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TECHNICAL AND ENVIRONMENTAL INVESTIGATION OF THE WASTE-BASED FUEL - DIESEL FUEL MIXTURES IN INTERNAL COMBUSTION DIESEL ENGINES

Thesis booklet

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1. Introduction

By the 21st century, the increasing exploitation of oil resources and ever stricter environmental regulations have had a positive impact on the research, use and spread of alternative fuels. The European Union (EU) has set a strategic goal to increase the biofuel content of motor fuels. To achieve the 2030 targets, the use of blending components from second generation waste is crucial.

In the 20th century, alternative fuels were only used when raw materials were at a shortage, with the first oil crisis in 1973 marking the beginning of research into replacing petroleum-based fuels. In the nearly fifty years since that time, research has produced promising results with a number of alternative fuels. One of these major areas of research is the potential for recycling automotive plastics and rubber waste, including the pyrolysis process, which has been developed over many years of research into an economical and environmentally friendly technology with a number of national and international patents.

Today, the number of cars has reached 1 billion worldwide, rising to 2-2.5 billion by 2050. Approximately 1 billion new tyres and 1 to 1.5 billion used tyres are produced annually. The storage, treatment and recycling of waste tyres in Europe and worldwide is becoming increasingly important in order to protect the environment.

The European Union gives directives on waste management. As part of this, a waste management pyramid has been created, which classifies waste management options according to their desirability, with waste prevention at the top of the pyramid.

Waste tyres (EWC 16 01 03), if contaminated with other hazardous substances, are banned from storage in the EU as they are considered hazardous waste. Due to storage problems, several methods have been developed for the treatment and recycling of waste tyres. One method is the incineration of tyres in incinerators or cement works, the other is the pyrolysis process. There are also known possibilities for recycling the material, for example in road construction, railway transport, paving of playgrounds and sports fields -recortane-, shoes, roof insulation, car parts, noise protection equipment, fine art. However, devulcanisation has not yet been solved, so the rubber cannot be recycled back to its original function, i.e. tyre, in bulk.

Incineration is a recycling process that produces thermal energy from bound chemical energy. This process is the energy utilization of tyres. The energy demand for tyre production is 32kWh/kg, the energy demand for recycling is about 9kWh/kg depending on the type of reactor. This means that the energy balance of recycling is favourable. The drawback of this process is the significant emissions of pollutants, which are a major environmental issue.

The other, more environmentally friendly method of processing rubber is pyrolysis. The pyrolysis oil extracted during this process can be used as an alternative fuel in internal combustion engines. In my work, I focus on rubber-based pyrolysis oil because its application can be a promising alternative to plant-based fuels, and pyrolysis, as recycling in its material, is the most important recovery and treatment solution. The latter is also ahead of energy recovery in the EU waste pyramid.

My research focuses on the potential use of rubber based pyrolysis oil in internal combustion diesel engines, including its effects on the modern CR (Common Rail) injection system, engine life, characteristics and emissions.

2. Objectives

1. After a review of the properties and potential applications of tyre-derived pyrolysis oil (TPO) obtained from scrap tyres available in the literature, simulation studies with different nozzle geometries to investigate the flow properties.

2. Evaluation of the resulting jet image for different fuel compositions using injector bench tests

3. Investigation of the physical properties and erosion effects on engine components of TPO gas oil blends with different percentages by volume.

4. To test the performance, specific fuel consumption and emissions of motorcycles in practice, by means of motorcycle measurements.

5. Mathematical modelling for the development of an optimal TPO-gas oil blend and emission testing

3. The impact of different blends ont he modern diesel injection system

3.1 Simulation studies

Combustion simulation studies can be used to perform cost-effective research tasks that closely approximate real motor processes. Numerical simulation studies of injector injection testing were used to investigate the processes in TPO-gas oil mixtures in modern high-pressure CR injectors. The main objective of the study was to investigate the processes occurring in the injector at steady state, in the nozzle and near the nozzle exit cross section at maximum needle lift and different pressures. The tests were carried out with commercially available diesel fuel and TPO blends of different percentages by volume and pure TPO fuel.

3.2 Results for diesel and TPO fuels tested at 350 bar rail pressure

The pyrolysis oil tests show that TKE is reduced everywhere, leading to poorer droplet decomposition, strongly affecting combustion quality and resulting emission values are worse than for diesel, if other deteriorating conditions are not taken into account for pyrolysis oil. The most noticeable change in this respect is at the ksd nozzle.

3.3 Results for diesel and TPO fuels tested at 1000 bar rail pressure

Based on the simulations, if one wants to run a diesel engine with pure pyrolysis oil, the ksd nozzle design gives the best results, when all aspects are taken into account. The cavitation of the cylindrical nozzle showed only an upward trend, the ks nozzle produced similar results with diesel, but the ksd nozzle produced better mixing and lower flow rates with both fuels.

