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By-products from thermal processing of rubber waste as fuel for the internal combustion piston engine

The article presents results of investigation on the combustion of a mixture of oil from pyrolysis of tires and basic fuel in an internal combustion reciprocating piston engine. The tested fuel consisted of: diesel oil and oil from pyrolysis of tires at amount of 10% by volume. The tests were carried out on a single-cylinder naturally aspirated compression-ignition engine. The engine is equipped with a common rail fuel injection system and an electronic control unit that allows changing injection timing. A comparative analysis of pressure-volume charts for the reference fuel, which was diesel, and for a mixture of diesel with the addition of 10% oil from tire pyrolysis was carried out during the study. Injector characteristics for the reference fuel and the mixture were determined. Engine efficiency for both fuels was determined. Unrepeatability of the engine work cycles for the diesel fuel and the tested mixture was calculated. Finally, the share of toxic exhaust components in exhaust gases was analyzed. It was found that pyrolisys oil from tires can be used as additive to regular diesel fuel at amount up to 10%, however, toxic exhaust gases emission was increased.

Key words: *pyrolysis oil, thermal conversion, biocrude, diesel engine, alternative fuels*

1. Introduction

Thermal processing of organic matter is an alternative method of obtaining fuel for internal combustion piston engines. Pyrolysis is one of the methods of thermal processing. Pyrolysis is a process in which organic material is heated up to temperature of approximately 500°C in oxygen-free atmosphere. The composition and quantity of individual fractions of pyrolysis products depends on the following [5,15]:

- physical-chemical properties of the input material,
- temperature,
- pyrolysis reactor type,
- process speed (heating up time, retention time).

During pyrolysis, organic material is converted into [12,13]:

- the gas fraction, also called pyrolysis gas, which apart from methane, ethane, carbon monoxide and dioxide, water vapor also contains vapors of hydrocarbon compounds,
- solid fraction: consisting of carbon, metals and other inert substances,
- the liquid fraction called pyrolysis oil, that is formed after cooling the pyrolysis gas to ambient temperature. The composition of pyrolysis oil includes: condensed hydrocarbon compounds, tars, water, alcohols and organic acids. Crude pyrolytic oil is a dark-brown substance with a strong characteristic odor [2,8].

Exemplary quantities of fractions produced from the pilot installation at the Czestochowa University of Technology are shown in Figure 1. The pyrolysis installation is equipped with a screw feeder for moving the input material. Heating is carried out by electric heaters. The system is equipped with a controller for adjusting the set point temperature and a frequency converter that allows you to change the time of keeping the charge material in the heating zone. The largest share has a solid fraction, which contains a significant amount of energy, it reaches 90% energy of the input material. The gas fraction constitutes about 30% and contains about 10% input energy of the feed material [10].

The most desirable product of waste pyrolysis is the oil fraction, which can be used as liquid fuel or as a source of selected chemical compounds. The gas fraction is most often used for process itself. The solid fraction is managed as final product - pyrolysis carbon black or as activated carbon [4,11,15].

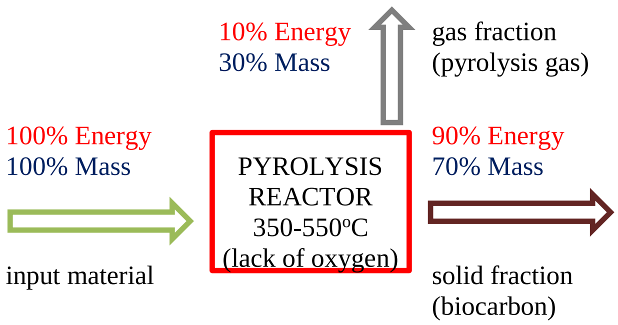

Fig. 1. Exemplary mass and energy distribution in pyrolysis process

Pyrolysis reactors can have different constructions. The most common installations are: fixed bed reactor, fluidized bed reactor, screw conveyor reactors, rotary cone reactor, ablation reactor. Depending on the type of reactor, the worn out tires can be thrown directly (fixed bed reactor) to a reactor, or require reinforcement removal and fragmentation (e.g. fluidized bed reactor). The pyrolysis process can be carried out with the addition of a catalyst, which aim is to remove unwanted compounds from the gas [7,12].

