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# An Alternative Method for Synthetic Polymers Waste Processing Using the Low Temperature Pyrolysis Process

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**ABSTRACT**

Plastics, due to their numerous advantages, are becoming materials more and more widely used in all branches of industry. The number of products, packaging and waste made of synthetic polymers is constantly increasing, which results in a growing threat to the environment due to long time of decomposition of the manufactured products. The future development of plastic recycling methods appears to be a necessary and significant step in materials processing and environmental protection. During the last two decades, a large number of promising research results on the catalytic pyrolysis process of plastics have been reported. This paper presents an alternative method for synthetic polymers waste processing using the low temperature pyrolysis process. The aim of this method is to manage the waste efficiently, but also to reduce the demand for fossil fuels. Commercial fuels and mixtures of these fuels with the pyrolytic oil obtained in low-temperature pyrolytic process were used for the purpose of this study, The following parameters of the obtained fuel mixtures were tested: density, viscosity, flash point, water content, cetane number, cold filter blocking temperature, cloud pint and lubricity, using following equipment: oscillating densitometer, Stabinger viscometer, Pensky-Martens Closed cup tester, apparatus for coulometric determination of water content by Karl-Fischer method, calorimeter. All tests were carried out in accordance with European standards for crude oil and petroleum products. The obtained results are promising and by contribution of the pyrolytic oil additives it is possible to significantly reduce the share of petroleum products used in the fuels production process and contribute to the beneficial management of artificial waste.

**Keywords:** recycling, priolysis, plastics, eco-energy, pyrolysis oil.

## INTRODUCTION

Since many years, there has been a noticeable rapid acceleration in the production and consumption of plastics, due to their implementation in many sectors of the economy. In the world, China is the leader in the production of plastics (approx. 25% of world production). For comparison, Europe and the NAFTA countries constitute approx. 20% of world production each. In Poland, more than 2.9 million tonnes are used annually (75 kg per person). Over 31% goes to the packaging industry (food, water and beverages, other goods), 28% are insulating materials, water pipes etc. (construction), the car industry accounts for 7%, and the electrical and electronic industry 5% [1–3].

The concept of plastics (polymers) is very broad [4–5]. The polymer materials are defined as materials whose basic ingredient are polymers [6], i.e. multi-molecular chemical compounds obtained in industrial polymerization processes [7–9]. In various areas of life and economy, we can distinguish a lot of different (in terms of chemistry) polymers. Physicochemical and mechanical properties are obtained by using special excipients or by combining them with other materials (eg carbon fibers) [10–12].

As a result, higher properties are obtained and the material can be used in many areas due to: relatively low price, ease of forming, unique properties - e.g. resistance to corrosion and chemicals, low electrical and thermal conductivity, good strength, impact resistance, low specific gravity, possibility of reprocessing through recycling [13].

As consumption patterns change together with populations and urbanization increases, countries face an important waste management challenge. Plastic waste are particularly problematic as many of single-use plastics are released into the environment, including the marine environment. There are three options: 1) prohibit the new plastic production, 2) replace with materials such as paper or glass, etc., 3) develop recycling methods [4].

Physicochemical transformations (conversion) of fuels are processes aimed at transforming the chemical energy of a fuel into another type of energy (direct transformation), or the transformation of fuel from one form into another, usually easier to further processing (indirect transformation) [14]. An example of an indirect conversion is pyrolysis [16–18]. Pyrolysis is the process of degradation (decomposition) of a complex molecule under the influence of a sufficiently high temperature in an anaerobic environment [19]. Thus, pyrolysis is a thermal conversion of fuels in a closed system, without supply of additional external substrates (mainly oxygen), the presence of which changes the spectrum of obtained products [20]. Depending on the temperature of the process, low-temperature (446÷696 °C) and high-temperature (896÷1096 °C) pyrolysis are distinguished.

Pyrolysis is used for thermal waste treatment [21–23]. The most common products of waste pyrolysis are: pyrolysis gas, liquid water-tar-oil fraction, biochar. The composition of the products obtained by waste pyrolysis is influenced by many factors. The type of waste subjected to pyrolysis determines the properties of the products in the first place. In addition, the quality and quantity of the products are determined by numerous parameters, such as: type of reactor, type of hydrocarbon vapor cooler, degree of material disintegration, purity of the material, residence time of the batch in the reactor, heating method, heating time, maintaining of constant temperature. Temperature affects the amount of individual end products and the residence time of the charge in the high temperature zone [24].

