HYDRO-TREATED VEGETABLE OIL AS A POTENTIAL BIOFUEL FOR SELF-IGNITION ENGINES

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Summary:

Hydro-treating vegetable oils or animal fats is an alternative process to esterification for the production of biodiesel. Hydro-treated products are also called renewable diesel fuels. Hydro-treated vegetable oils (HVO) do not have the harmful effects of FAME biodiesel such as increased NO_x emissions, deposit formation, storage stability problems, faster aging of the engine oil or poor cold performance. HVO are straight chain paraffinic hydrocarbons which are free of aromatic hydrocarbons, oxygen and sulphur and have a high cetane number. In the article below, the authors conduct a comprehensive analysis and evaluation of the possibility of running compression-ignition engine on the hydro-treated vegetable oil, which is a second-generation biofuel. On its basis, the information on the assessment of emissions of selected toxic components of exhaust gases and pollutants of the injection system when the engine is powered with this type of fuel, was systematized. The article ends with conclusions from the conducted analyses.

Keywords:

HVO fuel, 2nd generation biofuels, emission of toxic exhaust gas components, fuel injection system

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List of more important abbreviations:

BTL (Biomass to Liquids) - gas from biomass gasification,
DME (Dimethyl Ether),
FAME (Fatty Acid Methyl Esters) – methyl esters of both vegetable and animal fatty acids,
HVO (Hydro-treated Vegetable Oil),
LPG (Liquefied Petroleum Gas),
SNG (Synthetic Natural Gas).

Introduction:

Vehicle owners in developed countries have the option of using high-quality fuels, i.e. fuels with very little or no sulphur content, which are free from heavy fractions. From the point of view of vehicle users, this results in a longer service life of engines and emission control systems, fewer repairs and, consequently, an extended engine oil change interval. However, the continuous development of automotive technologies forces the search for even more high-tech methods of obtaining high-quality fuels [3, 5, 17]. Constant pressure of the market, which demands the highest quality fuels, necessitates further research on alternative fuels. One of the possible methods of obtaining new types of high-quality fuel is the hydro-treating vegetable oils or animal fats [7, 8, 11]. This process is different compared to the esterification process used in the production of fuels to power compression ignition engines.

Hydro-treating is a catalytic chemical process used in the refining industry, during which the raw material is stabilized by reducing the content of sulphur, nitrogen, halogens, oxygen and saturation of double bonds. The hydro-treating process is conducted in the presence of a hydrogen-rich gas under appropriate temperature and pressure. Hydro-treated vegetable oils (HVO) are straight chain paraffinic hydrocarbons that are free of aromatics, oxygen and sulphur and have a high cetane number. Fuels that are products of the hydro-treating process belong to the group of renewable fuels, i.e. fuels whose resource is regenerated in a relatively short time. In 2019, renewable energy sources satisfied 17.7% of humanity's energy needs [2, 5, 12]. At the beginning of the 21st century, global investment in renewable energy sources grew exponentially. It was caused, on the one hand, by a drop in their prices, and, on the other hand, by subsidies introduced by the governments of many countries. In Poland, one of the main legal acts concerning renewable fuels is the "Energy Law" act. It defines renewable energy sources as "sources that use in the course of processing (...) energy obtained from biomass (...)".

Fuel requirements are becoming more and more stringent due to new regulations on emissions of toxic exhaust gases as well as fuel economy. In addition, fuel distributors, when introducing biofuels to the market, must also take into account the stability of fuel storage and its tolerance to water [9, 16, 18]. In order to avoid additional costs, dedicated fuel distribution solutions must be compatible with the existing fuel storage and distribution base. Diesel fuel with the HVO biocomponent is also marked as Bio-ON, in contrast to diesel fuel with the biocomponent of fatty acid methyl esters (FAME), which is commonly called biodiesel. Hydro-treated vegetable oils (HVO) do not show the harmful effects of biodiesel fuels, such as increased NOx, emissions, deposit formation, problems with storage stability, faster aging of the engine oil or inferior properties at low temperatures.

