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The utilisation of oils produced from plastic waste at different pyrolysis temperatures in a DI diesel engine

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ABSTRACT

Chemical recycling is an attractive way to address the explosive growth of plastic waste and disposal problems. Pyrolysis is a chemical recycling process that can convert plastics into high quality oil, which can then be utilised in internal combustion engines for power and heat generation. The aim of the present work is to evaluate the potential of using oils that have been derived from the pyrolysis of plastics at different temperatures in diesel engines. The produced oils were analysed and found to have similar properties to diesel fuel. The plastic pyrolysis oils were then tested in a four-cylinder direct injection diesel engine, and their combustion, performance and emission characteristics analysed and compared to mineral diesel. The engine was found to perform better on the pyrolysis oils at higher loads. The pyrolysis temperature had a significant effect, as the oil produced at a lower temperature presented higher brake thermal efficiency and shorter ignition delay period at all loads. This oil also produced lower NO_X, UHC, CO and CO_2 emissions than the oil produced at a higher temperature, although diesel emissions were lower.

1. Introduction

The explosive growth in the production and everyday use of plastics over the past decades has made plastic waste disposal a serious environmental challenge. In 2015 global plastic production reached 322 million tonnes, a dramatic increase compared to the 279 million tonnes produces in 2011 [1]. The plastics demand in the European Union was 58 million tonnes, of which 29.7% was recycled, 39.5% was recovered in the form of energy (mainly incineration) and 30.8% was sent to landfill [1]. However, plastics contain a significant amount of energy due to the crude oil that is used in their production [2]. Moreover, most of the plastics are not biodegradable, therefore by sending them to landfill not only pollutes the environment, but also throws away a significant amount of energy that could be used to generate electricity and heat [3].

There are two main categories of recycling: mechanical and chemical. Mechanical recycling can be applied mainly to single polymer plastic waste, while chemical recycling can be performed on more complex and contaminated plastic waste [4]. Chemical recycling, or feedstock recycling, aims to chemically degrade plastic waste into its monomers or other chemicals (such as alternative fuels). Chemical recycling can be achieved by conventional refinery processes such as gasification, pyrolysis, hydrocracking and catalytic cracking. The pyrolysis process is one of the most promising technologies in the conversion of waste plastics into high quality oil [5–8]. During pyrolysis, plastic polymers are thermally degraded by heating them in the absence of oxygen. The main products of the pyrolysis process are liquid and gaseous, producing only a small amount of solid. The quantity and quality of the pyrolysis products depend on the waste plastics composition and the process parameters (temperature, residence time, catalyst, etc.) [9–12].

An important and extensively-studied process parameter is temperature, because it has a greater impact on the thermal cracking of plastic polymers than the other process parameters [13–15]. It has been shown that the pyrolysis temperature influences the characteristics of the liquid products to a much greater extent than the gaseous and solid products [5]. More specifically, the liquid product (or plastic pyrolysis oil) produced at lower pyrolysis temperatures has a higher viscosity due to the high content of long hydrocarbon chains [5], while higher pyrolysis temperatures increase the cracking of the C–C bonds, resulting in the formation of lighter hydrocarbons (shorter chains) [16,17]. The pyrolysis temperature also affects the amount of aromatic hydrocarbons in the plastic pyrolysis oil (PPO). The aromatic content of

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Nomenclature

PPO700 plastic pyrolysis oil produced at 700 °C
PPO700 75 75% PPO700+ 25% diesel fuel
PPO900 plastic pyrolysis oil produced at 900 °C
PPO900 75 75% PPO900+ 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
HRR heat release rate
MFB mass fraction burned
°CA crank angle degrees
ϕ equivalence ratio
BTE brake thermal efficiency

the PPO rises when the pyrolysis temperature increases due to the secondary reactions that take place [4,13,15]. Although the exact mechanisms underpinning the aromatics formation are disputed in the literature, it is generally hypothesised that there are two main routes; unimolecular cyclation reactions followed by dehydrogenation (pyrosynthesis) [15], and Dies-Alder reactions followed by dehydrogenation [18].