The input material for the pyrolysis process can be various kinds of organic waste: from the food industry, waste from the agricultural industry, waste from the fish industry, waste from the wood industry, municipal waste, special purpose crops. The problem of managing worn car tires has been growing in recent years. Tires do not degrade in the natural environment for up to 100 years, they are a nuisance waste and have been classified as waste that should be utilized industrially [6,9].

The amount of waste in the form of car tires increases year by year. All rubber waste constitute about 80%. It is estimated that 1.5 billion tires are produced annually in the world. After their use, they pass to the waste area that needs to be managed. Until now, the main method of tires recycling is to burn them in cement plants. Another option is to use them for the pyrolysis process [14].

Further in the work, an attempt was made to use crude oil from pyrolysis of tires as an additive to fuel that can supply a single-cylinder diesel engine.

2. Description of the research stand

The test stand shown in Figure 2 consists of the following elements: Three-phase electricity meter (1), which is connected to the electric grid. The meter is connected to a three-phase asynchronous generator/motor (2), with a power of 15kW at 400V rated voltage, which is used first of all as a drive needed to start the internal combustion engine and then as a load after the piston engine starts. The asynchronous motor has two operating speeds: 1465 rpm and 975 rpm. A lower rotation speed of 975 rpm was applied to investigation.

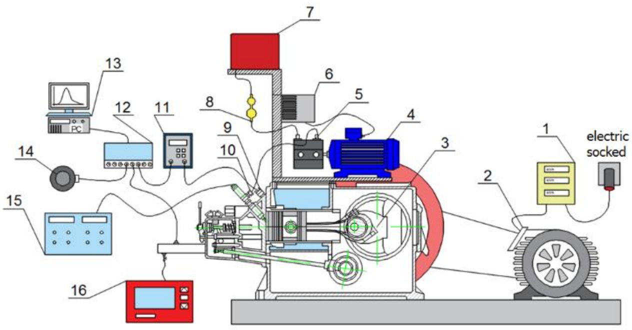

Fig. 2. Diagram of the test stand

The technical specifications of the compression ignition engine (3) are shown in Table 1.

Table 1. Technical data of engines S320

Type of engine	Four-stroke
Fuel	Diesel
Number of cylinders	Single
Direct of cylinder	Horizontal
Number of valves	2
Cylinder bore	120 mm
Piston stroke	160 mm
Engine displacement	1810 cm^3
Compression ratio	17
Nominal power(1)	13.2 kW for 1500 RPM
Maximum torque(1)	93 Nm for 1300 RPM
Specific fuel consumption	234 g/kWh 172 g/HPh
Capacity lubrication system	10.5 dm^3
Oil consumption	4.1 g/kWh
Beginning of fuel delivery	variable
Injection poressure	to 200 MPa
Suction valve timing	Opening: 23CA deg before TDC Closing: 40CA deg after BDC
Exhaust valve timing	Opening: 46CA deg before BDC Closing: 17CA deg after TDC
Valve clearance for cold engine	suction 0.4 mm exhaust 0.4 mm
Oil Pressure in the warm engine	150-300 kPa
Cooling	open water system
Dry engine mass	315 kg

(1) Parameters for temperature +15ºC, pressure 100kPa, relative humidity 60%

The engine underwent a number of modifications to be adapted to research. The most important change is the modification of the cylinder head. It has additional mounting sockets needed to mount an additional injector and a pressure sensor. Currently, two common rail injectors and a piezoelectric pressure sensor are installed in the cylinder head. The second important modernization of the engine is the replacement of the original evaporation based cooling system by an radiator. The cooling system works at ambient pressure. The cooling system and all elements of test stand are shown in Figure 3.

