Journal of civil engineering and transport **transEngin**

2023, Volume **5** Number **3** **ISSN 2658-1698, e-ISSN 2658-2120**

DOI: 10.24136/tren.2023.010

EFFECT OF OXIDIZED GRAPHENE ADDITION ON DIESEL FUEL QUALITY PARAMETERS

Wioletta **Górska-Włodarczyk** [1,*], Zdzisław **Bogdanowicz** [2]

[1] Military University of Technology, Faculty of Mechanical Engineering, Institute of Robots and Machine Design, gen. Sylwestra Kaliskiego 2 Street, 00-908 Warsaw, Poland, email: wioletta.gorskawlodarczyk@wat.edu.pl, https://orcid.org/0000-0002-4308-1539

[2] Military University of Technology, Faculty of Mechanical Engineering, Institute of Robots and Machine Design, gen. Sylwestra Kaliskiego 2 Street, 00-908 Warsaw, Poland, email: zdzislaw.bogdanowicz@ wat.edu.pl, https://orcid.org/0000-0002-4514-8610

* Corresponding author

Reviewed positively: 20.02.2023

Information about quoting an article:

Górska-Włodarczyk W., Bogdanowicz Z. (2023). Effect of oxidized graphene addition on diesel fuel quality parameters. Journal of civil engineering and transport. 5(3), 21-29, ISSN 2658-1698, e-ISSN 2658-2120, DOI: 10.24136/tren.2023.010

Abstract – The effect of oxidized graphene on the quality parameters of diesel fuel for transport was examined in this study. The research covered base diesel fuel and diesel fuel containing an additive package. Both tested fuels contained no biocomponent. The method of preparing a stable mixture of graphene material in each tested diesel fuels was developed for research purposes. Then, for the fuel samples prepared in this way, tests of quality parameters specified in EN 590 [1] were performed, and the test results were related to the criteria indicated in the mentioned standard. For parameters where it was technically possible to perform the determination, the results showed the influence of the graphene material on the content of solid impurities, oxidative stability and lubricity. For fuel samples containing oxidized graphene, the stability of the mixture under storage conditions was also examined.

Key words – oxidized graphene, diesel fuel quality parameters, fuel performance, transport

JEL Classification – O32

INTRODUCTION

Continuous improvement of diesel fuel functional parameters, including the engine combustion process and the performance, is the subject of both the development and the analysis of new additive types which should allow to achieve the desired effect without a negative impact on fuel quality. For this purpose, state-of-the-art technical solutions, including new generation nanotechnology materials are being tested. Over recent years, the introduction of "nano" type additives has confirmed the achievement of promising results in terms of performance, especially for diesel fuel containing a biocomponent, for improvement of reliability and durability of engines in transport chains. The application of graphene oxide to blends of diesel fuel with biodiesel produced from various feedstocks has been the subject of numerous studies. This was mainly because the addition of the biocomponent itself made a significant impact on the new quality of fuel - apart from several undoubted advantages, it also had disadvantages such as unfavorable interaction with materials, higher production costs or fuel gelling due to high viscosity at low temperatures – which makes it very difficult to long-lasting storage at a petrol station as well as fuel tanks.

Literature studies indicate that some properties of biodiesel in diesel engines can be significantly improved by adding as little as a few milligrams of "nano" type additives to these fuels [2-4]. The research authors in this field have investigated the effect of adding metallic nano-additives (containing metals, such as aluminum oxide, zinc oxide, titanium oxide, cerium oxide, cobalt oxide, etc.) and carbon-based nano-additives to diesel-biodiesel fuel blends. Some of them have reported an overall improvement in diesel engine performance and also emission reduction due to complete fuel combustion [2, 5-9].

Asymmetric graphene oxide (GO - graphene oxide) nanoparticles (asymmetry resulting from the presence of oxygen functional groups on the edges and on the basal plane), due to their improved thermal and chemical properties, were more effective in both reducing exhaust emissions and improving efficiency than their metal-based counterparts [10]. The highly exothermic process of generating heat by graphene oxide nanoparticles as well as the presence of oxygen functional groups promoted the formation of chemically active patches, which resulted in complete fuel combustion [11]. In addition, the possibility of preventing carbon deposition due to the presence of C, H, and O atoms after adding graphene oxide particles was reported [12].