The properties of the PPO are similar to the petroleum products, therefore it is likely to be used in internal combustion engines. Diesel engines are experiencing a large growth since the beginning of the 20th century due to their excellent drivability and high efficiency over a large range of loads. Moreover, diesel engines are robust and desirable for testing alternative fuels with the potential to replace petroleum diesel. Nonetheless, studies investigating the use of PPO in diesel engines are currently limited, and have largely focused on the use of PPO-diesel blends in single cylinder diesel engines [19–24]. The use of medium blends of PPO with diesel in larger, multiple-cylinder diesel engines has been investigated by J. Pratoomyod et al. [25] and C. Gungor et al. [26]. These investigations revealed that diesel engines can produce acceptable performance on medium blends with diesel. However, comparing the engine performance results of the investigations is challenging due to their different pyrolysis process parameters and feedstock, which are known to affect the quality of the PPO.

What has not yet been investigated in diesel engines is the use of PPO produced at different pyrolysis temperatures from the same feedstock. The aim of this study is to compare the performance of a larger diesel engine when running on plastic pyrolysis oils (at high blend rate and without diesel) produced from the same plastics feedstock but at different pyrolysis temperatures, and to estimate the best operational conditions for each one. To accomplish this purpose, the oils properties were characterised, and the engine combustion, performance and emission characteristics were analysed.

2. Materials and methods

2.1. Conversion process and fuel properties

The oils used for the experiments were produced in a pyrolysis plant consisting of three chambers; the primary chamber, the secondary chamber and the conversion chamber. The waste plastics were cut into small pieces (1–2 cm^2) and transferred into the primary chamber. Carbon dioxide was injected into the first two chambers, thereby pushing the air to the top while the feedstock was transferred from the bottom to the next chamber. This ensured that no oxygen was transferred into the fixed bed reactor (conversion chamber), where the fast pyrolysis of the plastics occurred. The conversion chamber was maintained at an elevated temperature (700 °C or 900 °C) to convert the plastics into gas and char. The conversion chamber had two exits: one for the gas and one for the char. The char (approximately 10% of the feed) was collected for disposal. The gas was passed into a condenser where it was cooled down to 20 °C and the pyrolysis oil separated out. The schematic layout of the pyrolysis plant can be seen in Fig. 1. The pyrolysis oil was filtered to 1 μm to remove the deposits that might be able to pass to the fuel lines and deteriorate the injection system condition. The composition of the plastics used as a feedstock can be seen in Table 1. It should be noted that the main components are the styrene butadiene and polyester type of plastics.

The plastics were pyrolysed in the conversion chamber at two different temperatures, 700 °C and 900 °C, at the same feeding rate. The oil products were dark brown (almost black) in colour with a strong acrid smell. The basic properties of the plastic pyrolysis oils produced at 700 °C (PPO700) and 900 °C (PPO900) are

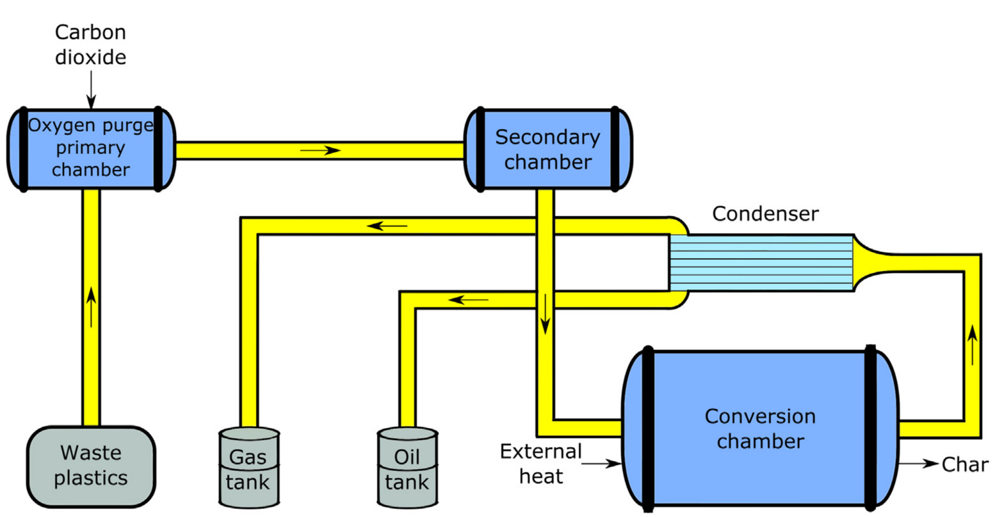

Fig. 1. Schematic layout of the pyrolysis process.