Waste plastic pyrolysis oils as diesel fuel components: analysis of emissions sensitivity to engine control parameters

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Efforts to phase out fossil fuels, reduce greenhouse gas emissions (GHG), and ensure energy security have led to a growing interest in renewable energy sources. In this theme, pyrolysis is a promising technology for converting organic and inorganic waste into useful energy or fuels. Such waste-to-fuel conversion not only offers alternatives to petroleum but also provides solution for waste minimization and secure waste utilization. Specifically, waste plastic pyrolytic oils are comprised of valuable hydrocarbon fractions with a diverse range of boiling points. This highlights the potential of pyrolysis in contributing to both energy sustainability and waste management goals (Hunicz, 2023) and (Kofi Parku, 2020).

In this study, polypropylene (PPO) and polystyrene (PSO) pyrolytic oils were explored as diesel fuel (DF) components. While both oils exhibit diesel-like properties, only PPO is a feasible as standalone diesel surrogate due to its suitable auto-ignition properties. PSO is mainly composed of aromatic hydrocarbons and has a very low cetane number (CN), which narrows it’s applications to blends with DF. (Mariappan, 2021).

Produced in a fixed-bed reactor using selectively collected plastic waste homogeneous granules, PPO and PSO underwent fast pyrolysis at 400-500°C in the absence of oxygen and without inert gas (Chen, 2014). Physicochemical parameters were determined for each fuel surrogate and compared (Table 1) before blending with DF. The blends containing 20% of pyrolytic oil and 80% DF (PPO20 and PSO20 respectively) were subjected to engine testing.

Table 1. Properties of tested fuels.

Property	Unit	DF	PPO	PSO
Molecular weight	kg/kmol	-	236.8	117.8
Density 15°C	kg/m^3	828	776	942
Kinematic viscosity @ 40°C	mm^2/s	2.28	1.69	1.22
Higher heating value	MJ/kg	45.5	44.6	41.5
Flash point	°C	62	>24	34
Cetane number	-	55.3	27,5	-

The engine experiments were performed on a single-cylinder AVL 5402 research engine fitted to fully automated dynamometer test stand. The engine featured a state-of-the-art combustion system used in EPA TIER 4 legislated applications, i.e. four-valve head and a toroidal in-piston combustion chamber. A high-pressure pump supplied fuel into the combustion chamber through an eight-hole electromagnetic injector. The fully-open engine management system enabled free adjusting of all operational parameters. The exhaust concentrations of gaseous components were measured with use of AVL's Fourier transform infrared (FTIR) multi-component analysis system. Particulate concentration was measured by a MAHA MPM-4 meter.

In the study the start of injection (SOI) and exhaust gas recirculation (EGR) were investigated as main combustion control parameters. They affect the most harmful and difficult to eliminate diesel engine emissions, namely particulate matter (PM) and nitrogen oxides (NO_X). In the tests, the engine was operated with split injection mode, with pilot injection sharing 10% of the total fuel value. The dwell between pilot and main injections was set to 14 Crank Angle Degrees (CAD). This injection strategy, in diesel reference, provided start of combustion at TDC, which secured high thermal efficiency (above 40%) and good balance between PM and NO_X (Januszewicz, 2023). In all tests the total mass of fuel injected was fixed, which at reference conditions produced 0.55 MPa of indicated mean effective pressure (IMEP) at 1500 rpm.

Figure 1 maps the results of NO_X emissions at varying EGR (0-30%) and SOI (+/- 4 CAD from the reference set point), for all tested fuel samples. Figure 2 does the same for PM emissions. For DF, one can immediately note a clear trade-off between NO_X and PM, typical for state-of-the-art CI engines. High EGR allows to mitigate NO_X but at the cost of elevated PM. Late SOI has in principle the same effect, however the sensitivity is slightly lower for PM than for NO_X allowing some cumulative emission calibration benefits, particularly at mild EGR rates.

At a reference set points (ΔSOI = 0 CAD; no EGR) NO_X emissions remain almost un-effected by the tested fuels. Given the absolute values of 5.43 g/kWh for diesel, PSO causes less than 5% reduction in specific NO_X.

while Switching to PPO20, without re-calibration, does not cause statistically relevant changes in nether NO_X or PM. Consequently, PM emissions from PSO are increased roughly 25% due to chemical makeup containing mainly aromatics and olefins.