Tests on various types of diesel-biodiesel blends enhanced with the graphene material additives are presented in Table 1 [5]. In these tests, the performance parameters of the test engine were evaluated, including combustion efficiency, emissions, smoke formation, hydrocarbon and CO reduction rate and fuel consumption.

Table 1. Effects of graphene oxide nano-additives on diesel fuel and diesel-biodiesel fuel blends in terms of diesel engine performance and emission characteristics [5]

Biofuel blends	Biodiesel and GO NPs size	Dosage of graphene	Engine type	Application output
D, B10, B20 and B20 nano-additive blends	Ailanthus altissima; 150 nm	30 ppm 60 ppm 90 ppm	4-S Lombardini3LD510; SC, DI, CI engine, 1500 rpm, 18:1 CR	- Reduction of BSFC, HRR and CP for B20G90 - Decrease in CO, NOx, smoke B20G90 and B10G90
D, B20 and B20 nano-additive blends	Jatropha; 8 nm thick, 5 µm wide	50 ppm 75 ppm	4-S HATZ-1B30-2, SC, DI, CI engine, 1500 rpm; 23°BTDC, AC, 21.5:1 CR,	- Improvement of calorific value, BTE and catalytic activity - Better combustion and HRR, and enhanced air-fuel mixing - Reduction of BSFC, NOx, CO, HC, smoke
D, B20 and B20 nano-additive blends	Camelina oil, Tree of heaven, Evening primrose; 150 nm	60 ppm	4-S Lombardini3LD510; SC, Non-TC, DI, CI 1500 rpm, engine, 18:1 CR	- Better atomization and rapid evaporation - Reduction in BSFC, CO, HC and NOx. - Increase in the oxidative stability
D, B20 and B20 nano-additive blends	Dairy scum oil; 23–27 nm	20 ppm 40 ppm 60 ppm	4-S Kirloskar (TV1), SC, DI, CI engine, 2400 rpm; 23°BTDC, WC, 17.5:1 CR, 3 FI	- Improvement of calorific value and HRR. Higher cetane number - Enhancement of BTE, rapid ignition and fuel combustion - Reduction in BSFC and an average temperature of cylinder - Increase in NOx emission - Significant reductions in HC, CO and smoke emissions
D, B30 and B30 nano-additive blends	Palm; 23–26 nm	50 ppm 75 ppm 100 ppm	4-S Kirloskar (TV1), SC, DI, CI engine, 2400 rpm; 0-25°BTDC, WC, 17.5:1 CR, HCC	- High surface area of graphene oxide NPs increased the combustion characteristics. - Increase in BTE and NOx emissions - Reduction in BSFC, CO, HC, smoke
D, B20, B20 nano-additive blends	Simarouba, 22.5–26.0 nm	20 ppm, 40 ppm, 60 ppm	4-S Kirloskar (TV1), SC, DI, CI engine, 1500 rpm; 23°BTDC, WC, 17.5:1 CR, 3 FI	- Improvement of calorific value, BTE and HRR. Higher cetane number - Reduction in BSFC and ID - Increase in NOx emission - Significant reductions in HC, CO and smoke emissions

Where:
NPs - nanoparticles
D - diesel fuel
B10-30 - diesel-biodiesel fuel blends, containing (10-30) %V/V of the biodiesel
B10-20G90 - diesel-biodiesel fuel blends, containing (10-20) %V/V of the biodiesel and 90 ppm of the graphene
BSFC - brake-specific fuel consumption
HRR - heat release rate
CP - cylinder pressure
BTE - brake thermal efficiency
CO, HC, smoke - carbon monoxide, hydrocarbons
SC - single cylinder
TC - twin cylinder
4-S - four stroke
DI - direct injection
WC - water-cooled
AC - air-cooled
FI - fuel injector
CC - combustion chamber
CI - compression ignition
CR - compression ratio
BDTC - before top dead centre
HCC - hemispherical combustion chamber
Rpm - revolutions per minute

The test results indicated an increase in thermal efficiency (BTE) due to the catalytic effect of graphene oxide nanoparticles. In addition, the brake-specific fuel consumption (BSFC) decreased because of the complete fuel combustion and improved air-fuel mixing ratio, which results from the increased oxygen presence in the combustion chamber. There was also an improvement in the heat release rate and a reduction in the cylinder pressure and a reduction in harmful emissions like CO, HC, smoke; however, in some cases, an increase in nitrogen oxide emissions [5] was observed.

