

TYRE PYROLYSIS OIL AS AN ENGINE FUEL

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Abstract

Tests have been carried out to evaluate the performance, emissions and heat release characteristics of a double cylinder direct injection diesel engine fuelled with tyre pyrolysis oil and diesel oil. The combustion parameters such as heat release rate, cylinder peak pressure, maximum rate of cylinder pressure, combustion knocking were also analysed. For purposes of this work raw pyrolysis oil was derived from waste vehicle tyres through vacuum pyrolysis realized in experimental installation. Results showed that the brake thermal efficiency of the engine fuelled with pyrolysis oil increased. THC, CO and CO₂ emissions were found to be higher due to high aromatic content and longer ignition delay, whereas NO_x shows increasing tendency due to greater heat release rate. The cylinder peak pressure did not change. The ignition delay became greater what can be the reason of problems with combustion knocking. Pyrolysis oil has a mass fraction of individual elements similar to diesel fuel but the chemical composition of hydrocarbons included in these fuels is different. The product of pyrolysis contains too much soot, sulphur, light and heavy hydrocarbons fractions for direct using it in engine. Aromatics content gives this fuel a distinctive smell. Pyrolysis oil is toxic and dangerous in use due to the polycyclic aromatic hydrocarbons (PAH). However raw pyrolysis oil is not suitable to use it as a CI fuel and requires additional distillation before using it in diesel engines as an alternative fuel in the future.

Keywords: *road transport, combustion engines, air pollution, environmental protection, alternative fuels, combustion*

1. Introduction

Worn rubber products, especially tyres, which account for 80% of the total amount of rubber used products, are a major environmental problem resulting from the production volume reaching almost 30 million tons per year all over the world. In Poland, is collected about 110 thousand tons per year of waste tires [3]. In the USA, about 303.2 million of waste tires were discarded in year 2007. The problem of tire disposal will be increasing due to the expanding of vehicle market. The tyre pyrolysis process converts waste tires into potentially recyclable materials such as flammable gas, pyrolysis oil, and carbon black.

According to global policy of reduction of greenhouse gas emissions, there are many initiatives to replace gasoline and diesel fuel due to the impact of fossil fuel crisis, hike in oil price and stringent emission norms. There are big investments in search for alternative fuels. On the other hand, the disposal of waste tyres from automotive vehicles is becoming more and more complex. Waste to energy is the recent trend in the searching of alternate fuels. Fuels like alcohols, RME, liquid fuel from plastics or rubber, biomethane etc. are some of the alternative fuels for the internal combustion engines. In order to prevent waste rubber and in particular discarded automobile tyres from damaging the environment, it is highly desirable to recycle this material in a useful manner. However, the total quantity of tyres currently recycled in a given year (excluding reuse, retreading, or combustion) is less than 7% of the annual tyre generation rate in the world.

One of technologies dedicated for tyre recycling is pyrolysis. Pyrolysis is chemical process in which rubber elements heated by a few hour in high temperature and atmosphere without oxygen is converted into mixture of hydrocarbons and residue. It is a complex series of chemical and thermal reactions to decompose or depolymerize organic material under oxygen-free conditions.

Waste tyre is needed to be shredded before process. The desulphurization is required in the pyrolysis system to eliminate the sulphur. It was determined that the oil production yield of tyre pyrolysis process has to have a maximum at 350 °C and decomposes rapidly above 400 °C [3]. The product output consists of 35% pyrolysis oil, 56% residue and the rest is pyrolysis gas. The amount of the residue is tire wire scrap and carbon black.