Fig. 3. The test stand

The original Andoria engine fuel system was replaced by a modern common rail fuel injection system. The three-section twin-piston pump (5) is driven by an asynchronous engine (4) with a power of 2.2 kW. The pump is made of three pressing sections arranged radially every 120°. The pump is adapted from a 2.0 engine from a truck. The pump is equipped with a pressure regulator. The fuel injection pressure can be adjusted using a potentiometer. During the tests, fuel was injected at a pressure of 100 MPa. The asynchronous motor (4) is powered by a frequency converter (6), which allows to regulate fuel flowrate from the pump. A fuel tank (7) was mounted next to the test stand. Fuel consumption is measured by the fuel consumption meter (8). The fuel system is equipped with a fuel pipe cooler and an additional preliminary, supporting low pressure fuel pump. The cooler is needed at the stand, because with prolonged operation of the engine the fuel temperature increases significantly. For fuel injection, the BOSCH 0445110076 (10) injector was used. An electronic system (15) was used to control the injector timing. The controller made it possible to adjust the injection time with resolution of 10µs. In addition, it allowed shifting start of injection. The electronic system reads pulses from an encoder which was installed on the camshaft (14). The encoder generates 360 pulses per revolution. Due to fact that the encoder was installed on the camshaft, the change of injection start was possible every 2 degrees of crankshaft rotation. For measuring in-cylinder pressure the Kistler piezoelectric sensor type 6061B (9) was used. The sensor was screwed into the head and additional liquid cooling of the measuring element was used. The sensor sensitivity is -25.8 pC/bar, measuring range up to 25 MPa. The signal from the piezoelectric sensor needs amplification, therefore another device in the measurement pathway is a charge amplifier (11). The signal after amplification was sent to the National Instrument measurement data acquisition card (12). The encoder signal (14) was used to display p-V diagram in real time working conditions. SAWIR program by Dr Michał Gruca (13) was used to register and process engine parameters. The view of the program window with real-time charts is shown in Figure 4.

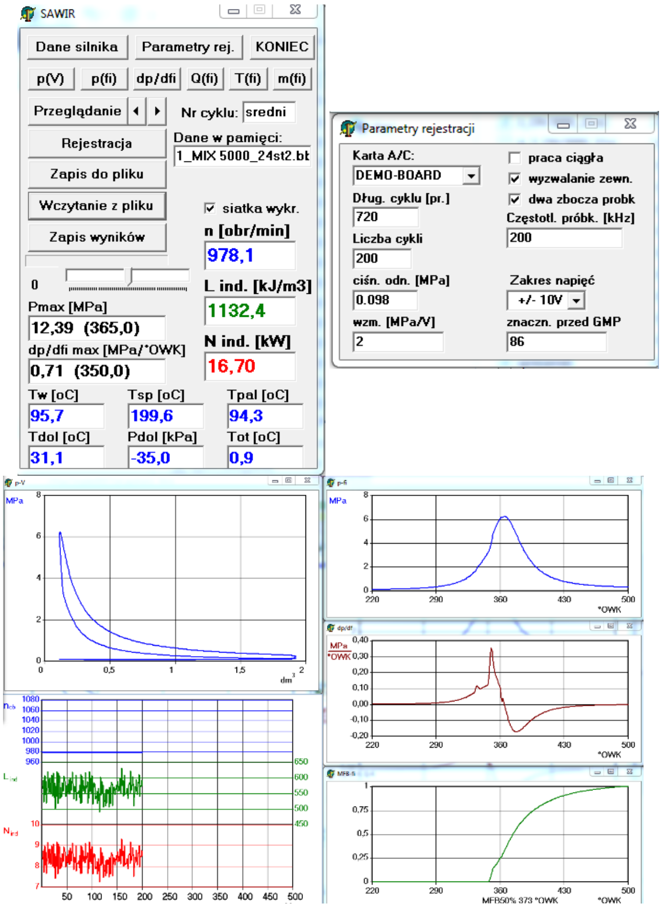

Fig. 4. View of the SAWIR program windows

The exhaust gas analyzer Radiotechnika model AI9600 (16) was used to measure the concentration of toxic exhaust compounds.

3. Analysis of results

The research consisted of several stages. In the first stage, engine tests were carried out with reference fuel, i.e. diesel. While the engine was running, the fuel injection angle was changed in the range of 24÷32 CA deg bTDC. The injection time was 5 ms at 100 MPa injection pressure. Start of injection was limited by diesel knock occurring at timings advanced over 32 CA deg bTDC. Graphs with exemplary in-cylinder pressure curves are shown in Figure 5.