The test results, summarized in Table 1, demonstrate the possibility of using GO in fuels, however, after the introduction of the newly introduced fuel additive, it is necessary to investigate whether the fuel still fulfils the quality requirements specified in EN 590 [1].

1. Research objective

The objective of this study was to develop a method for dosing graphene oxidized forms into diesel fuel in order to produce a stable homogeneous mixture which would demonstrate stability over a longer storage time and, then, to test the effect of the addition of the graphene material on the diesel fuel parameters in relation to the current quality requirements specified for this type of fuel in the EN 590 standard [1].

The accomplishment of this objective required the testing of the quality parameters listed in the EN 590 standard for diesel fuel before and after the addition of the graphene material, according to the referred testing methods.

2. Research objects

The following test materials were used to perform the tests:

a) graphene oxide (EOGO - Edge-Oxidized Graphene Oxide; manufacturer – Advanced Graphene Products S.A.) [13]:
   - low-oxidized flake graphene, having oxygen functional groups on the flake edges (Fig. 1); the material did not require additional purification;
   - flake size – under standard conditions, the flake size analysis (DLS – dynamic light scattering) demonstrating a Gaussian distribution with an average flake size of 500 nm. 90% of the flakes are <800 nm in diameter;
   - chemical composition: oxygen: 5-10% (dehydrated sample);
   - composition without oxygen regarding - as shown in Table 2.;
   - analysis of graphene oxide surface using a scanning electron microscope (SEM) (Fig. 2);
   - specific surface area: 230 m2/g;
   - number of layers: <10 (90% of the material);
   - color: black;
   - odor: odorless.

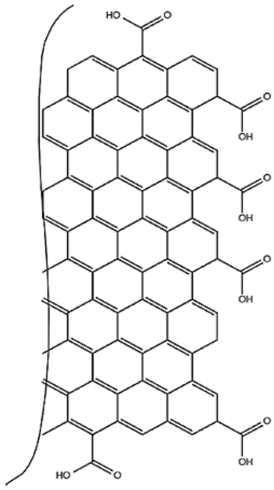

Fig. 1. Schematic diagram of graphene oxide structure [13]

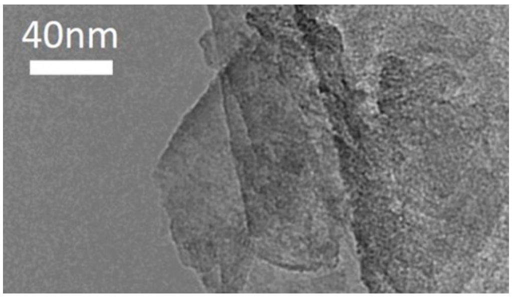

Fig. 2. SEM image of graphene oxide [**13**]

Table 2. Graphene oxide composition (**oxygen not regarded**) [13]

Component	Component concentration
Carbon	>99.8%
Silicon	<40 ppm
Phosphorus	<200 ppm
Sulfur	<60 ppm
Potassium	< 5 ppm
Calcium	<30 ppm
Chrome	<125 ppm
Manganese	<10 ppm
Iron	<900 ppm
Nickel	<20 ppm
Copper	<5 ppm
Zinc	<2 ppm

b) base diesel fuel containing neither additives nor biocomponent, with parameters defined in Table 3, referred to the standard EN 590 requirements [1].
c) diesel fuel containing additives but no biocomponent, with parameters defined in Table 4, referred to the standard EN 590 requirements [1].

Base diesel fuel met the quality requirements of the EN 590 standard [1] except for the parameter "Lubricity, wear scar diameter (WSD 1.4) at 60°C". This is due to the lack of additives improving these fuel properties. Diesel fuel containing the additives met the requirements of the specification described in the EN 590 standard [1].

The fuels used in the tests did not contain additives improving low-temperature properties, i.e. the B grade (summer type) diesel oils, for which the maximum cold filter blocking temperature (CFPP) was 0°C.

3. Research method introduction of graphene oxide into fuel

Investigating the effect of graphene oxide on diesel fuel quality involves the difficulty of introducing it into the fuel to obtain a stable, permanent emulsion. The elaboration of the method to obtain such an emulsion has been carried out in several stages.