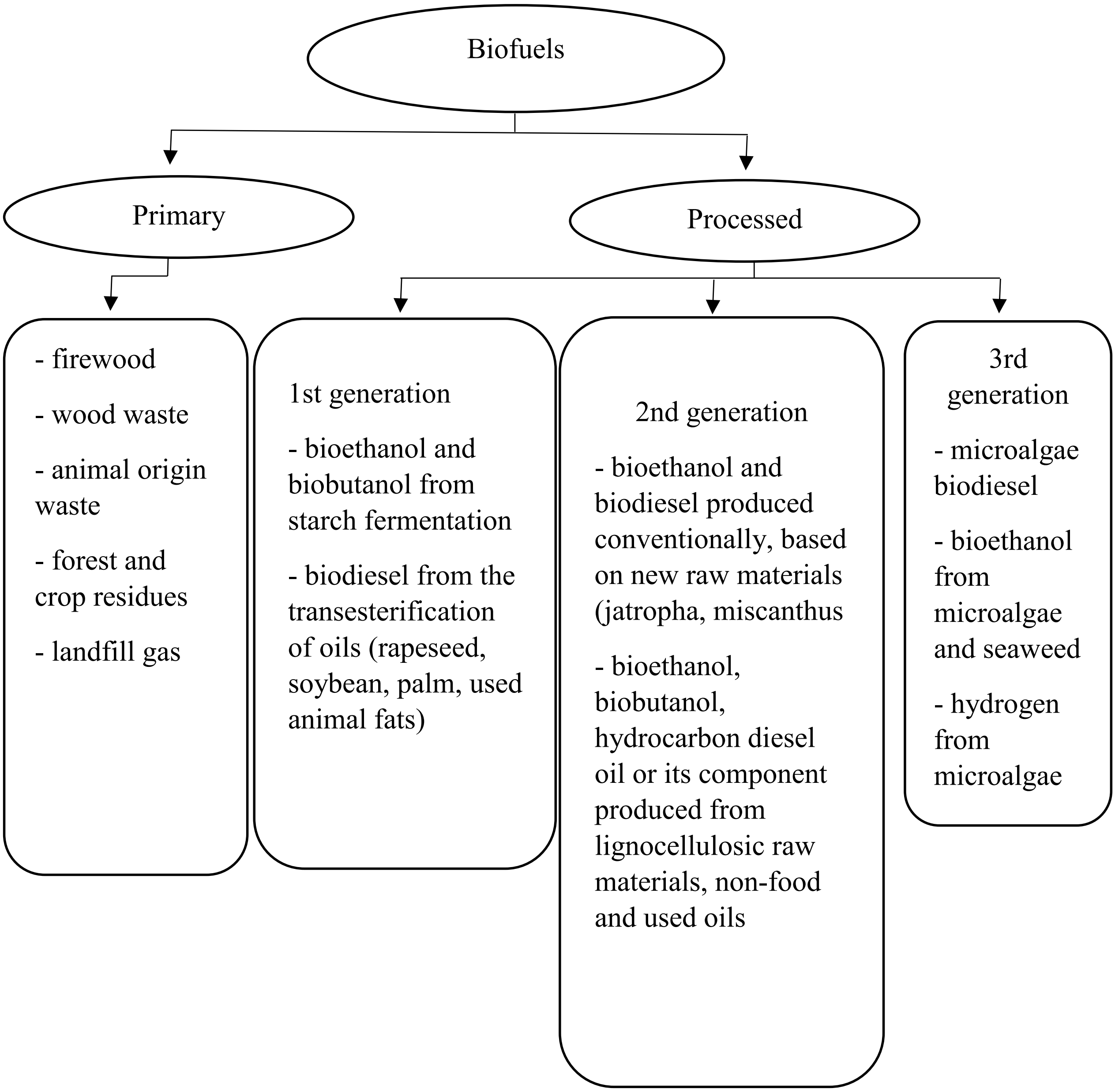
Biofuels:

Biofuels that are produced from bio-renewable resources can be divided into primary biofuels and processed biofuels. The processed biofuels include 1st, 2nd and 3rd generation biofuels [14, 19, 20]. Primary biofuels are natural and unprocessed biomass fuels that can be used directly to generate heat and energy, e.g. firewood. Processed biofuels are fuels obtained by processing biomass with the use of various technologies.
First generation biofuels are products of alcoholic fermentation and esterification, with the use of food raw materials, i.e. edible vegetable oils, potatoes, grain, sugar beets. First generation biofuels are mainly oxygen compounds, i.e. ethyl alcohol, fatty acid methyl esters (FAME) and ethers, which are made based on the biomethanol and bioethanol [1, 13, 15].
Second generation biofuels are products that are obtained from "non-food" raw materials. Such raw materials include waste biomass, non-consumable biomass (used oils). The most important group of second generation biofuels are hydrocarbon products. Second generation biofuels and biocomponents obtained from "non-food" raw materials have similar physicochemical properties compared to the products obtained from the processing of crude oil. The advantage of hydrocarbon biofuels and 2nd generation biofuels compared to 1st generation biofuels is the higher stability of the fuel during fuel storage and distribution. As a result, the second generation biofuels are more favourably accepted by the automotive industry compared to the first generation biofuels. The following products can be classified as second-generation biofuels [4, 6, 15]:

- bioethanol from lignocellulosic raw materials;
- synthetic fuels obtained from synthesis gas produced as a result of biomass gasification:
  - liquid hydrocarbon fuels from BTL (Biomass to Liquids) processes,
  - DME (dimethyl ether),
  - biomethanol,
  - SNG (Synthetic Natural Gas),
  - biohydrogen.
- hydrocarbon fuels obtained in the hydroconversion process:
  - bio-oil obtained in the process of hydro-pyrolysis of waste lignocellulose,
  - vegetable oils and animal fats (HVO process).

