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Combined influence of injection timing and EGR on combustion, performance and emissions of DI diesel engine fueled with neat waste plastic oil

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ABSTRACT

Disposal of waste plastic accumulated in landfills is critical from the environmental perspective. The energy embodied in waste plastic could be recovered by catalytic pyrolysis as waste plastic oil (WPO) and could be recycled as a fuel for diesel engines. This method presents a sustainable solution for waste plastic management as the gap between global plastic production and waste plastic generation keeps widening. The present study investigates the combined influence of EGR and injection timing on the combustion, performance and emission characteristics of a DI diesel engine fueled with neat WPO. Experiments were conducted at three injection timings (21°, 23° and 25°CA bTDC) and EGR rates (10, 20 and 30%) at the engine's rated power output. When compared to diesel, the combustion event occurred closer to the TDC when the injection timing is delayed from 25°CA bTDC to 21°CA bTDC. The peak in-cylinder pressures and HRRs dropped gradually as the injection timing was delayed from 25°CA bTDC to 21°CA bTDC at all EGR rates. The engine delivered diesel-like fuel consumption with 5.1% higher brake thermal efficiency. NOx decreased up to 52.4% under 30% EGR when WPO was injected lately 21°CA bTDC. Smoke density remained lower by 46% and 9.5% for 10% and 20% EGR rates respectively for WPO only at early injection timing of 25°CA bTDC. HC and CO emissions stayed lower at early injection timing of 25°CA bTDC under 10% EGR. WPO injected at the advanced injection timing of 25°CA bTDC and low EGR rate of 10% was found to simultaneously reduce smoke and NOx by 46% and 38% respectively.

1. Introduction

A plastic bag takes several hundred years to degrade and can affect the environment in several ways [1]. When buried deep into the landfills, it can secrete carcinogens and other toxic chemicals that contaminate ground water [2]. These toxic chemicals can deteriorate the fertility of the soil [3]. Over the years, waste plastic can disintegrate into smaller shreds and can infiltrate into human food-chain [4]. Research has shown that micro-organisms ingest micro-sized plastic particles and pass it on to human via fish [5]. Another study has shown that some chemicals from PVC-made medical supplies can accumulate in human blood [6]. The constituent chemicals that form plastics like polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), polyethylene (PU) and polycarbonate (PC) are carcinogenic and can affect human and animal life [7]. About 60 to 80% of marine litter was found to be plastic [8] and these alarming amounts accumulating in the oceans have already gathered global concerns on marine ecosystem that especially affects phytoplankton which forms the bottom of the marine food chain [9]. Trillions of micro-plastic particles are floating on ocean surfaces and poses a threat to the marine ecosystem [10].

Around 280 million metric tonnes (MMT) of plastic was produced globally in the year 2012 and more than half of this plastic litters both the land and the sea [10]. A latest study has estimated that the amount of global plastic waste adds up to a whopping 4.9 billion tonnes [11] of which only 9% was recycled while the remaining 79% was dumped as landfills in the natural environment as of 2015. If the current plastic consumption rate were to continue, it is predicted that another 33 billion tonnes of plastic would be added by 2050 of which a considerable amount could go to landfills and require recycling [10]. An alarming

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Nomenclature

Abbreviations

ANOVA	Analysis of Variance
ASTM	American Society of Testing and Materials
BDC	Bottom Dead Centre
Bmep	brake mean effective pressure
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CA	Crank angle
CCI	Calculated Cetane Index
CI	Compression Ignition
CR	Compression Ratio
DEE	Di Ethyl Ether
EGR	Exhaust Gas Recirculation
GC–MS	Gas Chromatography/Mass spectrometry
HDPE	High Density Polyethylene
HRR	Heat Release Rate
JME	Jatropha Methyl Ester
LDPE	Low Density Polyethylene
LHV	Low Heating Value
MMT	Million Metric Tonnes
MSW	Municipal Solid Waste
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PES	Polyester
PET	Polyethylene Terephthalate
PM	Particulate Matter
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
PVC	Poly Vinyl Chloride
RME	Ricebran Methyl Ester
WPO	Waste Plastic Oil
ZSM	Zeolite Socony Mobil

Symbols

bTDC	before top dead centre
by vol.	by volume fraction
by wt.	by weight fraction
°C	degree Celsius
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrocarbons
NOx	Oxides of Nitrogen
ppm	parts per million
rpm	revolutions per minute

trend in the gap between the waste generated and the waste recycled was also revealed in a prediction by Geyer et al. [11]. In case of India, 5.6 MMT of plastic waste is generated every year and only 60% of this is recycled while the remaining goes to landfills [12]. Open burning of plastics in landfills is another serious environmental issue that releases highly toxic emissions such as dioxins, furans and mercury [13].

