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Full Length Article

Experimental characterisation of a diesel engine running on polypropylene oils produced at different pyrolysis temperatures

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ABSTRACT

Polypropylene is the most common type of plastic found in municipal solid waste. The production of polypropylene is expected to increase due to the widespread utilization in daily life, resulting in even higher amounts of polypropylene waste. Sending this plastic to landfill not only exacerbates environmental problems, but also results in energy loss due to the elevated energy content of polypropylene. Pyrolysis is a process that can effectively convert polypropylene waste into fuel, which can then be used to generate power and heat. In the present study, the effect of the pyrolysis temperature on the pyrolysis of polypropylene was investigated, while the oils produced at 700 °C (PP700) and 900 °C (PP900) were used to fuel a four cylinder diesel engine. The engine's combustion, performance, and emission characteristics were analysed and compared to diesel operation. The results showed that both PP700 and PP900 enabled stable engine operation, with PP900 performing slightly better in terms of efficiency and emissions. However, PP700 and PP900 were found to have longer ignition delay periods, longer combustion periods, lower brake thermal efficiencies, higher NO_X, UHC and CO emissions, and lower CO_2 emissions in comparison to diesel operation. Nonetheless, the addition of a small quantity of diesel improved the overall performance of the oil blends, resulting in comparable results to diesel in the case of PP900.

1. Introduction

Over the past century the production of plastics has increased dramatically to accommodate the demands of the rapidly growing population and the modern lifestyle. Alongside food and paper, plastic waste is one of the major contributors to municipal solid waste, accounting for approximately 9–12% by weight [1]. Its volumetric contribution is even higher, considering the low density of the plastics (20–30% of municipal solid waste volume) [2]. Polypropylene (PP) is one of the most commonly used plastics, with around 55 million tonnes of production annually [3]. PP is a polyolefin polymer with a linear hydrocarbon chain that has low density, good process ability, attractive mechanical properties, and high chemical and heat resistance (melting point greater than 160 °C) [4]. Therefore PP has a wide variety of applications, ranging from textiles, laboratory equipment, automotive components, packaging, labelling, and more.

PP is the main plastic component found in municipal solid waste, contributing 24.3% of the total plastics [5]. The vast quantity of PP waste is expected to increase even further due to the high demand for PP products in our daily lives. Such a great amount of PP is found in landfill because mechanical recycling can be applied only to clean and single polymer waste; mixed PP cannot be recycled. Unfortunately, PP (like most plastics) has a low degradation rate, which can cause serious environmental problems such as soil and water contamination [6]. Furthermore, PP includes a significant amount of energy (46.4 MJ/kg) that could be utilised to replace conventional fossil fuels [7].

Conversion of PP into fuel can be achieved by conventional refinery processes such as hydrocracking, gasification, and pyrolysis. Pyrolysis is considered one of the most promising technologies for converting plastic waste into high quality oil [1,8–10]. The pyrolysis process is a thermo-chemical degradation reaction that takes place at elevated temperatures in the absence of oxygen. The conversion products can be found in gaseous, liquid (oil), and solid (char) phases. The quality and quantity of the pyrolysis products depend on the feedstock (plastic type) and the pyrolysis process parameters (e.g. reactor type, residence time, temperature, catalyst). Pyrolysis temperature is arguably one of the most important process parameters because it has great impact on the thermal cracking of the polymers [11–13]. Previous studies on the pyrolysis of PP have largely focussed on the use of catalysts [14–19], while only a small number have investigated the effect of temperature [20–23]. The latter studies, which have reported pyrolysis temperatures ranging from 300 °C to 740 °C, revealing the potential of these oil

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Nomenclature

PP700	polypropylene oil produced at 700 °C
PP700 75	75% PP700 + 25% diesel fuel
PP900	polypropylene oil produced at 900 °C
PP900 75	75% PP900 + 25% diesel fuel
NO_X	nitrogen oxides
CO	carbon monoxide
CO_2	carbon dioxide
UHC	unburned hydrocarbons
LHV	lower heating value
BMEP	brake mean effective pressure
IMEP	indicated mean effective pressure
COV_{IMEP}	coefficient of variation of IMEP
°CA	crank angle degrees
HRR	heat release rate
MFB	mass fraction burned
ϕ	equivalence ratio
BTE	brake thermal efficiency

products to replace fossil fuels in internal combustion engines.

Diesel engines are desirable for alternative fuel testing in the case of power generation applications, because of their high efficiency over a wide range of load, ability to operate on lower quality fuels, and less demanding exhaust emission regulations [24]. Experimental investigations into the use of oils derived from the pyrolysis of plastic waste in diesel engines has focused on single cylinder engines and oil-diesel blends, reporting lower engine performance and higher UHC, CO and NO_X emissions compared to diesel operation [25–30]. However, no studies have yet investigated the pyrolysis of pure PP at temperatures higher than 740 °C, or the use of pure PP pyrolysis oil in a diesel engine. In the present study, PP was pyrolysed at temperatures of 700 °C and 900 °C, and the oil and gas products characterised. Moreover, the produced oils were used in a four-cylinder diesel engine in order to evaluate the feasibility of utilizing them as alternative diesel engine fuels and estimate their optimum operational conditions. To accomplish this purpose, the engine's combustion, performance, and emission characteristics were fully analysed.