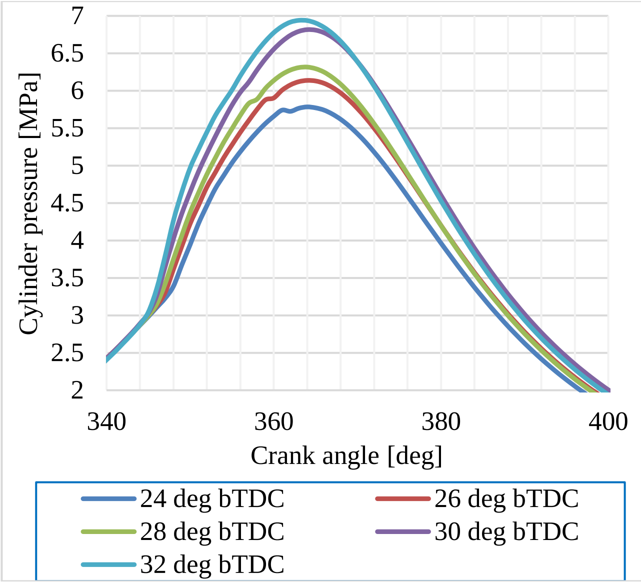

Fig. 5. Cylinder pressure vs. crank angle range 340÷400 deg for a variable start of fuel injection, fuel: Diesel

In next stage of research as seen in Figure 6, the fuel applied to tests was the following mixture: diesel fuel and oil from tire pyrolysis. The mixture contained 10% pyrolysis oil (PO) by volume. Amount of PO was limited to 10% only with risk of damaging the high pressure fuel pump. During the tests, the fuel injection angle was changed in the range of 24÷34 CA deg bTDC. The injection time was also 5 ms. The injection pressure was 100 MPa.

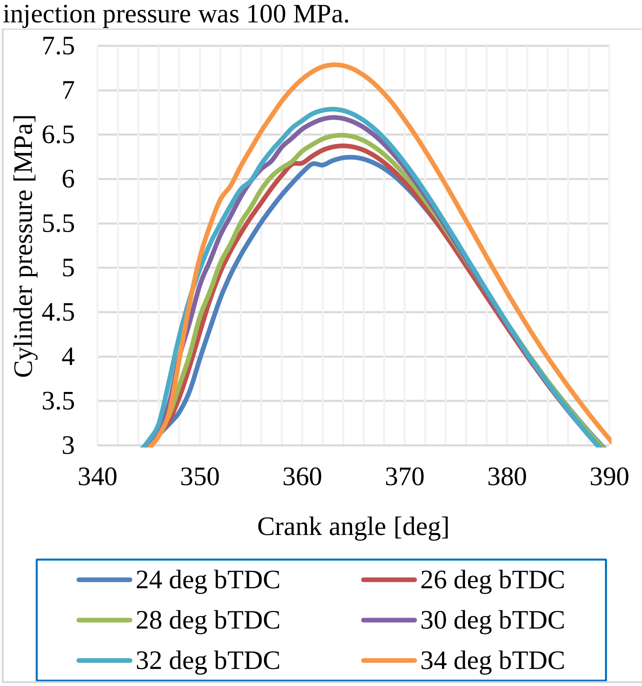

Fig. 6. Cylinder pressure vs. crank angle range 340÷390 deg for a variable start of fuel injection, fuel: Diesel+10%PO

On the basis of the data obtained, a comparative analysis of the pressure curves in the engine cylinder was carried out maintaining fixed injection timings. Both in-cylinder pressure and pressure rise rates for reference fuel and mixture: Diesel+10%PO are presented in Figure 7 and 9.