While incineration of plastics has helped recovering some amount of energy from plastics, it releases greenhouse gases that aggravate climate change. Hence recovering energy from waste plastic in a closed environment via pyrolysis offers an eco-friendly solution to reuse waste plastic as a fuel. In fact, pyrolysis is considered to be the only way to permanently eradicate plastic waste [11] which is adopted in this study to extract waste plastic oil from mixed waste plastic. Waste plastic is free of cost with some spending involved in gathering, segregating and washing. Indian plastic industry has witnessed a remarkable growth which is equivalent to 17% higher than what the other world countries have achieved together. India was the largest consumer of plastic after USA and China in 2010 [14]. There is no dearth of waste plastic supply and it can be rest assured that there will be a constant supply of waste plastic from which the embodied energy could be tapped by conversion into diesel grade oil which could otherwise don't degrade and challenge environmental security.

Global researchers are on a constant pursuit to explore sustainable fuels for diesel engines to realize a clean, affordable and safe energy future for addressing the mounting concerns of fossil fuel dependence and the subsequent degradation of air quality by burning them. In this regard, waste plastic which forms the third largest composition of municipal solid waste (MSW) [15] could be recycled to different forms and presents an attractive opportunity as energy sources for compression ignition engines which are at the moment heavily dependent on fossil reserves that are facing near depletion. WPO was earlier tested in a wide range of diesel engines from light duty (for powering pump-sets to irrigate farms) to heavy duty (marine and industrial equipment) applications.

Mitsuhara et al. [16] tested WPO derived from PS, PP and PE by 5% and 40% by wt. mixed with heavy oil in a DI diesel engine and reported similar performance as with heavy oil. NOx and CO emissions were found to be less for the blends. Mani and Nagarajan [17] evaluated the performance, emission and combustion characteristics of a single cylinder DI diesel engine fueled with neat WPO derived from catalytic pyrolysis of mixed waste plastic. The engine was found to deliver diesel-like performance but CO and UHC emissions were higher by 5% and 15% respectively than diesel operation. Smoke was lower by up to 50% irrespective of all loads and NOx shot up by up to 25% when compared to diesel. Mani and Nagarajan [18] also went on to evaluate the influence of retarding the injection timing (up to 9°CA bTDC from the standard injection timing of 23°CA bTDC) on the characteristics of the same engine using neat waste plastic as a fuel. Tests revealed that NOx, CO and UHC decreased while BTE and smoke increased at all conditions. Later the same research group studied the effects of cooled EGR on engine characteristics fueled with 100% waste plastic oil. The intention of using EGR was to distrupt combustion by introducing high specific heat inert gases that can bring down peak cylinder temperatures. Consequently the study found 20% EGR to be optimum for low NOx emissions with minimum possible smoke, CO, HC and diesel-like BTE [19]. The effect of 10%, 30%, 50% and 70% by vol. of WPO addition to diesel on performance, combustion and emissions of the same engine was also investigated by [20]. This study concluded that the engine performed better with WPO than WPO/diesel blends. NOx emissions were higher for WPO but reduced with increasing WPO concentration in diesel. Smoke increased with WPO addition to diesel and was highest for WPO at all load conditions. Kumar et al. [21] analyzed the performance and emission characteristics of a high speed diesel engine fueled with blends of diesel and WPO derived from HDPE under different load conditions. WPO was used up to 40% by vol. in diesel. The experimental results indicated lower BTE for WPO/diesel blends when compared to diesel. BSFC also increased with increase in WPO in the blends. NOx, CO and UHC increased with increasing WPO concentration in the blends. Güngör et al. [22] concluded that a 5% by vol. of WPO/diesel blends could be the best alternative in terms of performance in a four cylinder diesel engine.

In a detailed study on WPO/diesel blends (25%, 50% and 75% by vol. of WPO in diesel) in a DI diesel engine, Kaimal and Vijayabalan [23] concluded that 25% by vol. of WPO/diesel blend could be the best