The use of tyre pyrolysis oil as a substitution to diesel fuel is an opportunity in minimizing the utilization of the fossil fuels to save natural resources and to limit greenhouse gas emissions. Pyrolysis is the process of thermally degrading a substance into smaller, less complex molecules. The main pyrolysis products are three principal components: pyrolysis oil, gas and residues (char, ash and steel wires). The quality and quantity of these products depend upon the reactor temperature and its design. In the pyrolysis process, larger hydrocarbon chains break down at certain temperatures in the absence of oxygen that gives end products usually containing solids, liquids and gases. If the temperature is maintained at 400° C, the main product of pyrolysis is a liquid, which is a mixture of various hydrocarbons depending on the initial composition of the waste material. At temperatures above 700° C, the gas becomes the primary product due to further cracking of liquids and dividing longer hydrocarbons chain into shorter. The gas is basically composed of CH₄, with C₂H₆, C₂H₄, C₂H₂, and other gaseous hydrocarbons however in lesser quantities. In this paper pyrolysis oil used in engine, testing was obtained from waste tyres.

2. Characteristic of Pyrolysis Oil

The products of pyrolysis strong smell due to the high aromatic substance. The pyrolysis oil is a mixture of carbon composition, which are C₅-C₂₀ in tire pyrolysis oil, and C₁₀-C₃₀ in plastic pyrolysis oil. The obtained oil requires distillation process to separate the diesel-like oil from other compounds. The substance that evaporates below 180 °C should be taken out because it is not good component for CI engines. The properties comparison of plastic oil, tire oil and diesel oil are shown in Tab. 1.

Tab. 1. Properties of pyrolysis oil [4]

Property	Tire Pyrolysis oil	Plastic Pyrolysis oil	Diesel oil
Heating Value (MJ/kg)	43.22	46.19	45.81
C (%)	84.67	83.79	87
H (%)	10.44	11.36	13
O (%)	4.17	2	-
S (%)	≤1	-	-
Density @ 30°C (g/cm ³)	0.924	0.8147	0.7994
Viscosity @ 40°C (cp)	2.69	2.49	1-4.11
Flash Point (°C)	68	100	7

In effect of tyre, pyrolysis is obtained oil similar in properties to a light fuel oil, with similar calorific value, sulphur, and nitrogen contents. The oils contained significant concentration of polycyclic aromatic hydrocarbons some of which have been shown to be either carcinogenic and or mutagenic. The concentration of PAH increased from 1.5 to 3 up to 4% of oil as the pyrolysis temperature increased from 450 to 600°C. The formation of PAH was attributed to a Diels–Alder type mechanism involving cyclisation of alkenes and dehydrogenation to form aromatic hydrocarbons. A range of potentially high value volatile hydrocarbons was identified in significant concentrations in the oils. It was found [4] that tyre pyrolysis at temperature of 475° C found to be optimum pyrolysis temperature.

In the paper performance, emission and combustion characteristics of the engine were analysed and compared with diesel fuel operation. Aromatics (including, inter alia, PAH like benzene, toluene, xylene, ethyl benzene) were found to be about 34.7% to 75.6% when the operating temperature

at pyrolysis process varied between 300°C and 700°C, while aliphatics were about 19.8% to 59.2%. It was observed that more than 30% of the tyre pyrolysis oil was easily distillable fraction with boiling points between 70°C and 210°C, which is the boiling point range specified for commercial petrol. On the other hand, 75% of the pyrolysis oil has a boiling point under 370°C, which is the upper limit specified for 95% of distilled product of diesel oil. Distillation carried out between 150°C and 370°C has a higher proportion of the lighter and heavier products and a lower proportion of the middle range of products than commercial diesel oil.

Tyre pyrolysis oil has different values of physiochemical properties, like heating value, viscosity, flash point, pour point etc. compared to diesel oil. These properties may affect the spray characteristics, performance, combustion, and emissions of the engine. The viscosity of tyre pyrolysis oil is higher by about 1.5 times than diesel. The flash point and fire point of the of diesel oil are closer to diesel. Sulphur and carbon content are also higher for of tyre pyrolysis oil than diesel oil.

3. Preparing fuel for engine testing

The fuel delivered for engine testing was produced in experimental installation shown on Fig. 1 and 2. Worn out tires were subjected to pyrolysis process in the reactor shown in Fig. 1. The tyres were heated up to temperature 400°C for 4 hours in oxygen free atmosphere. As a result of this process were formed in the reactor hydrocarbon vapours, which after cooling and condensation were collected in the reservoirs (Fig. 2). Obtained fuel after filtration to separate the soot, was used to power the engine.