Direct introduction of graphene oxide in the form of a powder or through intermediate stages e.g. preparation of a stable paste with a high content of the graphene material in diesel oil (Masterbatch method), followed by the dispersion of the graphene material in diesel oil (using a dispersing tip), was not an effective method for obtaining a stable emulsion. Sedimentation occurred within a time shorter than an hour after the completion of the mixing process.

A more stable emulsion could be obtained by lowering and maintaining the temperature of the diesel fuel around 0°C. Due to the higher viscosity of the diesel fuel at this temperature, sedimentation of the graphene material is inhibited, however, after heating, the rapid disintegration of thus produced emulsion occurs.

In order to obtain an effective and stable emulsion, it is necessary to introduce dispersing additives compatible with diesel fuel. For this purpose, poly(isobutylene) succinimide (PiBSi) showed the best results. The PiBSi additive used to disperse graphene in the oil phase was selected because of its usual dosage in the fuel industry. A suspension of 3% m/m graphene oxide in base diesel fuel was prepared for the tests.

Table 3. Test results for base diesel fuel without additives or biocomponent

Property	Base diesel fuel	Unit	Limits		Test method
			Min.	Max.	
Cetane number	53.0	–	51.0	–	PN-EN 16715
Cetane index	52.1	–	46.0	–	PN-EN ISO 4264
Density at 15°C	836.6	kg/m3	820.0	845.0	PN-EN ISO 12185
Polycyclic aromatic hydrocarbons	2.2	% (m/m)	–	8.0	PN-EN 12916
Sulfur content	5.9	mg/kg	–	10.0	PN-EN ISO 20846
Manganese content	<0.5	mg/l	–	2.0	PN-EN 16576
Flash point	68.0	°C	> 55.0	–	PN-EN ISO 2719
Carbon residue (on 10% distillation residue)	0.01	% (m/m)	–	0.30	PN-EN ISO 10370
Ash content	0.001	% (m/m)	–	0.010	PN-EN ISO 6245
Water content	60	mg/kg	–	200	PN-EN ISO 12937
Total contamination	<12	mg/kg	–	24	PN-EN 12662
Copper strip corrosion (3 h at 50°C)	Class 1	rating	Class 1		PN-EN ISO 2160
Oxidation stability	7	g/m3	–	25	PN-EN ISO 12205
Oxidation stability*	24.1	h	20.0	–	PN-EN 15751
Lubricity, corrected wear scar diameter (WSD 1,4) at 60°C	520	µm	–	460	PN-EN ISO 12156-1
Viscosity at 40°C	2.825	mm2/s	2.000	4.500	PN-EN ISO 3104
Distillation % (V/V) recovered at 250°C % (V/V) recovered at 350°C 95% (V/V) recovered at	 37.2 92.9 357.3	 % (V/V) % (V/V) °C	 85 	 < 65 360.0	PN-EN ISO 3405
Fatty acid methyl ester (FAME) content	<0.05	% (V/V)	–	7.0	PN-EN 14078
Cold Filter Plugging Point (CFPP)	–5	°C	–	0^1 -10^2 -20^3	PN-EN 116

Table 4. Test results for base diesel fuel containing additives but no biocomponent

Property	Diesel fuel containing additives	Unit	Limits		Test method
			Min.	Max.	
Cetane number	54.7	–	51.0	–	PN-EN 16715
Cetane index	53.3	–	46.0	–	PN-EN ISO 4264
Density at 15°C	834.4	kg/m3	820.0	845.0	PN-EN ISO 12185
Polycyclic aromatic hydrocarbons	2.4	% (m/m)	–	8.0	PN-EN 12916
Sulfur content	6.2	mg/kg	–	10.0	PN-EN ISO 20846
Manganese content	<0.5	mg/l	–	2.0	PN-EN 16576
Flash point	70.0	°C	> 55.0	–	PN-EN ISO 2719
Carbon residue (on 10% distillation residue)	0.01	% (m/m)	–	0.30	PN-EN ISO 10370
Ash content	0.001	% (m/m)	–	0.010	PN-EN ISO 6245
Water content	70	mg/kg	–	200	PN-EN ISO 12937
Total contamination	<12	mg/kg	–	24	PN-EN 12662
Copper strip corrosion (3 h at 50°C)	Class 1	rating	Class 1		PN-EN ISO 2160
Oxidation stability	6	g/m3	–	25	PN-EN ISO 12205
Oxidation stability*	62.3	h	20.0	–	PN-EN 15751
Lubricity, corrected wear scar diameter (WSD 1,4) at 60°C	390	µm	–	460	PN-EN ISO 12156-1
Viscosity at 40°C	2.848	mm2/s	2.000	4.500	PN-EN ISO 3104
Distillation % (V/V) recovered at 250°C % (V/V) recovered at 350°C 95% (V/V) recovered at	 36.6 92.8 357.9	 % (V/V) % (V/V) °C	 85 	 < 65 360.0	PN-EN ISO 3405
Fatty acid methyl ester (FAME) content	<0.05	% (V/V)	–	7.0	PN-EN 14078
Cold Filter Plugging Point (CFPP)	–6	°C	–	0[1] –10[2] –20[3]	PN-EN 116

