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Combustion and emission formation phenomena of tire pyrolysis oil in a common rail Diesel engine

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ABSTRACT

A pure tire pyrolysis oil produced from waste tires was utilized in a modern 4-cylinder, turbocharged and intercooled, automotive Diesel engine. Due to its low cetane number, cetane improvers, external energy addition or increased compression ratios are generally required for its use in Diesel engines. Successful utilization of pure tire pyrolysis oil is also achievable with the addition of pilot injection but limited to mid- to high-load operating range. The first objective of the present study is therefore focused on further extension of the operating range towards lower loads by novel combined application of the exhaust gas recirculation and tailored main injection strategy. As the second objective, the article provides for the first time an in-depth analysis of the particulate emissions of the tire pyrolysis oil measured with two different methods. In this area it identifies and reasons challenges related to determination of the particulate emissions for alternative fuels. The original contribution of the presented approach thus arises from the holistic assessment of interactions between the exhaust gas recirculation ratios, injection parameters and combustion as well as gaseous and particulate emissions formation phenomena.

1. Introduction

Increasing fuel demand on one side and a growing problem of waste disposal on the other drive the attentions of researchers to seek for new, clean and efficient waste-to-energy technologies. About one billion waste tires are produced every year over the globe [1] and many of them are landfilled. Since they are non-degradable material and their thermo-mechanical properties prevents their direct reuse, their high calorific value (35–40 MJ/kg) [2] as well as considerable amount of carbon black makes them a good feedstock for fuel production.

Pyrolysis represents an environmental friendly and efficient way to transform solid wastes into fuels with acceptable chemical and physical properties for the use in the internal combustion engines [3]. The most suitable pyrolysis subtype for conversion of waste vehicle tires, is vacuum pyrolysis [4], by which also tire pyrolysis oil (TPO) used in this study was produced. Since the main distillation properties of the TPO are similar to commercial Diesel fuel (D2) [5], compression ignition engines stand out as being potential power units for the use of the TPO.

Most of the existing research with TPO was done on non-automotive engines. Authors in [1] and [3] were running tests on a single cylinder 0.4 l, air cooled engine, in [6] tests were performed on a single cylinder water cooled engine and in [7] 1.5 l single cylinder engine was used. Since analysed engines have limited possibilities of control strategy adaptions those results can, in general, not be properly transferred to modern engines. In addition, there is a limited number of studies found in the literature on utilizing TPO in modern multi-cylinder automotive compression ignition (CI) engines. Authors in [8] were running tests on a 4-cylinder, 3.3 l, marine engine with mechanically controller direct injection, authors in [9] were using 6-cylinder, 6.9 l, heavy duty engine with the same direct injection system and in [2], tests were performed in a 4-cylinder, 2 l, light duty engine with common-rail fuel system. However, none of listed studies successfully utilize pure TPO on modern multi-cylinder automotive CI engine.

Selected studies indicate that because of its low cetane number, TPO must be mixed with the Diesel fuel, Jatropha methyl ester or cetane improver in order to be used in Diesel engines. Authors in [1] were using several D2-TPO blends from 5% to 100% TPO, where diesel like combustion was not achieved at higher TPO concentrations. In [2] authors were running tests with only 5% TPO blend, while in [3] authors have stated that over 40% TPO, added in the D2, makes engine behave extremely irregular. In [8] only up to 10% blend was used in the study and in [10], up to 75% low sulphur

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Nomenclature

BC	black carbon
CA	crank angle
CCV	cycle-to-cycle variations
CI	compression ignition
CLD	chemiluminescent detector
CO	carbon monoxide
CO_2	carbon dioxide
COV	coefficient of variation
D2	commercial Diesel fuel
ECU	electronic control unit
EGR	exhaust gas recirculation
FBN	fuel bound nitrogen
FID	flame ionization detector
FIR	finite impulse response
GFM	gravimetric filter module
H_2O	water
IE	injector energizing
IMV	inlet metering valve
LHV	lower heating value
MI	main injection
MSS	Micro Soot Sensor
% m/m	mass/mass percentage
NDIR	non-dispersive infrared analyser
NO_x	nitrous oxides
PAH	polyaromatic hydrocarbons
PI	pilot injection
PM	particulate matter
ROHR	rate of heat release
SO_2	sulphur dioxide
SOI	start-of-injection
TDC	top dead centre
THC	total hydrocarbons
TPO	tire pyrolysis oil

TPO fuel were used. In both studies, where TPO was blended with Jatropha methyl ester [11,12], maximum concentration of the TPO fuel in the tested blend was limited to 80% in [11] and up to 50% in [12]. In [6] authors were using diethyl ether as a cetane improver to increase the cetane number of TPO fuel.