The target of the engine testing was to find the answer to the question is it possible to use raw pyrolysis oil without any treatment and pyrolysis gas direct as a CI engine fuel. Since products of pyrolysis, e.g. oil and gas are an effect of tyre transformation into potential engine fuels, was tested a way of using this fuel in gensets for production of electricity.

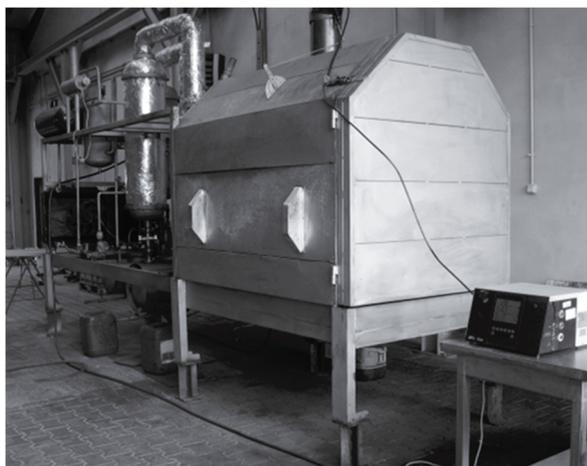


Fig. 1. Tyre pyrolysis reactor

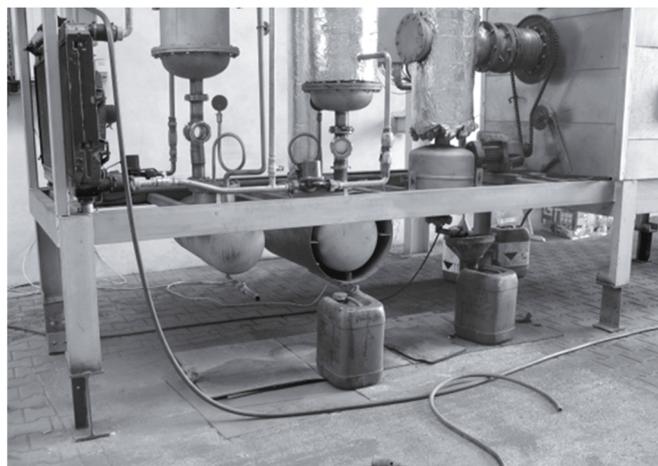


Fig. 2. Liquefiers of pyrolysis oil

4. Engine testing

The tested engine had the following specifications: displacement 3.62 dm³, rated speed 1500 rpm, power output 27.2 kW. The engine was originally used in stationary genset and due to this, it did not conform any regulation regarding to emissions. Practically emission level of the engine was on the level Euro 0.

On Fig. 3, cylinder pressure curves of the tested engine fuelled with diesel and pyrolysis oil are shown as well. Signs of the combustion knocking appeared at the highest loading of the engine fuelled with pyrolysis oil. Combustion knocking at medium values of indicating mean effective

pressure (IMEP) equals to 4.5 bar means that raw pyrolysis oil is sensitive to knocking. Maximal values of cylinder pressure are similar for both tested fuels.