* Oxidative stability tests (stability value expressed in hour units) were performed according to the PN-EN 15751 standard, dedicated to diesel fuel containing more than 2% of higher fatty acid methyl esters; however, the results obtained by this method for diesel fuel containing no biocomponent are considered reliable.

[1] For the summer period – from 16 April to 30 September.

[2] For the transitional period – from 1 March to 15 April and from 1 October to 15 November.

[3] For the winter period – from 16 November to the end of February.

A dispersing stirrer was placed in a beaker containing the mixture of fuel and the graphene material (base diesel oil + 3% m/m oxidized graphene) and the contents of the beaker were stirred to distribute the material evenly throughout the fuel volume; while stirring, the dispersing agent (0.5% m/m PiBSi) was gradually added. The resulting dispersion was left in the fume hood. No graphene sedimentation was observed after 15, 30, 60 and 120 minutes. Also after three days, the oxidized graphene was still suspended in the fuel with no visible sedimentation (Fig. 3).

The stable emulsion produced in this way was used to prepare two testing systems:

– base diesel fuel with no biocomponent or additives, with graphene oxide concentration of 100 ppm m/m;
– diesel fuel with additives but no biocomponent, with graphene oxide concentration of 100 ppm m/m.

Fig. 3. Dispersion of diesel fuel containing PiBSi after 3 days

The applied level of the graphene material dosage was related to the level of classical additives dosage [14].

After the emulsion of the graphene material was introduced into each of the aforementioned fuels, no sedimentation was observed at the bottom of the sample container. Quality parameters were tested for the samples prepared in this way and the results were related to the requirements of EN 590 [1].

4. TEST RESULTS AND DISCUSSION

Test results for base diesel fuel and diesel fuel containing additives and graphene oxide are shown in Table 5 and Table 6.

The test results for base diesel fuel with 100 ppm m/m graphene oxide showed a negative effect on the content of mechanical impurities. The exceeded value of this parameter resulted from the level of the dosed graphene additive; however, the amount of added GO can be adjusted to meet fuel quality requirements with a simultaneous positive effect on fuel performance, which may require further research. A significant deterioration of the quality parameter was observed for the oxidative stability expressed both in g/m³ and h units. This stability decreased within 10 days of mixture preparation, i.e. over the time of conducting the quality parameter tests from 24.1 h to 12.2 h. On the 14th day, the test for stability was repeated and the result was 11.7 h. In terms of the lubricity parameter, the preliminary results carried out without the addition of graphene oxide did not meet the quality requirements due to the lack of additives improving these properties. The presence of graphene oxide caused a further slight deterioration of this parameter.

Table 5. Test results for base diesel fuel containing additives but no biocomponent