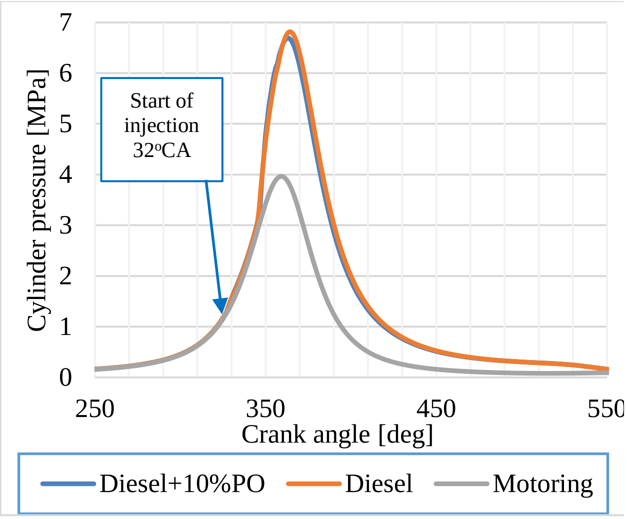

Fig. 7. Cylinder pressure vs. crank angle range 250÷550 deg for a variable fuel

The graph (Fig. 7) shows a slight decrease in in-cylinder pressure after adding 10% oil from tire pyrolysis. It affected lower combustion pressure and decrease in the indicate work and engine power. Pressure rise rate slightly increased with PO addition as shown in Figure 8. The mean indicated work from 200 measurements is 578 kJ/m^3. The unrepeatability of the engine's cycles is 4.18%. In the case of an engine fueled with a mixture of diesel oil and oil from pyrolysis of tires, the mean indicated work is 530 kJ/m^3 (decrease by 8.3%) and the engine work cycles unrepeatability unremarkably increased to 4.93%.

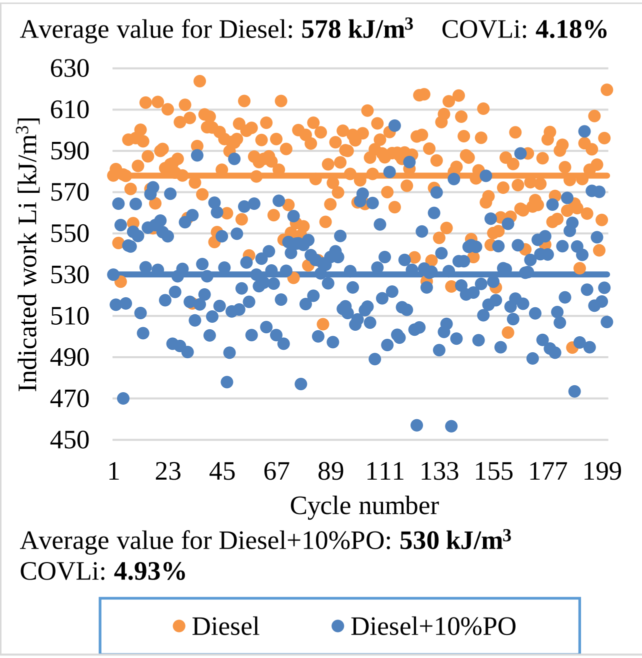

Fig. 8. Unrepeatability of the engine work for reference fuel and for research fuel

Figure 9 shows the rate of pressure rise. It can be seen that in the initial phase there is a faster pressure increase for Diesel+10%PO than for reference fuel. Visible peaks, deviations from mileage caused by the start and end of fuel injection.