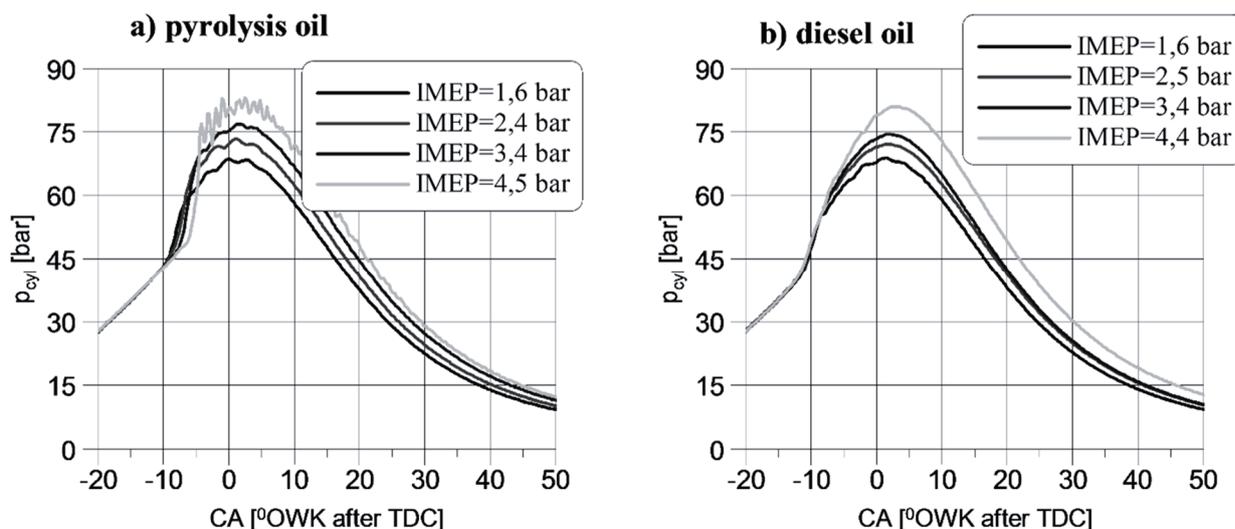


Fig. 3. Cylinder pressure for various fuels

Both tested fuels were characterized by different positions of the beginning of pressure rise over compression curve in the cylinder after the first signs of self-ignition. In diesel-powered engine, the moment of self-ignition is always the same for all engine loadings and begins in the vicinity of the crankshaft angle equals to 9° before TDC. In the case of pyrolysis oil the greater is engine loading, the greater is self-ignition delay.

On Fig. 4 compared cylinder pressure obtained for tested fuels. Increase of self-ignition delay causes greater rate of cylinder pressure due to injection of greater dosage of fuel in the period between beginnings of the fuel injection and the moment of appearance of the first signs of ignition. It causes acceleration of heat release in its initial phase after longer ignition delay.

On Fig. 5, the course of maximum cylinder pressure derivate ($dp/d\phi$) is shown. With increasing of engine loading for engine fuelled with pyrolysis oil the pressure rate is still increasing, while in the engine fuelled with diesel oil this value is almost constant and does not exceed of $7 \text{ bar}^\circ/\text{CA}$. Similar increase occurs in the case of the crankshaft position corresponding to a maximum rate of heat release. For diesel-powered engine this position is almost constant (Fig. 7) and varies from 10° to 9° CA before TDC, whereas for the pyrolysis oil this value is continuously growing towards TDC with increasing engine loading. Greater rate of cylinder pressure means greater noise emission from the engine.

On Fig. 8 is shown specific emissions from the engine measured for both tested fuels. Heavier pyrolysis oil with less hydrogen weight factor gives greater emissions of CO_2 , CO and THC. Increase of CO and THC emissions is almost double, while the increase of CO_2 is approximately 3%. The greater concentration of THC for pyrolysis oil is probably due to the lower temperature of the exhaust gas at the end of the expansion stroke and the formation of thicker layers of unburned fuel on the combustion chamber walls.

Pyrolysis oil small influences the NO_x emissions in the exhaust gases. This is a small surprise taking into account the fact that this fuel very strongly influences heat release in cylinder (Fig. 9). Use of pyrolysis oil causes increase of ignition delay, in which is injected greater dosage of fuel. As an effect of this, greater quantity of fuel is burnt in an explosive, premixed way, much faster than in the case of the combustion of regular diesel fuel. As a result of these phenomena, the curve of heat release rate for pyrolysis oil is shifted towards TDC by the value of self-ignition delay. Maximum value of heat release rate for pyrolysis oil is greater than for diesel oil, especially during premixed combustion. Starting with an engine loading of IMEP=3.4 bar the maximum heat release rate is even two times greater.