Property	Base diesel fuel	Base diesel fuel containing 100 ppm m/m graphene oxide	Unit	Limits		Test method
				Min.	Max.	
Cetane number	53.0	**	–	51.0	–	PN-EN 16715
Cetane index	52.1	52.6	–	46.0	–	PN-EN ISO 4264
Density at 15°C	836.6	836.6	kg/m³	820.0	845.0	PN-EN ISO 12185
Polycyclic aromatic hydrocarbons	2.2	**	% (m/m)	–	8.0	PN-EN 12916
Sulfur content	5.9	5.7	mg/kg	–	10.0	PN-EN ISO 20846
Manganese content	<0.5	**	mg/l	–	2.0	PN-EN 16576
Flash point	68.0	70.0	°C	> 55.0	–	PN-EN ISO 2719
Carbon residue (on 10% distillation residue)	0.01	0.01	% (m/m)	–	0.30	PN-EN ISO 10370
Ash content	< 0.001	< 0.001	% (m/m)	–	0.010	PN-EN ISO 6245
Water content	60	**	mg/kg	–	200	PN-EN ISO 12937
Total contamination	<12	> 30 (51.5) [4])	mg/kg	–	24	PN-EN 12662
Copper strip corrosion (3 h at 50°C)	Class 1	Class 1	rating	Class 1		PN-EN ISO 2160
Oxidation stability	7	18	g/m³	–	25	PN-EN ISO 12205
Oxidation stability*	24.1	12.2	h	20.0	–	PN-EN 15751
Lubricity, corrected wear scar diameter (WSD 1.4) at 60°C	520	600	µm	–	460	PN-EN ISO 12156-1
Viscosity at 40°C	2.825	2.848	mm2/s	2.000	4.500	PN-EN ISO 3104
Distillation % (V/V) recovered at 250°C % (V/V) recovered at 350°C 95% (V/V) recovered at	 37.2 92.9 357.3	 36.2 92.3 359.6	 % (V/V) % (V/V) °C	 85 	 < 65 360.0	PN-EN ISO 3405
Fatty acid methyl ester (FAME) content	<0.05	**	% (V/V)	–	7.0	PN-EN 14078
Cold Filter Plugging Point, (CFPP)	–5	**	°C	–	0[1] –10[2] –20[3]	PN-EN 116

Table 6. Test results for diesel fuel containing additives and 100 ppm m/m graphene oxide

Property	Diesel fuel containing additives	Diesel fuel containing additives and 100 ppm m/m graphene oxide	Unit	Limits		Test method
				Min.	Min.	
Cetane number	54.7	**	–	51.0	–	PN-EN 16715
Cetane index	53.3	53.1	–	46.0	–	PN-EN ISO 4264
Density at 15°C	834.4	834.4	kg/m³	820.0	845.0	PN-EN ISO 12185
Polycyclic aromatic hydrocarbons	2.4	**	% (m/m)	–	8.0	PN-EN 12916
Sulfur content	6.2	6.1	mg/kg	–	10.0	PN-EN ISO 20846
Manganese content	<0.5	**	mg/l	–	2.0	PN-EN 16576
Flash point	70.0	71.0	°C	> 55.0	–	PN-EN ISO 2719
Carbon residue (on 10% distillation residue)	0.01	0.01	% (m/m)	–	0.30	PN-EN ISO 10370
Ash content	< 0.001	< 0.001	% (m/m)	–	0.010	PN-EN ISO 6245
Water content	70	**	mg/kg	–	200	PN-EN ISO 12937
Total contamination	<12	> 30 (66.8)[4]	mg/kg	–	24	PN-EN 12662
Copper strip corrosion (3 h at 50°C)	Class 1	Class 1	rating	Class 1		PN-EN ISO 2160
Oxidation stability	6	33	g/m³	–	25	PN-EN ISO 12205
Oxidation stability*	62.3	35.5	h	20.0	–	PN-EN 15751
Lubricity, corrected wear scar diameter (WSD 1.4) at 60°C	390	340	µm	–	460	PN-EN ISO 12156-1
Viscosity at 40°C	2.848	2.845	mm2/s	2.000	4.500	PN-EN ISO 3104
Distillation % (V/V) recovered at 250°C % (V/V) recovered at 350°C 95% (V/V) recovered at	 36.6 92.8 357.9	 36.6 92.8 358.1	 % (V/V) % (V/V) °C	 85 	 < 65 360.0	PN-EN ISO 3405
Fatty acid methyl ester (FAME) content	<0.05	**	% (V/V)	–	7.0	PN-EN 14078
Cold Filter Plugging Point (CFPP)	–6	**	°C	–	0[1] –10[2] –20[3]	PN-EN 116

** It is not technically feasible to conduct the analysis due to the sample form.
[4] The actual measurement result is shown in parentheses.