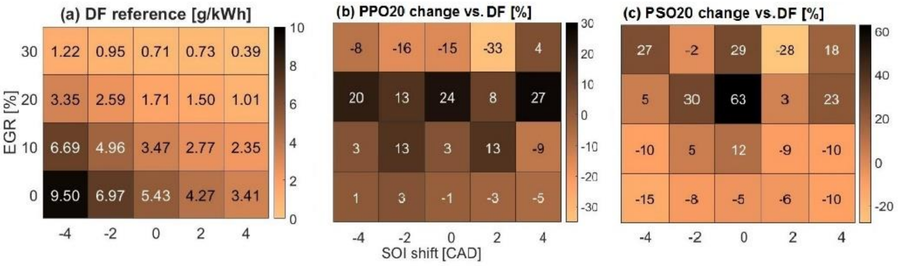

Fig.1. NO_X emissions for DF (a) and percentage changes in emissions for 20% PPO and PSO blends (b, c) with respect to DF reference.

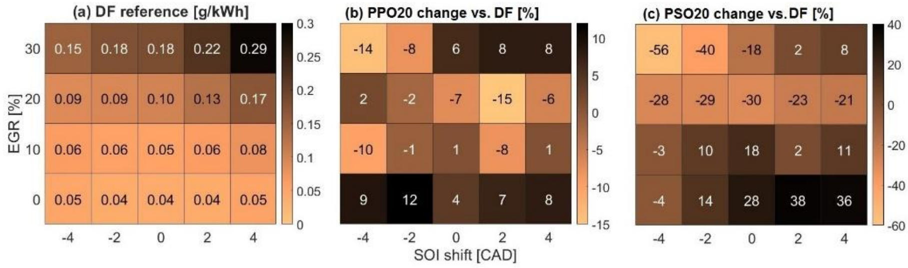

Fig.2. PM emissions for DF (a) and percentage changes in emissions for 20% PPO and PSO blends (b, c) with respect to DF reference.

When re-calibration is considered, lower reactivity (Cetane Number) and volatility (flash point) of pyrolytic oils (refer to Table 1) cause increased PM emissions at high EGR rates, where start of combustion is elongated and combustion becomes restricted by oxygen deficit (Paul Daniel, 2017). The negative PPO/PPS response to EGR in PM emissions can be mitigated by injection advance, opening room for emission trade-off optimization with concurrent benefits of PPO producing low NO_X in partially-premixed combustion regime. Note, that contrary to PPO, PSO exhibits elevated NO_X at high EGR with too early injections, due to a high fraction of kinetic combustion.

Expending beyond the results presented in this abstract, the compete study advocates that contemporary Off-road diesel engines can operate on pyrolysis fuels without re-calibration. For up to 20% PPO admixtures the combustion is affected only at low engine loads and heavy EGR. At the same time PPO lower Cetane Number can be utilized as enabler for practical realization of ultra-low emission premixed combustion concept. More generally, different sensitivities of different pyrolytic oils to control parameters are enablers for elaborating blending strategies suitable for all diesel engines.

References

Hunicz J., *et al.* Waste Plastic Pyrolytic Oil Blends as Valuable Fuels for Modern Compression Ignition Engines, SAE Technical Paper, No. 2023-32-0133, 2023.

Kofi Parku G., *et al.* Pyrolysis of waste polypropylene plastics for energy recovery: Influence of heating rate and vacuum conditions on composition of fuel product, Fuel Process. Technol., 209, 106522, 2020.

Januszewicz K., *et al.* An experimental assessment on a diesel engine powered by blends of waste-plastic-derived pyrolysis oil with diesel, Energy, 281, 128330, 2023.

Mariappan M., *et al.* Pyrolysis plastic oil production and optimisation followed by maximum possible replacement of diesel with bio-oil/methanol blends in a CRDI engine, J. Clean. Prod., 312, 127687, 2021.

Chen D., *et al,* Pyrolysis technologies for municipal solid waste: a review, Waste Manag., 34 (12), 2466-2486, 2014

Paul Daniel M., *et al,* Performance and emission characteristics of diesel engine operated on plastic pyrolysis oil with exhaust gas recirculation, Int. J. Ambient Energy, 38 (3), 295-299, 2017.

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