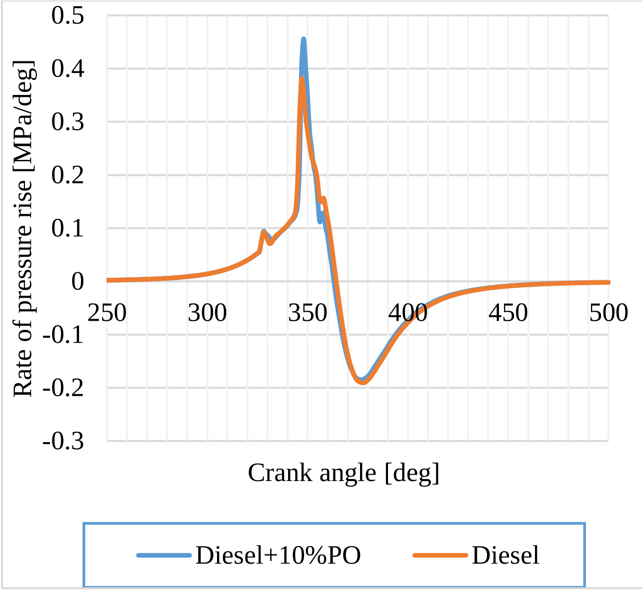

Fig. 9. Rate of pressure rise vs. crank angle

Figure 10 shows the pressure increase due to fuel combustion in the engine cylinder. The graph is the difference in pressure in the cylinder when feeding a given fuel and the pressure curve in the engine cylinder in motoring mode. The ignition timing in the studied case is 17 CA deg. The injection time is 5 ms, i.e. fuel injection in crank angle was 29.25 deg bTDC. Fuel injection ends approximately 1 CA deg bTDC. The combustion process continues until the exhaust valve opens.

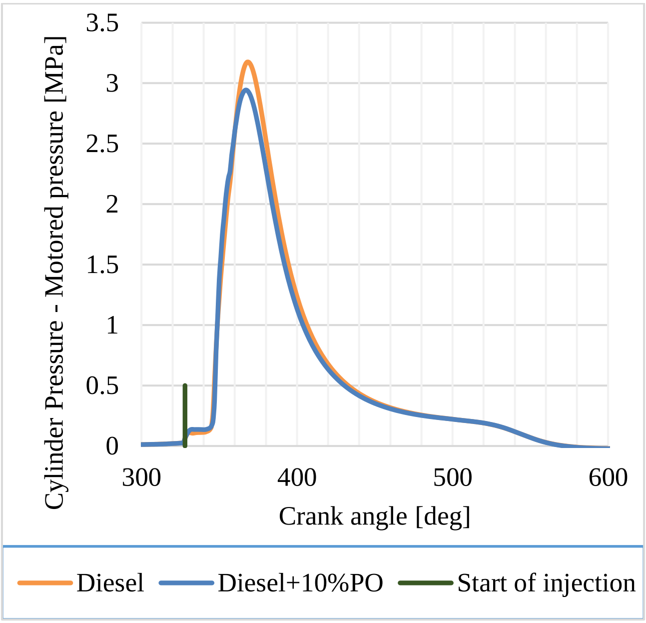

Fig. 10. Pressure increase as a result of fuel combustion

The injector characteristics were determined for the reference fuel and for the tested mixture: Diesel+10%PO. The results are shown in Figure 11.

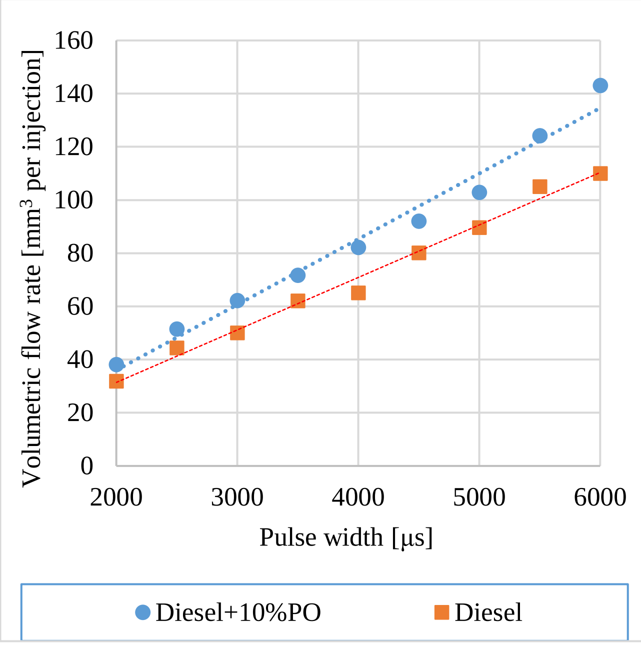

Fig. 11. Characteristic curves of the injection rate for both fuel

From the injector characteristics it can be seen that the addition of 10% oil from tire pyrolysis increases volumetric flow. Based on the measurement of the amount of fuel burned in a given time and indicated work, the engine efficiency could be calculated according to the equation:

$$\eta_T = \frac{Li}{Q_F} \quad (1)$$

where: L_i – indicated work [kJ]
Q_F – fuel energy injected to the cylinder [kJ]