With respect to diesel fuel-containing additives, the presence of graphene oxide at the concentration of 100 ppm m/m also showed a negative effect on both mechanical impurities content and oxidation stability expressed both in g/m³ and h (the decrease from 62.3 h to 35.5 h). The result of oxidation stability repeated on the 14th day after the mixture preparation showed a result of 28.1 h. It should be stressed that the diesel oil used for the testing contained an additive package protecting the product against the loss of quality in this parameter aspect.

Regarding the remaining quality parameters, for which the determination was technically possible, no negative effect of graphene oxide was observed at the applied concentration. With respect to lubricity, a positive influence of graphene oxide on its value was observed, which proves a positive interaction with these additives.

In order to analyze the solution stability, prepared diesel fuel mixtures containing 100 ppm m/m oxidized graphene and a dispersant were observed for a period of 3 months after their preparation. After this time, mixtures showed sedimentation of oxidized graphene. Thus, it can be assumed that the persistence of dispersion of the graphene material in the fuel is limited in time.

SUMMARY AND CONCLUSIONS

It can be concluded from the review that the introduction of a new type of fuel additives based on graphene derivatives can improve the diesel fuel performance parameters, including the combustion, the reduction of the following properties: fuel consumption, emission, smoke formation degree or presence of harmful substances – all parameters which are substantial to the modern engines appliances.

Taking into consideration the importance of diesel fuels to the transportation industry and supply chains, when considering the introduction of a new substance into diesel fuel, it is necessary to obtain a mixture stable with the fuel, and durable under storage conditions. The presence of the new additive must not adversely affect the fuel quality; therefore, it is necessary to examine its impact on the quality parameters in relation to the requirements described in the specification for this type of fuel (EN 590 [1]). The tests should cover different diesel fuel formulations (with different levels of additives and bio-component addition) to verify the behavior over its lifetime.

In this study, the effect of the graphene material was investigated for diesel fuel, summer grade without biocomponent, without and with the additive package.

As a result of the performed testing, it has been found that:

– Acquiring a stable suspension of oxidized graphene in diesel fuel is only possible after using fuel-compatible dispersing agents (polyisobutylene succinimides – PiBSi – has been found as highly effective).
– The mixture containing graphene oxide in diesel fuel showed durability for up to about 3 months; after this time, sedimentation of the graphene material was detectable. To maintain the durability of this fuel mixture with the graphene material for a longer storage time; it would be necessary to optimize the amount of graphene oxide itself and the dispersing agent, which requires further research.
– The addition of graphene oxide at the concentration of 100 mg/kg in diesel fuel adversely affected the increase of impurity content in the fuel; meeting the requirements for this parameter with the introduction of graphene oxide could be optimized by adjusting the dosage level.
– Graphene oxide adversely affected the parameter of oxidative stability expressed both in h and in g/m^3 units, which is due to the presence of oxygen functional groups in the graphene material structure.
– The graphene material of the tested concentration had a positive effect on the lubricity when the diesel fuel tested contained an additive package, including a lubricity additive; however, for the base diesel fuel without the additive package, the presence of graphene oxide caused an unfavorable change of this parameter.

In order to obtain synergy, i.e. to obtain optimal operating conditions with the simultaneous fulfilment of quality requirements, the dose of the graphene material added to diesel fuel shall be optimized, which requires further research for a specific application.

The scope of further research work should include the investigation into the effect of the oxidized graphene on other diesel fuel grades, i.e. the transitional and winter grades, containing the appropriate level of the dedicated additive package.

WPŁYW DODATKU UTLENIONEGO GRAFENU NA PARAMETRY JAKOŚCIOWE OLEJU NAPĘDOWEGO

W pracy zbadano wpływ utlenionego grafenu na parametry jakościowe oleju napędowego przeznaczonego do transportu. Badaniami objęto bazowy olej napędowy oraz olej napędowy zawierający pakiet dodatków uszlachetniających. Oba badane paliwa nie zawierały biokomponentu. Dla celów badawczych opracowano metodę przygotowania stabilnej mieszaniny materiału grafenowego w każdym z badanych olejów napędowych. Następnie dla tak przygotowanych próbek paliwa przeprowadzono badania parametrów jakościowych określonych w normie EN 590 [1], a wyniki badań odniesiono do kryteriów wskazanych w tej normie. Dla parametrów, dla których wykonanie oznaczeń było technicznie możliwe, wyniki wykazały wpływ materiału grafenowego na zawartość zanieczyszczeń stałych, stabilność oksydacyjną oraz smarowność. Dla próbek paliwa zawierających utleniony grafen zbadano również stabilność mieszaniny w warunkach przechowywania.