Other approaches to overcome issue of low cetane number suggest increasing the temperature at start of fuel injection to achieve sufficient temperature required for auto ignition of the fuel. This was achieved either through increasing the intake air temperature by external heater [13] or by increase of engine compression ratio to 22–24 [7]. The first approach deteriorates total energy efficiency and thus applicability of the system, while the second approach cannot be realized with highly boosted engines, which yield high power densities and high effective efficiencies. Both methods also results in higher in-cylinder temperatures and thus higher nitric oxides (NO_x) emissions. In the foremost study [14] a pure TPO was utilized in a turbocharged multi-cylinder engine without any of the aforementioned aids. Results indicate that TPO can be efficiently used in turbocharged non-intercooled CI engines at high loads, which opens its use in power generation. Although above mentioned results are promising, it is suboptimal to utilize the engine without intercooler as it decreases engine efficiency and increases temperature loading of the components and NO_x emissions. In another study [15], it was elaborated that addition of pilot injection (PI) and tailoring of the PI strategy can optimize thermodynamic parameters of turbocharged intercooled Diesel engine, which allows for successful mid- to high-load operation under the use of pure TPO.

To further enlarge the operation range while utilizing the pure TPO without the addition of cetane improvers and without any external heat addition, the first objective of this study is focused on further extending operation of a modern turbocharged and intercooled Diesel engine to low loads. To achieve this objective an in depth analyses of impacts of different exhaust gas recirculation (EGR) ratios and different injection parameters on the combustion and emission formation phenomena of the pure TPO are performed for the first time. These results are benchmarked against the data obtained for the Diesel fuel. This holistic assessment provides guidelines and pinpoints suitable control strategies for efficient utilization of the pure TPO. The novelty of the proposed approach is schematically presented in the Fig. 1, which summarizes on the left side existing methods for TPO utilization in Diesel engines and on the right side the proposed novel approach.

The second objective of this paper is focused on analyses of particulate emissions. In this area, the article provides, to the best of authors' knowledge, a foremost in-depth analysis of the particulate emissions of the TPO measured with different methods: the Micro Soot Sensor and the Gravimetric Filter Module. This analysis identifies and reasons significant differences between both methods when determining particulate mass for the alternative TPO, which opens many challenges that are discussed in the Results.

2. Fuel properties

The TPO used in this study was produced by vacuum pyrolysis method, which has the potential to produce a low sulphur fuel with reasonably high yield from tires [16]. Waste tires were cut into pieces (mean size 100 mm × 100 mm) where steel wires and fabric fibres were previously removed. Pyrolysis process was performed between 600 °C and 700 °C and the retention time was 60 min. Fraction between 190 °C and 350 °C was used for further studies.

Properties of the TPO and Diesel fuel were analysed with standard methods and results are presented in Table 1. Utilized commercial Diesel fuel complies with the specifications of the SIST EN-590 standard. TPO features higher density and lower heating value (LHV) on mass basis, which results in slightly higher volumetric energy density. Major properties (Table 1) as calorific value, viscosity and density are comparable to those of D2 while sulphur content of the tested TPO is significantly higher, which restricts its use in road vehicles. If required, this could be solved by reduction of the sulphur content in the fuel or with desulfurization of exhaust gases as described in [14].

Another important difference between the TPO and the D2 arises from significantly lower cetane number of the TPO, which is reflected in its poor ignition properties thus making its use in CI engines a lot more challenging. It seems generally accepted that the cetane number of TPO is certainly below 30. In [7] authors claim that it was estimated that the cetane number values of TPO are typically between 5 and 25, while in [11] it was reported that cetane number is in the range 25–30. However, the authors in [17] claim that cetane number of 44 could be achieved for the TPO before entering desulfurization process. On the other hand conventional Diesel fuels have much higher cetane number of at least 51, as set in the European standard SIST EN-590 [5]. Difference between D2 and TPO cetane number was confirmed by the