Table 2. Net heating value of fuels used [1,3]:

	Diesel	Pyrolysis oil	Diesel+10%PO
Net heating value [J/mg]	42.5	39	42.15
Density [g/cm³]	0.82	0.95	0.833
Net heating value [J/mm³]	34.85	37.05	35.07

The results of the indicated efficiency for the tested fuels and for different fuel injection times are shown in Figure 12. The efficiency of the engine slightly decreased while supplying the engine with Diesel+10%PO mixture. The engine achieved its highest efficiency for the earliest fuel injection angle (32 CA deg bTDC). The efficiency was over 36%. The efficiency decreased with subsequent fuel injection. The lowest calculated efficiency was 26% at injection timing of 24 CA deg bTDC.

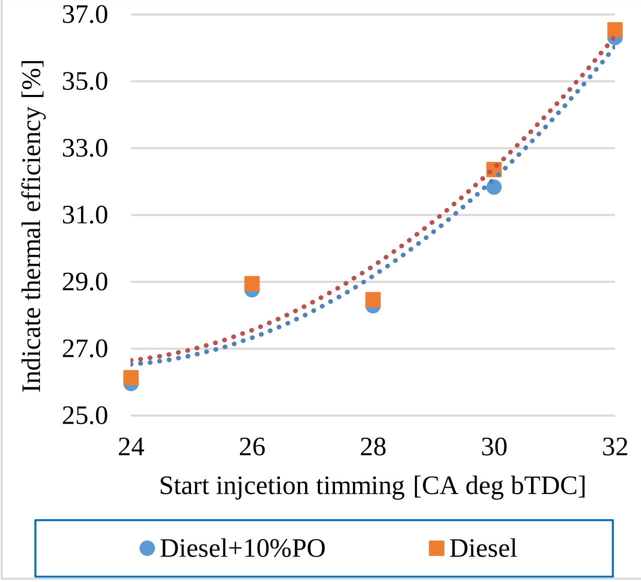

Fig. 12. Indicated thermal efficiency curves

The concentration of toxic exhaust compounds was also measured during the tests. The results of the CO concentration in exhaust gases are shown in Figure 13. The CO concentration increased significantly after adding 10% of tire pyrolysis oil. The lowest value of CO concentration was recorded for the fuel injection angle: 28 CA deg bTDC in the case of Diesel+10%PO and it was 0.61%, and for the reference fuel the lowest value was 0.49%, which was the result at injection timing of 30 CA deg bTDC. Delaying or overtaking the injection increased the CO content in the exhaust gas.

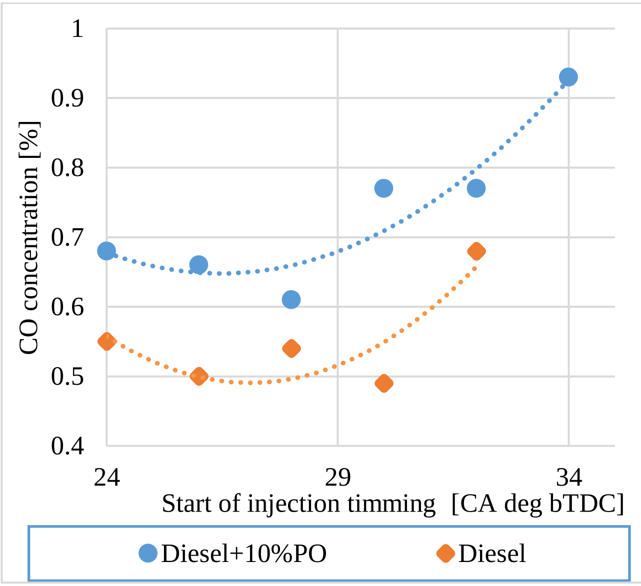

Fig. 13. CO concentration in exhaust gases

The NOx content is shown in Figure 14. Regardless of the fuel fed, the earlier the fuel injection into the cylinder, the higher the NOx content in the exhaust gas. For all cases, the NOx concentration was higher when the engine was fueled with Diesel+10%PO.