Słowa kluczowe: utleniony grafen, parametry jakościowe oleju napędowego, wydajność paliwowa, transport

REFERENCES

[1] Polish Committee for Standardization. (2017) *Automotive fuels – Diesel Requirements and test methods*, EN 590:2013+A1:2017.

[2] Soudagar M.E.M., Nik-Ghazali N.N., Kalam M.A., et al. (2018) The effect of nano-additives in diesel-biodiesel fuel blends: A comprehensive review on stability, engine performance and emission characteristics, *Energy Conversion and Manag*., 178, 146–177. https://doi.org/10.1016/j.enconman.2018.10.019.

[3] Achten W.M., Mathijs E., Verchot L., et al. (2007) Jatropha biodiesel fueling sustainability?, *Biofuels Bioprod. Biorefin*. Innov. Sustain. Econ., 1, 283-291. https://doi.org/10.1002/bbb.39.

[4] Heidari-Maleni A., Gundoshmian T.M., et al. (2020) Performance improvement and exhaust emissions reduction in diesel engine through the use of Graphene quantum dot (GQD) nanoparticles and ethanol-biodiesel blends, *Fuel*, 267: 117116. https://doi.org/10.1016/j.fuel.2020.117116.

[5] Khan H., Soudagar M.E.M., Kumar R.H., Safaei M.R., et al. (2020) Effect of Nano-Graphene Oxide and n-Butanol Fuel Additives Blended with Diesel—Nigella sativa Biodiesel Fuel Emulsion on Diesel, Engine Characteristics, *Symmetry*, 12(6), 961. https://doi.org/10.3390/sym12060961.

[6] Soudagar M.E.M., Nik-Ghazali N.N., Kalam M.A., Badruddin I.A., et al. (2020) An investigation on the influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion and emission characteristics, Renew. *Energy*, 146, 2291–2307. https://doi.org/10.1016/j.renene.2019.08.025.

[7] Soudagar M.E.M., Nik-Ghazali N.N., Kalam M.A., Badruddin I.A., et al. (2019) The effects of graphene oxide nanoparticle additive stably dispersed in dairy scum oil biodiesel-diesel fuel blend on CI engine: Performance, emission and combustion characteristics, *Fuel*, 257: 116015. https://doi.org/10.1016/j.fuel.2019.116015.

[8] Basha J.S. (2018) Impact of Carbon Nanotubes and Di-Ethyl Ether as additives with biodiesel emulsion fuels in a diesel engine - An experimental investigation, *Journal of the Energy Institute*, 91(2), 289–303. https://doi.org/10.1016/j.joei.2016.11.006.

[9] Akram N., Sadri R., Kazi S.N., Zubir M.N.M., et al. (2020) A comprehensive review on nanofluid operated solar flat plate collectors, *Journal of Thermal Analysis and Calorimetry*, 139, 1309-1343. https://doi.org/10.1007/s10973-019-08514-z.

[10] Ooi J.B., Ismail H.M., Swamy V., Wang X., et al. (2016) Graphite oxide nanoparticle as a diesel fuel additive for cleaner emissions and lower fuel consumption. *Energy Fuels*, 30, 1341-1353. https://doi.org/10.1021/acs.energyfuels.5b02162.

[11] Kim F., Luo J., Cruz-Silva R., Cote L.J., et al. (2010) Self-propagating domino-like reactions in oxidized graphite. *Advanced Functional Materials*, 20(17), 2867-2873. https://doi.org/10.1002/adfm.201000736.

[12] Mauter, M.S., Elimelech, M. (2008) Environmental applications of carbon-based nanomaterials, Environmental Science & Technology, 42(16), 5843-5859. https://doi.org/10.1021/es8006904.

[13] Advanced Graphene Products. (2018) Technical Specifications: EOGO – Edge-Oxidized Graphene Oxide.

[14] Srivastava S. P., Hancsók J. (2014) *Fuels and Fuel-additives*. Hoboken, New Jersey. Published by John Wiley & Sons, Inc. ISBN 978-0-470-90186-1.