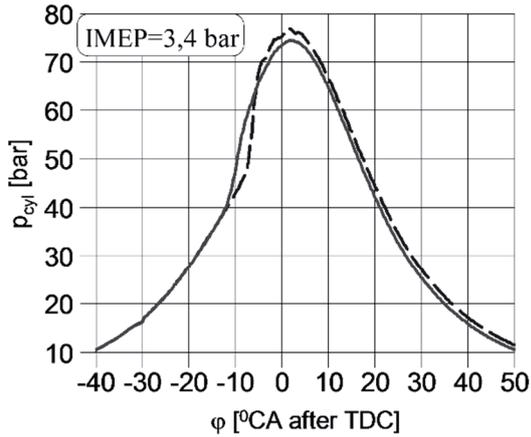


Fig. 4. Cylinder pressure vs. crankshaft angle

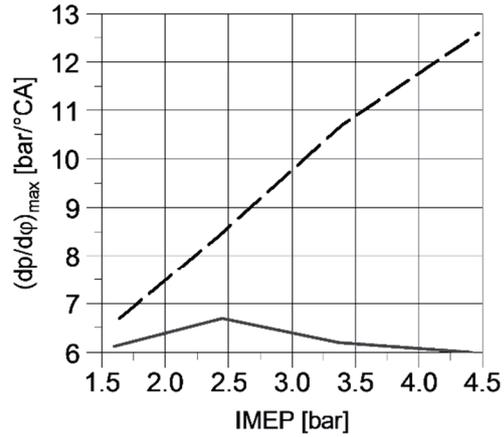


Fig. 5. Maksimal cylinder pressure rate vs. engine loading

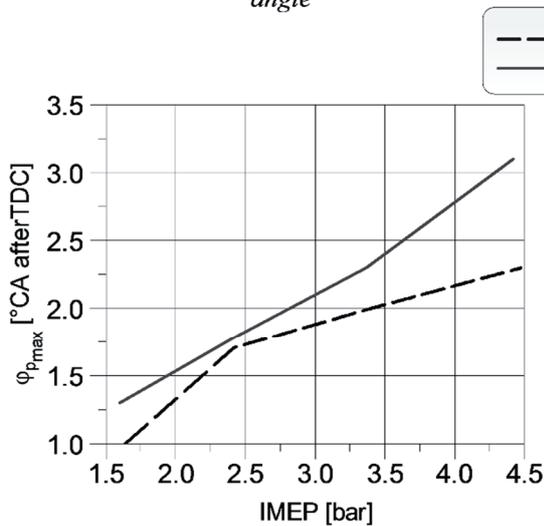


Fig. 6. Angle of maximum cylinder pressure position

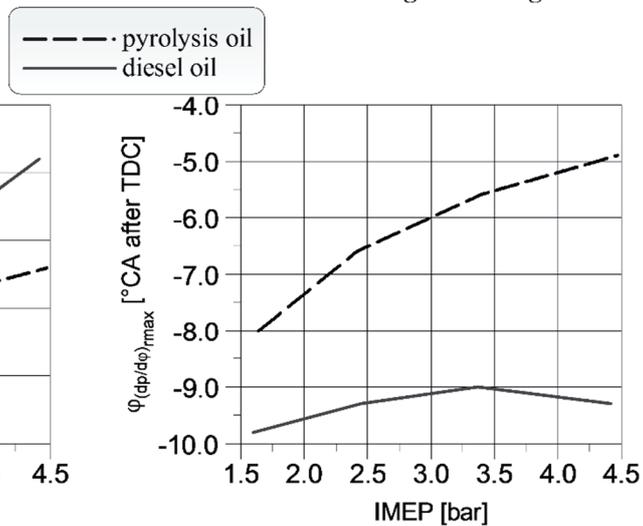


Fig. 7. Angle of maximum heat release rate position

For study of the effect of heat release rate on NO_x emissions, we are dealing with two different phenomena that have a significant impact on the emissions. One of them is the value of the heat release rate, and the second is position of the heat release rate curve relative to TDC. In this case of the using pyrolysis oil, at the same time has been occurred a delay of heat release and increase of its rate. It seems that both phenomena are mutually compensate their impact on the NO_x emissions. Self-ignition delay has resulted in shifting the maximum of heat release rate towards the top death centre, and resulted in an effect similar to delay of injection advance. The delay of injection advance is one of the most popular ways to reduce NO_x emissions due to reducing the maximum temperature of the charge in cylinder. On Fig. 8 however, it can be seen for pyrolysis oil the tendency to increasing of the NO_x emissions with the increase of engine loading, while for engine fuelled with diesel oil NO_x emission has rather a downward trend.

Heat release characteristics were made using methodology described in [6]. Use of pyrolysis oil has increased the share of the premixed combustion phase in heat release. In diesel-powered engine, 40-50% of the heat is released in premixed combustion stage, which is completed from 6° to 5° CA before TDC. In the engine fuelled with pyrolysis oil share of premixed combustion increases to 60%, and is completed from 5° to 3° CA before TDC. A greater share of premixed combustion in heat release, greater compactness of this phase and shifting the centre of gravity of this process towards TDC make the engine operates with greater efficiency due to better approximate of the heat release process to heat release at constant volume (Otto cycle).