The article [21] presents a preliminary study of the possibility for recovery valuable products and energy from PCB waste in the pyrolysis process. PCB waste pyrolysis was carried out in a fixed bed reactor. Pyrolysis oil properties and residues were analyzed. The research [25] verified the influence of temperature and time on products obtained in pyrolysis of plastic waste. The authors [22] presented thermal and catalytic pyrolysis of primary low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP) and LDPE/PP mixtures. Research was carried out in a batch reactor with a laboratory volume of 200 ml at a temperature of 460°C in nitrogen atmosphere. A number of studies have been carried out and acquired results have prove that the oil obtained from the catalytic pyrolysis of plastic waste has potential as an alternative fuel. The research [26] focused on assessing the potential of converting municipal solid waste (MSW) into biofuel through the pyrolysis process. The products of the MSW pyrolysis reaction were: pyrolysis liquid, solid carbon and a gas mixture. Pyrolysis oil and residual carbon were subjected to elemental analyzer and Fourier transform infrared (FTIR) spectroscopy. The FTIR results showed that the petroleum product had significant amounts of alkenes, alkanes and carbonyl groups due to the high content of organic compounds in MSW.

Due to the fact that there are not many research devoted to the properties of diesel with the addition of pyrolysis oil, it was decided to conduct them. The main objective of this research was to reduce the generation of organic waste and the use of pyrolysis oil for energy purposes (heating) and to power diesel generators. Research has shown that it is possible to use waste fuel as an additive to the basic fuel, which transfer into its use in the economic sphere.

## MATERIALS AND METHODS

The main task of the Research Team was to develop an appropriate technology of low-temperature pyrolysis process and to obtain samples of alternative fuels made of plastics from three waste groups, i.e. PE (polyethylene), PP (polypropylene), PS (polystyrene). A series of tests of the composition and physicochemical properties, such as: density, viscosity, flash point, water content, cetane number, cold filter blocking point, cloud point and lubricity were carried out for 9 samples of commercial diesel fuel and pyrolysis oil mixtures, and 3 reference samples. The test were carried out in the third party laboratory with the number of repetitions compliant with the applied test standards (test methodology), which are presented in Table 1.

**Table 1.** Research standards

| Parameter | Norm |
|---|---|
| Density at 150°C | PN-EN-ISO 12185, PN-EN-ISO 3675 |
| Kinematic viscosity at 400°C | PN-EN 16896:2016-2012 |
| Cetane number | PN-EN-ISO 5165 |
| Flash point 0°C | PN-EN-ISO 2719 |
| Cold filter blocking point | PN-EN- 116 |
| Cloudy point 0°C | PN-ISO 3015 |
| Water content mg/kg | PN-EN ISO 12937 |
| Lubricity | PN-EN ISO 12205 |

**Table 2.** Average values of obtained products during waste processing

| Material | Quantity | | |
|---|---|---|---|
| | Oil | Gas | Charred residues |
| PE-HDPE | 83.5% | 16% | <1% |
| PP | 84.2% | 15.7% | <0.25% |
| PS | 93% | 4% | 3% |

In the pyrolysis of plastics, a system of direct cooling of hydrocarbon vapors in water was used, which resulted in obtaining three products in the form of a gas, liquid and solid phase.

**Fig. 1.** Pyrolysis reactor with water cooler

The average value of the acquired products during the processing of plastic waste is presented in Table 2.

PP, PE and PS materials were selected for the experiments. The raw materials were subjected to low-pressure pyrolysis with direct cooling in the apparatus shown in Figure 1.

The main element of the installation is a reactor composed of the following parts:

- loading chamber with a capacity of 2 L, thermally insulated
- LPG burner with a heating power of 3 kW
- vapor cooling system (water cooler with discharge of finished gas and oil products)
- control cabinet.

Three batches were prepared for the tests. The first type of waste was made of PP plastics, second was made of PE waste, and the third one was made of the PS plastics group. Figure 2 shows photos of the waste used for pyrolysis. All the samples were manually chipped into smaller pieces in order to accelerate the pyrolysis process. Figure 3 shows the samples placed in the reactor.

The process of obtaining each of the samples lasted about 5.5 hours and was carried out with temperature up to 430°C measured at the bottom of the reactor. Figure 4 shows the samples submitted for further testing.