3.4 Simulation results with 10 vol% and 20 vol% TPO gas oil fuel blends

Overall, the results for 10 vol% and 20 vol% pyrolysis oil can be said to be almost identical based on the simulations. The cavitation values for both the cylindrical and ksd nozzles deteriorated slightly, with the ks nozzle stagnating in this case. The velocities were similar compared to conventional diesel. The kinetic energy of the cylindrical and ksd nozzles showed almost the same trend as a result of the blends, whereas the ks nozzle showed a rather decreasing trend.

3.5 Summary of simulations with TPO gas oil blends

Tests have shown that pyrolysis oil can be used in CR injectors, even without changing geometric dimensions, but the air-fuel mixture produced in most cases worse values and increased harmful cavitation.

4. Validation of simulation results

Injection characteristics were tested on a BOSCH CRIN 1 injector developed for first generation commercial vehicles. The results obtained were those obtained in the simulation tests. Since the shape of the injection jet pattern has a decisive influence on the subsequent combustion process and then on the emission values, these experiences provided the basis for my further research.

5. Study of erosion effects of mixtures

In the injection system tests, different engine modes were tested by varying the pressure, injection time and engine speed. At the same time, tests were conducted using pure diesel and an increasing concentration of TPO blend.

The Ishikawa diagram describes the factors that would lead to premature wear of the equipment.

5.1 Testing the wettability of TPO fuel

Fuel wettability is an important consideration for diesel injection systems, as atomization is achieved by fine machining and displacement of precision-fitted components. It was determined using the resting drop method. Both fluids behaved similarly, with similar lubricity. This can be described as a positive property for pyrolysis oil.

5.2 Test bench testing of injection injectors

The aim of the test bench studies of the injectors was to analyse the chemical and mechanical properties of the pyrolysis oil on the injection system.

When the other structural components of the injector were examined, no more significant wear or deposits were observed than in injectors that had been operated for the same number of hours with diesel under normal operating (or road service) conditions. There was also no evidence of damage or wear at the injector tip.

5.3 Homogeneity testing of fuel mixtures

During my research, the life tests showed failures that indicated precipitation of some of the fuel components, problems with the homogeneity of the fuel mixture. In order to test the homogeneity of the fuel mixture, the individual components of the injection system were tested by immersing them in TPO for a period of three months. During the tests, I found that 0.2g of rubber-like material was deposited on the injector pin and 0.1g on the housing.

The tests were repeated by mixing premium diesel fuel with TPO for the same period of time. In this case, the mixtures maintained their homogeneity and I did not observe any deposition on the tested structural elements that could lead to failures.

No signs of fuel supply or injection system failure were observed during the experiments. Before and after the tests, the structural condition of the engine (cylinder wall, combustion chamber, piston, valves) was checked by endoscopic camera examinations and no deterioration was observed.

5.4 Carrying out control measurements

In determining the injector test operating points, idle, transient, part load and full load operating conditions were simulated.

After each test was run, I performed injector test bench tests to determine the extent to which the injector delivery deviated from the factory values and whether the injector nozzle seal was adequate. Following the test bench tests, I performed an injection radiography study to visually inspect the injector spray pattern. The jet image tests showed no anomalies in the measured delivery rates and sealing tests after the 2.5% test. The injection jet image also showed a satisfactory shape. Abnormalities were observed after the tests with the 5% mixture, after which a structural examination of the injectors was necessary to identify the cause of the failure.

6. Extension of the Szabados model to pyrolysis fuels

Pure pyrolysis oil should not be used in modern CR-type injectors. Efforts should be made to achieve an optimum mixing ratio in order to maintain the injector lifetime and combustion emission values at an appropriate level. In the following, I will focus on the development of an optimal mixing ratio and further research and measurements will be carried out to develop this.

7. Engine testbench investigations

At 1900 rpm on a Mitsubishi S4S-DT medium duty industrial diesel engine with a TPO mixture at lower loads, there was a minimal increase in power, but the difference diminished as the load increased. This is most likely caused by the higher calorific value of TPO. At full load at 2200 rpm, the engine only showed a torque value 0.5 Nm higher, which is a negligible value. The 2200 rpm and 80% load figures are different because the engine was operating close to its stall limit.

Specific fuel consumption showed an increasing trend until the engine was fully loaded. At 40% load at 1900 rpm, specific fuel consumption was 10% higher with TPO. At full load at 1900 rpm, consumption levelled off. Further increase in engine speed resulted in a decrease in consumption, which can be attributed to the higher calorific value of TPO. The 2200 rpm and 80% load figures are different because the engine was operating close to its stall limit.