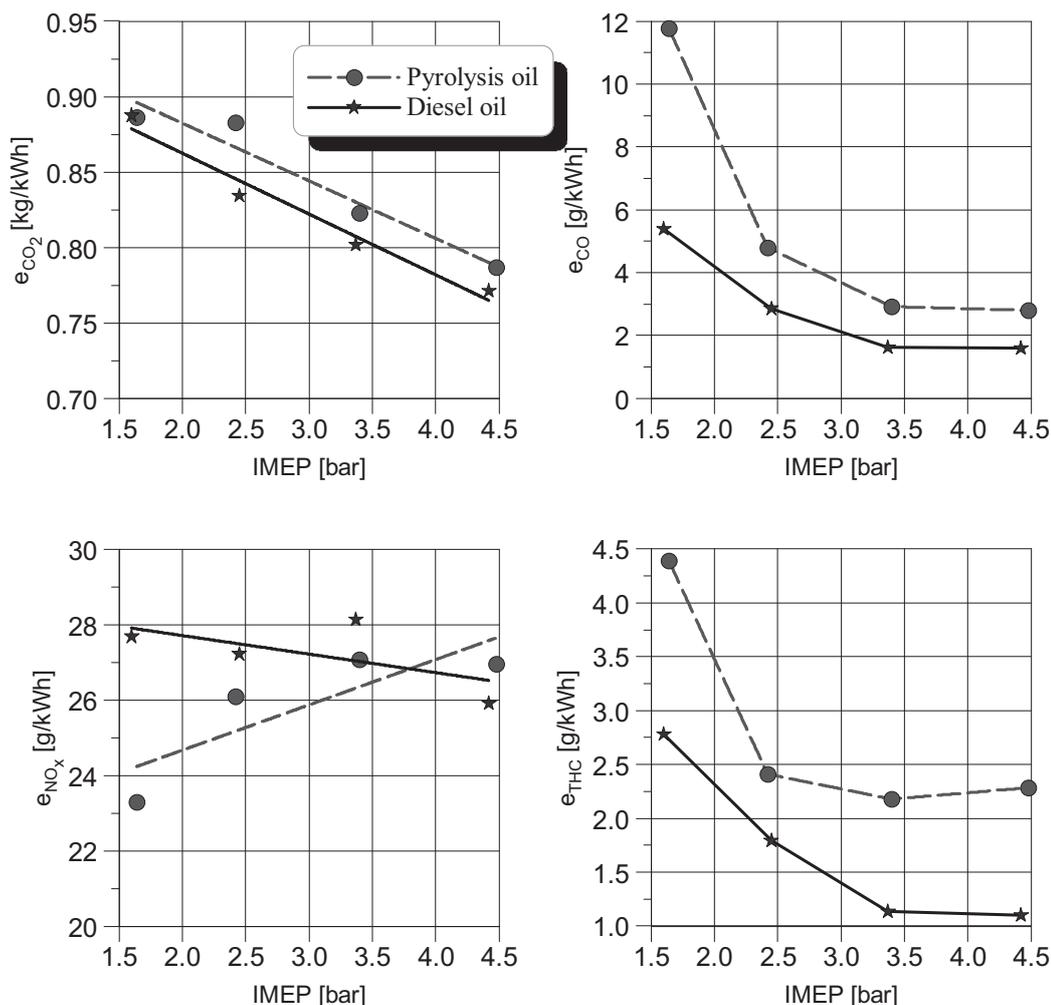


Fig. 8. Specific emissions of CO, CO₂, THC and NO_x versus engine loading

On Fig. 10 it can be seen that with the increase of engine loading is delayed the beginning of heat release ($\varphi_{5\%}$), and accelerated angel of 50% heat release ($\varphi_{50\%}$), with virtually the same position of the end of heat release ($\varphi_{90\%}$). In the engine fuelled with diesel oil combustion period between 5% and 50% of the fuel dosage contained in the cylinder is increased with the increase of loading (in Fig. 10 it is an increase from 6° to 12° CA), while for the engine fuelled with pyrolysis oil this value is a constant and equal to app. 4° CA.

For the case of pyrolysis oil the curve of maximum heat release rate position is approximately parallel to the graph corresponding to releasing of 50% of heat ($\varphi_{50\%}$), what means that the crankshaft angle of maximum of heat release rate roughly corresponds to the angle of 50% of fuel burned in the cylinder.

In the case of diesel oil the crankshaft angle corresponding to release of 50% of heat ($\varphi_{50\%}$) clearly receding with load increasing from position of maximum heat release rate. This means that the premixed combustion phase is a much smaller part in the combustion process occurring in the cylinder, and diffusive combustion is completed before the burning of 50% of the fuel dosage contained in the cylinder.

Increased ignition delay caused by use of pyrolysis oil, and violent heat release process characteristic for this kind of fuel can result in formation of the knocking combustion in peripheral areas of the combustion chamber. In the tested engine, knocking combustion appeared at loading equal to 4.5 bar. It is very small loading and practically means that raw pyrolysis oil is not useful as an engine fuel.

The carried out tests gave a proof that raw pyrolysis oil is not useful fuel for a diesel engine. Tyre pyrolysis oil requires using of such technology of its production, which would ensure obtaining the properties required for the engine fuel. First from the raw pyrolysis, oil must be remove sulphur and soot to lower PM emissions. In the next step from the fuel should be distillate light fraction responsible for knocking and too long self-ignition delay causing late, violent combustion after self-ignition.