**Fig. 2.** Waste used in pyrolysis process

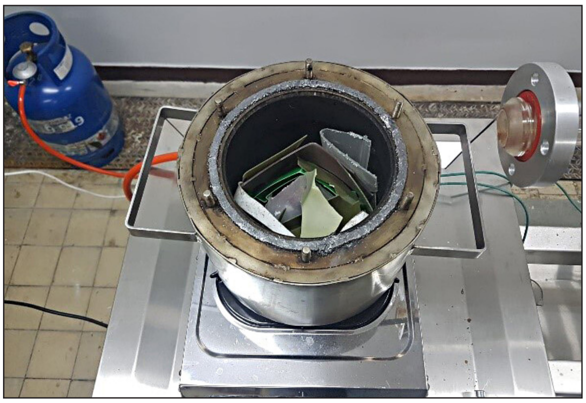

**Fig. 3.** Samples in the reactor

**Fig. 4.** Samples submitted for tests

**Table 3.** List of samples from PE plastics batch delivered to the laboratory

| Sample name | B7 content | PE contenet |
|---|---|---|
| PE-A | 50% | 50% |
| PE-B | 75% | 25% |
| PE-C | 85% | 15% |
| D - B7 reference sample | 100% | 0% |
| PE – reference sample | 0% | 100% |

**Table 4.** List of samples from PP plastics batch delivered to the laboratory

| Sample name | B7 content | PP contenet |
|---|---|---|
| PP-A | 50% | 50% |
| PP-B | 75% | 25% |
| PP-C | 85% | 15% |
| PP- reference sample | 0% | 100% |

**Table 5.** List of samples from PS plastics batch delivered to the laboratory

| Sample name | B7 content | PS contenet |
|---|---|---|
| PS-A | 50% | 50% |
| PS-B | 75% | 25% |
| PS-C | 85% | 15% |

The tables (Table 3÷5) present the lists of samples transferred to the laboratory for further testing.

All samples used in the research were containing 15, 25 and 50% of pyrolysis oil respectively, additionally, for comparative purposes, reference samples of pure PE pyrolytic oil, pure PP pyrolytic oil and commercial automotive diesel were tested. The following tests were carried out in accordance with the applicable standards: density (DMA 4500 apparatus); kinematic viscosity (TAMSON TV 2000); cetane number (HERZOG CETANE ID 500); flash point (closed cup); cold filter plugging temperature and cloud point (ISL FPP - 5Gs); water content (apparatus for coulometric determination of water content by Karl-Fischer method); calorific value (calorimeter "PAN 6200").

## RESULTS

DMA 4500 was used to measure the density in accordance with PN-EN-ISO 12185, PN-EN-ISO 3675 (petroleum and petroleum products – Density determination – Oscillation method with a U-tube).

The diagram (Fig. 5) shows the density of the fuel sample at 15°C, the appropriate fuel density is important for the quality of fuel-air mixture atomization and the quality of combustion. According to the standard, the density should be in the range of 800÷840 kg/m$^3$. Samples with 50% addition of pyrolysis fuel made of PP and PS do not meet the standards, as PP density is 793.51 kg/m$^3$, and for PS 863.92 kg/m$^3$. The sample with 50% addition of PE meet the standards, as density is 801.92 kg/m$^3$. Samples with 25% addition of PP and PE are compliant with the standard because their density is at the level of 811.47 kg/m$^3$ for PP and 813.67 kg/m$^3$ for PE. The sample with 25% PS additive does not meet the standard because it has a density of 847.22 kg/m$^3$. Samples with a 15% addition of pyrolysis oil meet the standard, because their density is respectively for PP 818.79 kg/m$^3$, PE 820.42 kg/m$^3$, PS 838.83 kg/m$^3$. Samples with a 0% addition are B7 (diesel) reference samples.

The kinematic viscosity was measured in accordance with the PN-EN 16896: 2016–2012 standard (Petroleum products and similar products – Determination of kinematic viscosity – Method with Stabinger viscometer) using the TAMSON TV 2000 apparatus. Figure 6 shows the dependence

