furthermore, fuels derived through thermal cracking of waste plastic are said to have a lower cetane number compared to diesel. In contrast, the diesel fractions obtained through catalytic thermal cracking have been observed to have lower viscosity, density, and higher calorific value than that of diesel fuel [9,20] because these catalysts reduce the aromatic content of the fuel [5,7–9,20]. This wide variance in resultant waste plastic fuel properties indicates the variability in this field that can influence fuel economy and emissions when combusted in a CI engine.

In particular, when fuel derived from assorted waste plastics through catalytic pyrolysis was used as a neat fuel, Mani et al. reported increased NO_x, carbon monoxide (CO), and hydrocarbon (HC) emissions due to a lower cetane number, reduced calorific value, and longer ignition delay in comparison to diesel [28]. They also indicated higher brake thermal efficiencies, higher exhaust gas temperatures, and lower smoke levels for the waste plastic derived fuel. This was attributed to a larger premixed combustion phase, faster flame propagation, and larger oxygen content in the fuel. Murugan et al. also similarly found higher brake thermal efficiencies with a rise in thermal pyrolysis derived fuel (from waste tires) concentration with diesel [29]. They additionally saw greater NO_x, CO, HC, and smoke emissions that they attributed to a higher aromatic content of the derived fuel along with a longer measured ignition delay. Similar to Murugan et al., Kumar et al. found that HC, NO_x, and CO emissions all increased with blend percentage via catalytic pyrolysis (waste HDPE) [30]. Carbon dioxide (CO_2) emissions for the blends were determined to be lower than neat petroleum diesel at almost all loads via lower brake thermal efficiencies. Whereas these researchers found significant differences during combustion when blending with waste-plastic derived fuels, Özcanli saw similar performance and emission characteristics as that of diesel

fuelled engines when testing CynDiesel™ at small quantities (5% by volume) [31]. This outcome is encouraging because waste plastic derived fuel blends should not significantly change the performance and emissions characteristics of the engine, in order to support available fuelling infrastructure and engine after treatment devices.

Therefore, in order to obtain a greater understanding of the effects of a waste plastic derived fuel on the CI combustion process, this effort investigates the prior mentioned CynDiesel™ as a blend with common Ultra Low Sulfur Diesel (ULSD) in ratios of 5%, 10%, 20%, and 100% by volume. CynDiesel™ was supplied by Cynar Plc (Portlaoise, Ireland) and is derived using a proprietary catalytic thermal pyrolysis methodology using commercial and industrial packaging (i.e., a blend of HDPE, LPDE, PP up to 25% by total weight, and PS up to 20% by total weight) as the feedstock source. All plastic feedstock was fed as a 10–15 mm flake, and the total weight of materials other than the plastics mentioned did not exceed 10%. According to their patent [32], the pyrolysis reactor is maintained at a temperature in the range of 450–700 °C. The fuel is defined under the ISO 14025:2006 product category rule for product group UN CPC 33360; however, due to commercially sensitive information, the catalytic material employed in pyrolysis was not disclosed. This effort additionally employs a higher pressure injection system more indicative of modern CI engines. This ensures that the results are based primarily on fuel properties and not combustion timing through normalization of waste plastic blend injection timings to match the peak in-cylinder pressure location of ULSD. In prior efforts, combustion normalization may not have been accomplished and the results presented may be a combination of changes to both injection timing and fuel properties.

In the following sections, the experimental setup and methodology, fuel physical properties, in-cylinder pressure traces, rate of heat release, brake specific fuel consumption, and brake specific emissions (CO, CO_2, HC, NO_x, and PM) of CynDiesel™ blends are discussed in detail with respect to changes in fuel physical properties from those of ULSD.

2. Experimental setup

For brevity, only major instrumentation highlights will be presented here as Langness et al. [33] provides thorough documentation of the experimental setup along with the specific hardware employed. The test engine is a Yanmar L100V single cylinder direct injection CI engine with the stock mechanical fuel injection replaced with a common-rail electronic fuel injection system controlled by a Bosch MS15.1 Diesel Electronic Control Unit (ECU). This allows for variable injection timings with resolution of 0.02° per crank angle (up to five injections per thermodynamic cycle), while modulating the injection pressures from 40 to 200 MPa (50.0 ± 0.5 MPa used for this study). An alternating current (AC) air-cooled regenerative dynamometer from Dyne Systems, Inc. acts to maintain the speed of the engine, with load adjusted through the fuel injection amount. Torque is measured using a FUTEK transducer (Model #TRS-705) that is installed using couplings between the Yanmar engine output shaft and dynamometer input shaft. A Merriam laminar flow element (Model #50MW20-2) and an Omega differential pressure transducer (Model #PX277-30D5V) are used to measure inlet air mass flow. Fuel flow rate is characterized using a Micro-Motion Coriolis flow meter (Model #CMF010M). A Kistler (Model #6052c) pressure transducer is used to measure in-cylinder pressures, and the corresponding crank angle is measured using a Kistler (Model #2614B) encoder. The stock Exhaust Gas Recirculation system for the Yanmar engine has been disabled. To characterize emissions in the exhaust stream, an AVL SESAM Fourier Transform Infrared Spectroscopy (FTIR) emission analyzer is employed. This device measures total hydrocarbons (THCs), CO, and NO_x emissions among others. Oxygen is measured using a Magnos 106 oxygen sensor. Finally, PM emissions are monitored using AVL (Model #415S) Variable Sampling Smoke Meter.

The injection timing (standard) of the engine is calibrated for ULSD such that the minimum amount of fuel is consumed at a particular