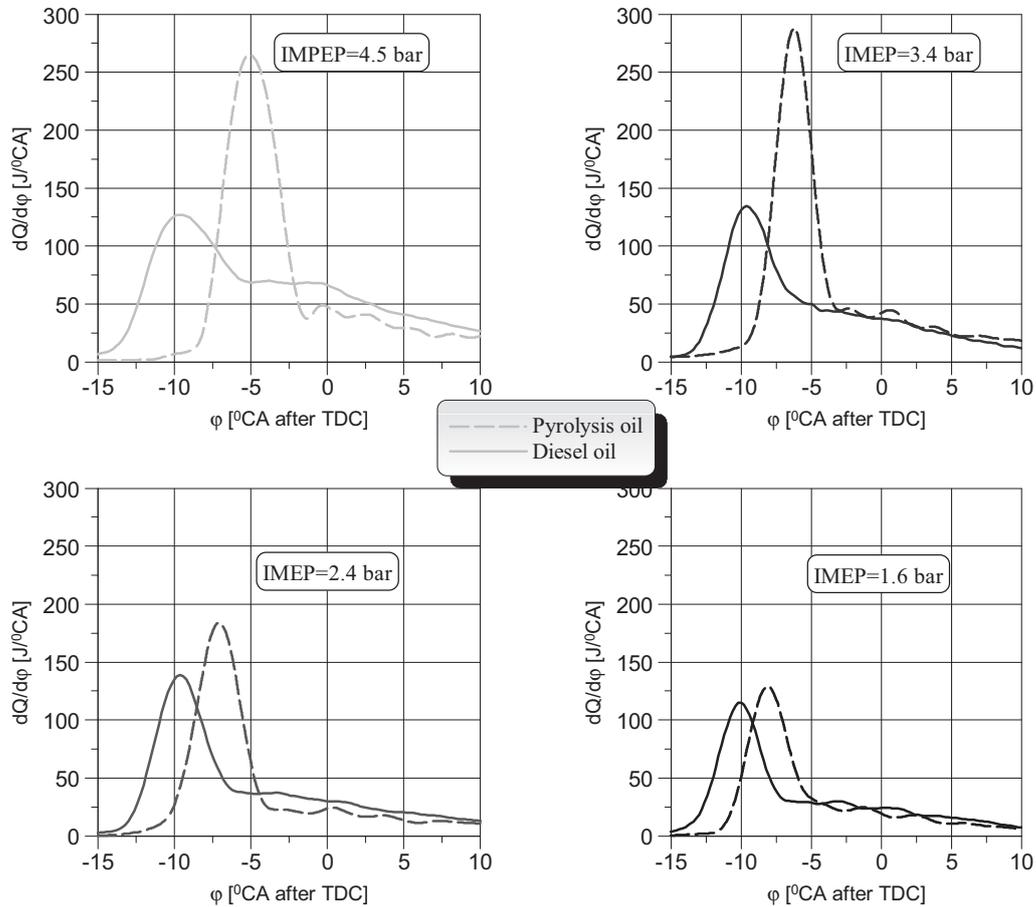


Fig. 9. Heat release rate versus crankshaft angle (CA)

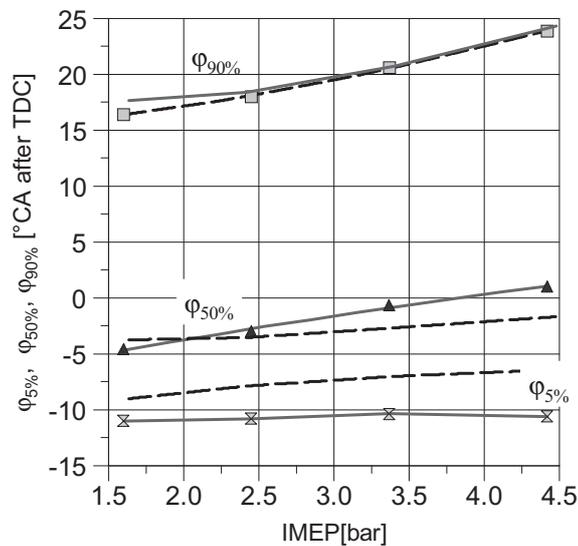


Fig. 10. Heat release expressed with crankshaft angle versus engine loading

The next problem concerns the safety. Due to the large share of aromatics hydrocarbons and PAH content, their vapours are harmful to health [5] and the fuel is dangerous in testing and using.

5. Conclusions

1. Raw pyrolysis oil is not suitable for direct use as a fuel in CI engines due to the high content of sulphur and soot.
2. Pyrolysis oil contains too much light fractions, causing delay of ignition and late heat release as well as excessive sensitivity to the knocking combustion.
3. Due to the chemical composition pyrolysis, oil may be a component or raw material for the production of engine fuels. Before using it in CI engines, it requires separation of light and cracking of heavy fractions, moreover it requires desulphurization and purification from soot.
4. The contents of toxic compounds (PAH) are making a dangerous use of this fuel.

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