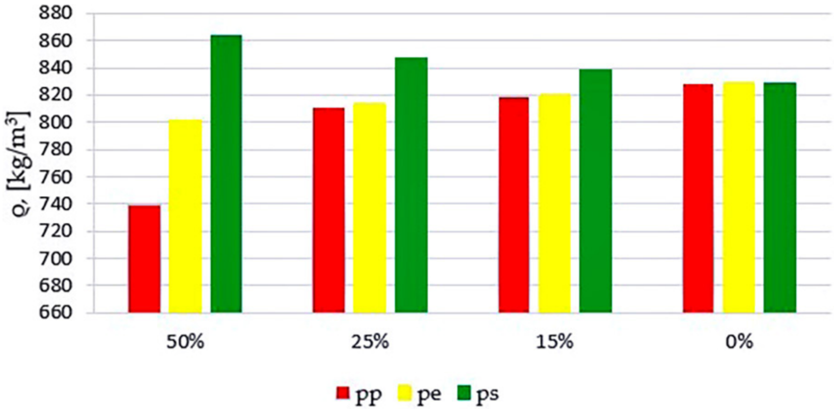


**Fig. 5.** Density at 15°C, depending on the sample tested

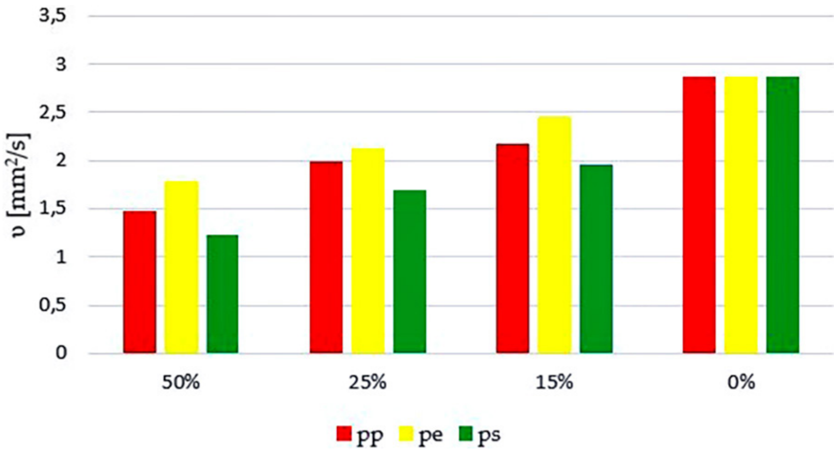


**Fig. 6.** Kinematic viscosity graph according to pyrolysis oil content

of the kinematic viscosity on the type of the tested sample and the pyrolysis oil content.

The graph (Fig. 6) shows the kinematic viscosity which is responsible for the lubrication of the injection and engine components. According to the standard, the kinematic viscosity should be in the range from 1.5 to 4.0 $mm^2/s$. Samples with 50% content of PP and PS additive do not meet the standard, because the kinematic viscosity is respectively for PP 1.48 $mm^2/s$, and for PS material it is 1.23 $mm^2/s$. The sample with 50% addition of PE meet the standard and has a kinematic viscosity of 1.78 $mm^2/s$. Samples with 25% content of pyrolysis oil additives are within the standard and are at the level of: PP sample 1.98 $mm^2/s$, PE sample 2.13 $mm^2/s$, PS sample

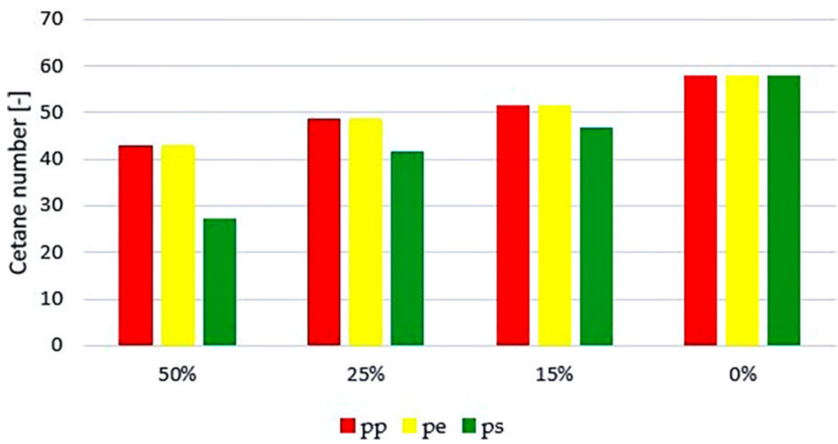


**Fig. 7.** Cetane number, depending on the sample tested

1.70 mm$^2$/s. For 15% additive content samples, the tests showed that all 3 meet the standards and are on following levels, PP sample 2.18 mm$^2$/s, PE sample 2.45 mm$^2$/s, PS sample 1.96 mm$^2$/s. Samples with 0% additive content are the reference sample of diesel fuel.

The HERZOG CETANE ID 500 apparatus was used to measure the cetane number in accordance with the PN-EN-ISO 5165 standard (Petroleum products – Determination of the ignition properties for diesel fuels – Engine method for the cetane number determination), the results of this measurement are shown in Figure 7.

According to the Polish standard for diesel fuels, the minimum cetane number is set at 51. The operational tests of diesel engines have shown that the fuel with a lower cetane number has a negative effect on the engine and reduces the driving economy. Considering the samples with 50% additives content, they do not meet the standard because the sample with the addition of PP has a value of 42.91, the sample PE is 42.91 and the sample PS 27.32. Samples with 25% of additives also do not meet the Polish standards, as the sample with PP additive is 48.84, the PE sample obtained the result of 48.84 and the PS sample has the cetane number 41.54. Two samples with a 15% addition of oil after pyrolysis are within the standard, i.e. the PP and PE samples obtained the cetan number 51.69, but the sample with the PS additive with obtained result of 46.86 is below this standard.