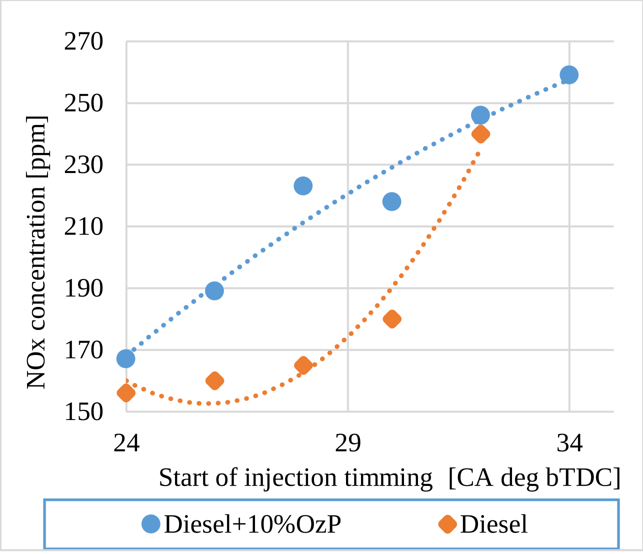

Fig. 14. NOx concentration in flue gases

The last toxic exhaust gas compound measured was unburnt hydrocarbons (HC). The share of unburnt hydrocarbons in exhaust gas is shown in Figure 15. The share of hydrocarbons was also significantly higher in the case of engine operation on the mixture: Diesel+10%PO rather than for reference fuel.

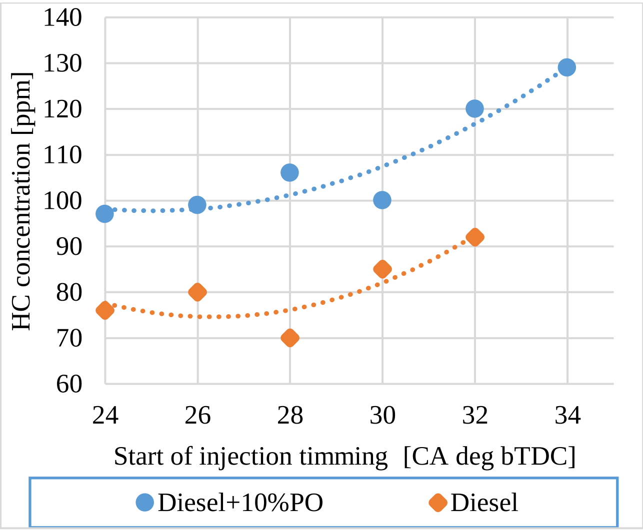

Fig. 15. HC concentration in exhaust gases

3. Conclusion

Combustion in the IC engine as technology for utilization of liquid products from the thermal treatment of waste rubber is one of the methods of utilizing substances that are harmful to the environment.

The pyrolysis parameters and the properties of the charge material determine the amount of liquid fraction (pyrolysis oil) obtained. The oil can be further processed or used in crude form.

Tire pyrolysis oil is permanently mixed with the basic fuel used to power diesel engines.

The addition of oil from the pyrolysis of tires causes decrease in in-cylinder combustion pressure, as a consequence of which the indicated work and the engine power as well as its efficiency, all decrease.

After adding oil from tire pyrolysis, the unrepeatability of consecutive engine work cycles increased slightly.

Tire pyrolysis oil added to diesel causes increase in injector flowrate availability by 15÷25%.

The addition of oil from the pyrolysis of tires to diesel causes increase in the concentration of toxic exhaust compounds: carbon monoxide, nitrogen oxides and unburnt hydrocarbons.

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Nomenclature

BDC	bottom dead center
bTDC	before top dead center
CA	crank angle
CI	compression ignition
CO	carbon monoxide
COV	coefficient of variation
HC	unburnt hydrocarbons
HPh	horse power-hour
Li	indicated work
NOx	nitrogen oxides
PO	pyrolysis oil
QF	fuel injected energy
RPM	revolutions per minute
TDC	top dead center

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