2. Materials and methods

2.1. Conversion process and fuel properties

The pyrolysis of the polypropylene was conducted in a pyrolysis plant consisting of three chambers; the primary, secondary, and conversion chamber (fixed bed reactor). The schematic layout of the pyrolysis plant is presented in Fig. 1 while the details of the pyrolysis plant are described in our previous study [31]. PP was used as a feedstock and converted into gas, oil and char, via the fast pyrolysis process at conversion chamber temperatures of 700 °C and 900 °C. More gas and less oil were produced at the conversion temperature of 900 °C compared to 700 °C, which is in accordance with the literature review [11,32,33]. More specifically, at 900 °C gas production was 50% of the feed mass, 40% oil and 10% char, while at 700 °C gas production was 25% of the feed mass, 65% oil and 10% char.

The produced gases were analysed using the Gas Chromatography-Thermal Conductivity Detector (GC-TCD) and Gas Chromatography-Mass Spectrometry (GC–MS) methods. The compositions of the gas products at the different pyrolysis temperatures are shown in Table 1. These results indicate that the effect of pyrolysis temperature on the composition of the gaseous phase products is small. Both gas products present similar compositions, consisting mainly of hydrogen, methane, and carbon dioxide, with small fluctuations.

The polypropylene pyrolysis oils produced at pyrolysis temperatures of 700 °C (PP700) and 900 °C (PP900) have a mild smell and a dark black colour. The Gas Chromatography-Mass Spectrometry (GC-MS) method was used to identify the most abundant compounds of PP700 and PP900. The analysis showed that the pyrolysis oils contain a mixture of hydrocarbons with more than 50 compounds. Table 2 depicts the compounds with the highest concentrations which detected for the polypropylene oils.

The basic physio-chemical properties of the PP700 and PP900 are presented in Table 3, benchmarked with diesel fuel. Density, carbon, hydrogen and ash content of PP700 and PP900 are comparable with diesel, while the poly-aromatic hydrocarbons, aromatic and oxygen content are higher. Lower heating value (LHV) of PP700 and PP900 is slightly lower than diesel, indicating their good potential to fuel diesel engines. The 10% distillation temperature of PP700 is significantly lower than that of diesel, indicating that PP700 contains a large amount of lighter compounds (i.e. shorter hydrocarbon chains). In addition, the 90% distillation temperature of PP700 is higher in comparison to diesel, revealing that the PP700 includes heavier products too (longer hydrocarbon chains and poly-aromatic hydrocarbons).

The cetane index, which indicates the compression required to ignite the fuel, is lower for PP700 compared to diesel, revealing that the ignition delay period (the period from start of injection until the start of

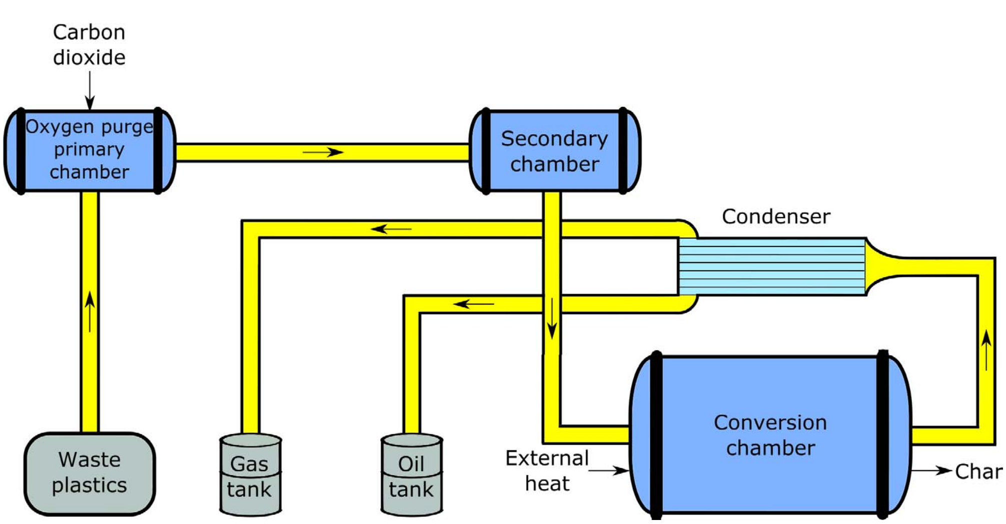

Fig. 1. Schematic layout of the pyrolysis process.