**Table 6.** Flash point °C

| Sample name | Flash point of sample °C | B7 flash point °C |
|---|---|---|
| PP-A | <20 | 56 |
| PP-B | <20 | 56 |
| PP-C | <20 | 56 |
| PE-A | <13 | 56 |
| PE-B | <13 | 56 |
| PE-C | 14 | 56 |
| PS-A | <20 | 56 |
| PS-B | <20 | 56 |
| PS-C | <20 | 56 |

The flash point was measured with the use of a closed cup in accordance with the PN-EN-ISO 2719 standard (Flash point determination – Pensky-Martens closed cup method). According to the Polish standard for diesel fuel, the minimum temperature of ignition is 55°C. Table 6 shows the aquired ignition temperature values, it can be seen that the temperature for alternative fuels, regardless of the additive and its content, is below 20°C. Unfortunately, none of the tested samples meets the standard.

The cold filter plugging temperature was measured in accordance with the PN-EN-116 standard (Diesel oils and light heating oils – Determination of the cold filter plugging temperature – Gradual cooling method) with the use of flow temperature measurement apparatus with an integrated ISL FPP - 5Gs cryostat. The results of the conducted tests are shown in Figure 8.

The cold filter blocking temperature (CFPP) is a parameter given in diesel oil standards and for moderate climate conditions in winter is set on -20°C. Below this temperature, paraffin precipitation occurs, which causes a blockage on the filter and prevents the engine from starting. For comparison, winter diesel was used as the 0% reference sample. From the diagram (Fig. 8), it can be read that for 50% of PP pyrolysis oil additive sample CFPP is -15 °C therefore sample do not meet the standard, the results of PE -23°C and PS -29°C samples are fulfilling. Looking at the fuels with 25% post-pyrolysis oil additive, all of

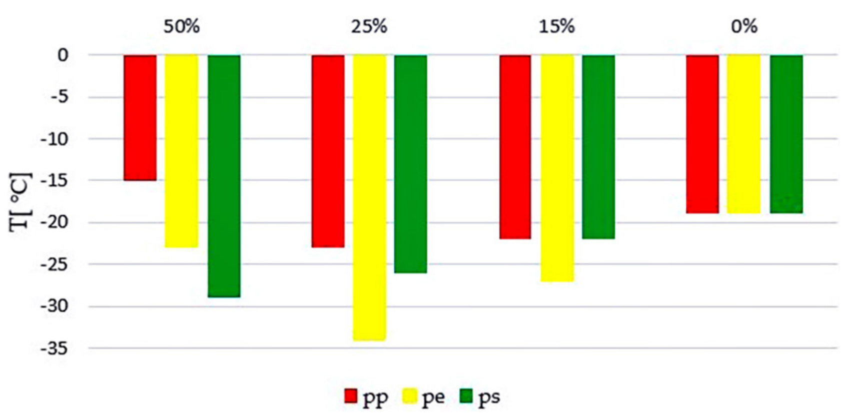


**Fig. 8.** Cold filter blocking temperature, depending on the sample tested

them meets the standard as all the results are below -20°C, the sample with the PP additive have achieved -23°C and accordingly the PE sample -34°C, and the PS sample -26°C. The results obtained from samples with a 15% alternative fuel addition also fulfill the criteria. The temperature of the sample with the 15% addition of PP is -22°C, the sample of PE has a temperature of -27°C, and the sample with the addition of 15% PS has the temperature of -27°C.

Cloud point was measured with the use of the ISL FPP - 5Gs apparatus according to PN-ISO 3015 standard (Petroleum products and similar products of natural or synthetic origin - Determination of the cloud point). According to the standard, the fuels should reach a maximum of -22°C. The obtained results are shown in Figure 9.

As can be seen on the bar graph (Fig. 9), samples with 50% of pyrolysis oil additives reach the following temperatures: PP -13°C, PE -12°C, PS -83°C. Samples with the addition of PP and PE are within the standard. The sample with 50% of PS additive significantly exceeds the norm. The addition of 25% of post-pyrolysis oil reaches the following temperatures for individual plastics, PP -9°C, PE -9°C, PS -109°C. Samples with the addition of PP and PE are within the standard. The sample with 25% PS addition significantly exceeds the norm. Considering the 15% pyrolysis oil additive, the following results are obtained: PP -9°C, PE -9°C, PS -9°C. All 3 samples with 15% additive meet the standard.