At low loads the TPO blended diesel showed lower emissions than gas oil, but with increasing loads the carbon dioxide emissions of the pyrolysis oil exceeded those of normal diesel. At 2200 rpm the difference was smaller than the standard deviation of the measurement.

HC emissions showed different results. At low speed and low load, TPO showed 16% higher emissions. With increased engine load, HC emissions decreased and were 42% lower than conventional diesels at 100% load. NOx emissions have increased overall, except at maximum load at 2200 rpm. This is due to a lack of oxygen at the measuring point. CO emissions showed an increase at all test points. Overall, the values increased by about 10%.

Measurements show that soot emissions can be up to 20% higher on low-performance points, due to the strong soot-forming tendency of TPO. However, at higher load points, this trend changes and can result in an increase in soot emission of up to 10%. As engine speed increases, the variation in soot content becomes minimal, less than 1%.

Engine power and torque increased minimally, and specific fuel consumption was lower with TPO blends. The engine was not equipped with an exhaust aftertreatment system and the measured values are the raw emissions. They can be further treated with the usual exhaust aftertreatment systems. Overall, it was found that there were only minimal differences between the measured values for some parameters, which can be kept within the permitted emission levels with the exhaust aftertreatment systems used today.

8. Mathematical modelling

The results show that none of the fits to the data at 1000 bar rail pressure are significant. While the fits to the average diameters of the 350 bar rail pressure radiographs are both square and cubic significant at the 10% significance level.

Simulations, measurements and mathematical modelling have shown that TPO blended with low-volume diesel can be a promising alternative fuel to replace plant-based fuels in the near future.

At 100% engine load there is no difference in THC emissions, all other values are significantly different.

At 60% and 80% engine load there is no difference in CO_2 emissions, while at 100% engine load there is a significant difference.

For pure diesel, there is no significant difference between the 40% and 80% CO values, and using a 10% pyrolysis oil blend at 80% engine load and pure diesel at 100% engine load results in the same CO emissions. For 60% engine load there is no difference in THC emissions, but for the other two engine loads there is a significant difference in CO emissions.

At 40% engine load there is no significant difference between pure diesel and 10% pyrolysis oil blends, nor is there a significant difference between NOx values at 80% and 100% engine load. All other values are significantly different. At 60% engine load there is no significant difference in NOx emissions, while all other values are significantly different according to the Tukey HSD post-hoc test.

9. New scientific advances

1. THESIS

I used simulations to investigate the effect of TPO fuel on the flow properties in the diesel engine injector. I have found that of the three nozzle designs investigated, the cylindrical nozzle suffers from high directional deflection due to the small radius of curvature of the fuel, which adversely affects the flow properties of both diesel and TPO. It was found that the cavitation rate for TPO fuel at the cylindrical nozzle was 20% higher compared to diesel fuel, which is explained by the higher density of TPO.

2. THESIS

Based on simulations validated by measurements, I found that the shape of the beam pattern differs for the TPO mixture. In the case of the measurements with gas oil, the regular cone-shaped liquid spray started to "ripple" with the addition of TPO, which is explained by cavitation due to the higher density of TPO.

3. THESIS

I measured the wettability of TPO and gas oil and found that they were the same. I have shown that increasing the volume percentage of TPO up to 5% does not cause abnormal wear on the injector components. I have demonstrated that TPO mixed with diesel oil retains its homogeneity for 3 months. Thereafter, the amount of rubber deposits increases proportionally with time. The time proportionality does not start at 3 months, only until the amount of deposition is such that the blend meets the specifications for diesel.

4. THESIS

I have shown by motorcycle measurements that TPO blended with up to 10% diesel oil does not cause any significant difference in engine performance and specific fuel consumption. CO2 emissions at low loads showed more favourable values due to lower combustion temperatures, while THC showed more favourable values at higher engine speeds due to higher combustion temperatures. I found that the 10% TPO mixture did not cause any damage to the engine components during the measurements. I have demonstrated that TPO could be an environmentally promising alternative fuel in the near future, replacing plant-based fuel components.

5. THESIS

I used a mathematical model to determine the maximum TPO volume percentage (10%) up to which the radial properties of the blend do not show significant differences compared to diesel. Using analysis of variance, I have shown that the significant increase in NOx, CO, CO2 emissions is due to the engine load, with no significant effect of the blend ratio.

Publications on which the thesis is based:

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[P6] Kondor István Péter, Zöldy Máté. Experimental Investigation on the Performance and Emission Characteristics of a Compression Ignition Engine Using Waste-Based Tire Pyrolysis Fuel and Dízel Fuel Blends. ENERGIES 2021; 14: 7903. **IF:3,004**

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