Water content was measured using the apparatus for coulometric determination of water content using the Karl-Fischer method in accordance with PN-EN ISO 12937 (Petroleum products – Water determination – Coulometric Karl Fischer titration method).

According to the standard, the maximum level of water in the fuel may be 200 mg/kg. The individual results are shown on diagram (Fig. 10).

According to obtained results, samples with 50% additives are at the level of: PP 127.9 mg/kg, PE 20 mg/kg, for PS 276.5 mg/kg. Samples with PP and PE additives are within the norm, but 50% PS additive sample do not meet the

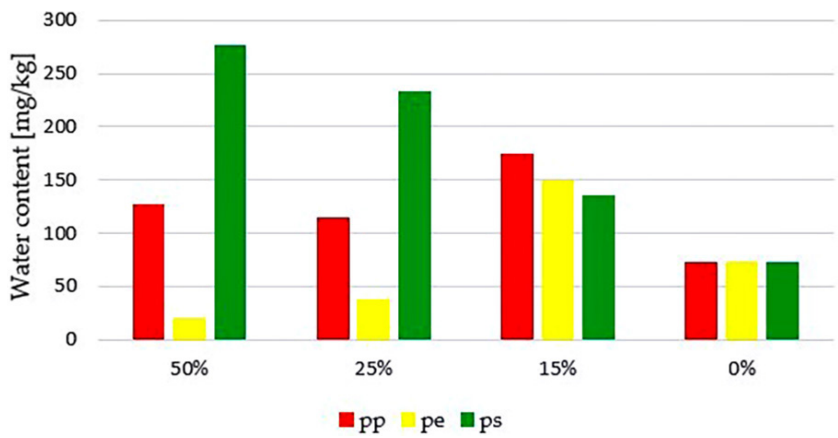


**Fig. 9.** Cloud point, depending on the sample tested

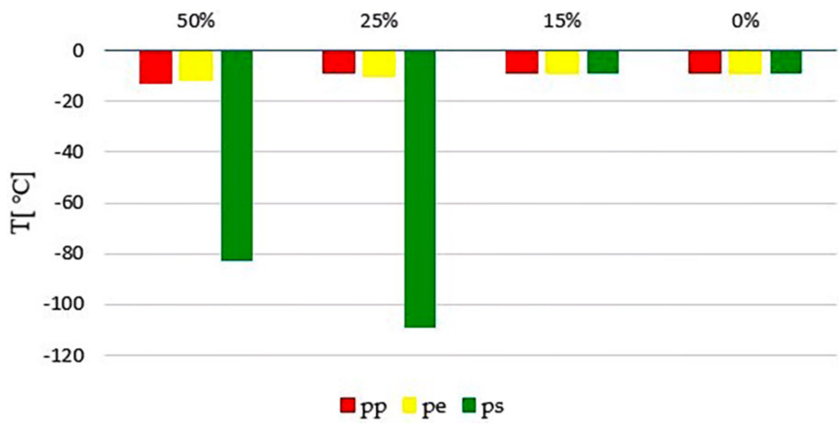


**Fig. 10.** Water content, depending on the sample tested

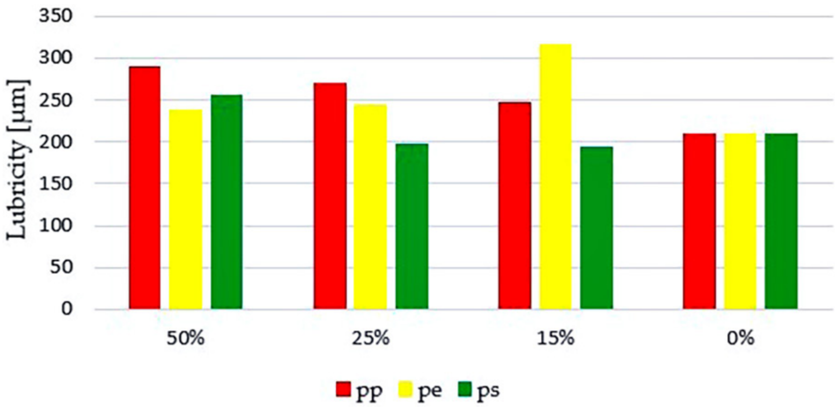


**Fig. 11.** Lubricity, depending on the sample tested

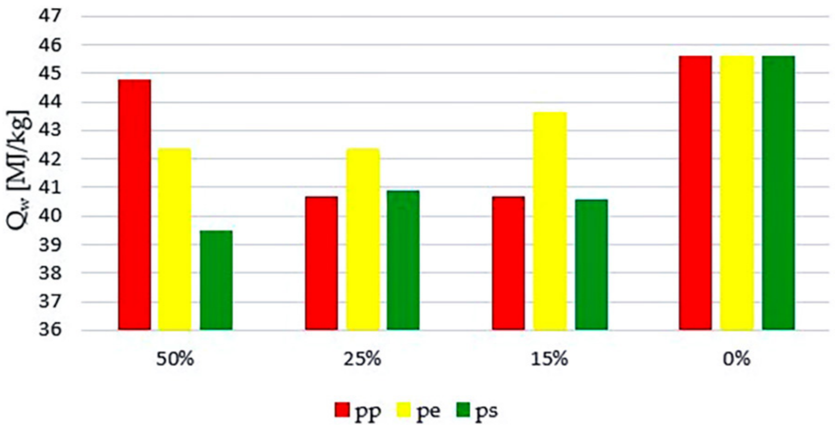


**Fig. 12.** Heating value, depending on the sample tested

standard. Samples with 25% additives are at the level of: PP 115.2 mg/kg, PE 38 mg/kg for PS 233.1 mg/kg. Samples with PP and PE additives are within the standard, but the addition of 25% PS is out of the norm range. The samples with 15% additives are at the level of: PP 175.5 mg/kg, PE 150 mg/kg, PS 135.6 mg/kg. All samples with a 15% addition of pyrolysis oil meet the requirements of the standard.

The lubricity was measured with the use of equipment (DMA 4500) in accordance with the PN-EN ISO 12205 standard (Petroleum products – Determination of oxidative stability of middle fuel distillates). The obtained results are shown in Figure 11.

Lubricity according to the standard under condition of normal steam pressure of 1.4 kPa, should not exceed 460 µm. As can be seen on the bar graph (Fig. 11), samples with 50% alternative fuel additives have the following lubricating values: PP 291 µm, PE 239 µm, PS 270 µm. All 3 samples with 50% additives meets the standard. Samples with 25% of pyrolysis product additives have the following lubricating values: PP 270 µm, PE 244 µm, PS 198 µm. All samples with a 25% additive of pyrolysis oil meets the standard. Samples with 15% of alternative fuel additives have the following lubricating values: PP 247 µm, PE 317 µm, PS 195 µm. All samples with a 15% additive of pyrolysis oil meets the standard.

The calorific value was measured with the use of equipment to determine the heat of combustion of fuels – isoperobolic calorimeter "PAN 6200" in accordance with the PN-C-04-062 standard (Petroleum products – Determination of the heat of combustion for liquid fuels in a calorimetric bomb and calculation of the calorific value using empirical formulas). Graph (Fig. 12) shows the calorific values for the individual samples.

For samples with 50% addition of pyrolysis oil, the calorific values are: PP 44.8 MJ/kg, PE 42.36 MJ/kg, PS 42.36 MJ/kg. For samples with 25% addition of pyrolysis oil, the calorific values are: PP 40.7 MJ/kg, PE 42.34 MJ/kg, PS 40.90 MJ/kg. For samples with a 15% addition of pyrolysis oil, the calorific values are: PP 40.7 MJ/kg, PE 43.66 MJ/kg, PS 40.60 MJ/kg. The results are summarized in Tables 7–9.

Table 7 presents the parameters obtained as a result of the tested mixtures of industrial fuels with different proportions of the addition of pyrolysis oils obtained from PP (polypropylene) group, a certain dependence can be observed regarding the percentage concentration of pyrolysis oil. The higher the percentage concentration, the greater is the deviation from the standard of quality parameters for diesel oil. It can be noted that most of the tested parameters of the sample with 15% PP additive meet the quality requirements for diesel oils in accordance with the Regulation of the Minister of Economy dated on October 9, 2015. regarding the quality requirements for liquid fuels. The only parameters that does not meet these requirements is the flash point, however, it does not exclude this mixture as an alternative to standard fuels. In the Polish standard for diesel oils, the minimum cetane number is set at 51, because the diesel engine exploitative tests have shown that fuels with a lower number have a negative effect on the engine and significantly reduce driving economy. They also generate more noise, and increased fuel consumption which results in increased soot emissions. On the other hand, an increase in the cetane number above 50 significantly improves the exploatation properties of the engine, the engine operation is more "smooth" and rotation speed increases more easily, facilitates the engine start-up, slows down the contamination of the injector nozzles, reduces the proportion of solid particles in the exhaust gas and lowers the engine noise.

Considering the rest of the samples with 25% and 50% PP additive, it can be observed that the cetane number is below the quality standard. Additionally, the sample with 50% PP additive does not meet the density requirements at 15°C. Samples with 25% and 50% PP additive are characterized by a significant reduction in the quality parameters for diesel fuels, but this does not exclude their use in other industries, e.g. heat and power plants.

Table 8 presents the parameters obtained as a result of the tested mixtures of industrial fuels with different proportions of the addition of pyrolysis oils obtained from the PE group (Polyethylene), a certain dependence regarding the percentage concentration of pyrolysis oil can be observed. The higher the percentage concentration, the greater is deviation from the standard of quality parameters for diesel oil. It can be noticed that the sample with a 15% addition of PE meets most of the tested quality parameters for diesel oils in

**Table 7.** Summary of the test results obtained for the mixture of fuel with the addition of PP

| Parameter | PP 50%<br>B7 50% | PP 25%<br>B7 75% | PP 15%<br>B7 85% |
|---|---|---|---|
| Density at 15°C | - | + | + |
| Kinematic viscosity at 40°C | + | + | + |
| Cetane number | - | - | + |
| Flash point °C | - | - | - |
| Cold filter plugging point °C | - | + | + |
| Cloud point °C | + | + | + |
| Water content mg/kg | + | + | + |
| Lubricity | + | + | + |

**Table 8.** Summary of the test results obtained for the fuel mixture with PE additive

| Parameter | PE 50%<br>B7 50% | PE 25%<br>B7 75% | PE 15%<br>B7 85% |
|---|---|---|---|
| Density at 15°C | + | + | + |
| Kinematic viscosity at 40°C | + | + | + |
| Cetane number | - | - | + |
| Flash point °C | - | - | - |
| Cold filter plugging point °C | + | + | + |
| Cloud point °C | + | + | + |
| Water content mg/kg | + | + | + |
| Lubricity | + | + | + |

**Table 9.** Summary of the test results obtained for the mixture of fuel with PS additive

| Parameter | PS 50%<br>B7 50% | PS 25%<br>B7 75% | PS 15%<br>B7 85% |
|---|---|---|---|
| Density at 15°C | - | - | + |
| Kinematic viscosity at 40°C | - | + | + |
| Cetane number | - | - | - |
| Flash point °C | - | - | - |
| Cold filter plugging point °C | + | + | + |
| Cloud point °C | - | - | + |
| Water content mg/kg | - | - | + |
| Lubricity | + | + | + |

accordance with the Regulation of the Minister of Economy dated on October 9, 2015. regarding the quality requirements for liquid fuels. The only parameter that does not meet these requirements is the flash point, however, this does not exclude this mixture as an alternative to standard fuels.

Considering the remaining samples with 25% and 50% PE additive, it can be noted that the cetane number is below the quality standard. Samples with 25% and 50% PE additive are characterized by a significant reduction in quality parameters for diesel fuel, but this does not exclude their use in other industries, e.g. heat and power plants.

Table 9 presents the parameters obtained as a result of the tested mixtures of industrial fuels with different proportions of the addition of pyrolysis oils obtained from PS (polystyrene) group. It can be noted that the sample with 15% PS additive meets most of the tested quality parameters for diesel oils in accordance with the Regulation of the Minister of Economy dated on October 9, 2015. regarding the quality requirements for liquid fuels. Although it does not meet the flash point requirement (flash point below 20°C) and the cetane number is slightly below the standard (46.86), this does not exclude this mixture as an alternative to diesel fuels. Considering the remaining samples with 25% and 50% PS additive, it can be noted that most of the tests do not meet the standard, which excludes the addition of PS above 15% as an alternative to standard fuels.

## CONCLUSIONS

The conducted research shows the great potential of the applied waste processing method for the plastics from the PP, PE and PS groups in the low-temperature pyrolysis process. The obtained results allow us to conclude that the products obtained in the applied process may have a positive impact on waste management, through the possibility of post-production waste processing directly in the production plant, with the simultaneous use of the processed material for various purposes (e.g. plant heating), this would limit transport activities and significantly shortened the waste life cycle.

For the production of alternative fuels, we can successfully use pyrolysis oil additives obtained by low-temperature pyrolysis of PE and PP group materials with a percentage concentration of 15%, 25%, 50% and PS group material with a concentration of up to 15%.

Due to fact that the addition of pyrolysed oil mixed with diesel fuel does not significantly deteriorate the quality parameters set for motor engine fuels the pyrolysis product additives obtained from waste on an industrial scale implemented in the fuel production process allow us to significantly reduce petroleum products used for the production of fuels and contribute to the beneficial management of this waste management.

In addition, further detailed research on the fractional composition and laboratory tests with these fuels on diesel engines will be carried out – e.g. the effect of pyrolysis oils additives on the operational properties of a diesel engine.

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