Third generation biofuels use microalgae as a raw material. Apart from that, third generation biofuels are processed in similar ways, which are used to produce first and second generation biofuels [4, 15]. The diagram of the biofuels division is presented in Figure 1.

Fig. 1. The division of biofuels according to the method of production and the raw materials used [4, 15, 20]



Currently, the dominant biocomponent used in fuels to power spark ignition engines is bioethanol, obtained from sugar cane, maize, potatoes, cereals and sugar beet. The basic biocomponent for diesel engines is FAME, made of rapeseed and soybean oil. However, due to the continuous development of the automotive and refining industries and the increasingly stringent emission standards of toxic exhaust gases, major fuel producers are looking for new solutions. The largest Polish fuel and energy company, a leader among petrochemical companies in Central and Eastern Europe, PKN Orlen S.A. is working on the implementation of modern technology for the production of hydro-treated vegetable oil (HVO). It is an ecological and innovative solution that is the response of petrochemical companies to the EU package "Fit for 55", which contains a set of new challenges for the refining industry in terms of reducing transport fuel emissions. The production of hydro-treated vegetable oil (HVO) will facilitate achieving the national indicative target (the amount of biofuels) and meeting European Union requirements in terms of increasing the share of biofuels in the production and consumption structure of transport fuels. This in turn will help cut emissions from transport fuels sold on the markets, in line with the EU's 'Fit for 55' package.

Biofuels for compression ignition engines

Hydro-treating vegetable oils is a modern method of producing very high-quality biofuels that do not adversely affect the operation of the engine and its exhaust gas treatment systems. These fuels are currently referred to as Bio ON renewable diesel fuels. Chemically Hydro-treated Vegetable Oils (HVO) are mixtures of paraffinic hydrocarbons. These fuels are free of sulphur and aromatics. HVO's cetane number is very high, and their other properties are similar to the fuels currently used to power compression ignition engines. Table 1 shows a comparison of the physicochemical properties of four fuels: HVO, FAME, diesel oil and liquid natural gas (GTL).

Table 1. Physical and chemical properties of four fuels: HVO, FAME, diesel oil, liquefied natural gas (GTL) [5, 6, 9, 16]

Parameter	Unit	HVO	FAME (rapeseed oil methyl esters)	Diesel fuel	GTL
Density at 15°C	kg/m^3	780	885	835	775
Viscosity at 40°C	mm^2/s	2,5 - 3,5	4,5	3,5	3,2 - 4,5
Cetane number	-	80 - 99	51	53	73 - 81
Distillation range	°C	180 - 320	350 - 370	180 - 360	190 - 330
Cloud point	°C	−5 ... −25	−5	−5	−0 ... −25
Calorific value	MJ/kg	44	37,5	42,7	43
Calorific value	MJ/l	34,4	33,2	35,7	34
Sulphur content	%	0	0	30	0
Oxygen content	%	0	11	0	0
Storage stability	-	good	poor	good	good

The table above shows i.a. physicochemical properties of FAME fuel (rapeseed oil methyl ester). The physical and chemical properties of this fuel depend mainly on the properties of the raw material used for its production. This, in turn, limits the materials that can be used to produce FAME in moderate and cold climates. Many types of vegetable oils can be used as a raw material for HVO fuel production. Importantly, the raw materials used, i.e. rapeseed, sunflower and soybean oil, as well as palm oil, do not worsen the quality of the HVO fuel obtained. Animal fat waste and non-food oils, i.e. oils from jatropha seeds or algae, can also be used as raw materials for the production of HVO fuel. Hydrogen is used to remove oxygen from triglycerides (vegetable oil) in the production of HVO fuel. The HVO production process does not result in glycerine production as a by-product, which is the case in the production of FAME fuels, and no other chemical compounds such as methanol are needed, which is used in the production of FAME fuels. The by-product of HVO fuel production is LPG, which should be considered an advantage as it can be used on-site to cover heat or energy needs.

The use of HVO biocomponents in diesel fuel

HVO fuel can be used to power compression ignition engines in three ways. The first option is to add only a few percent of the biocomponent to the diesel fuel. This is a common approach for ester type biodiesel (FAME) fuels. Currently, at the fuelling stations, we can most often find diesel with a 7% addition of methyl ester of higher fatty acids of rapeseed oil. This amount takes into account the conclusions of the research on fuel stability and the formation of deposits in the fuelling systems of compression ignition engines.

The second option is to mix several dozen percent of HVO fuel with diesel fuel. It is possible with Hydro-treated Vegetable Oils (HVO) without deterioration of fuel quality, unfavourable changes in exhaust emissions and deterioration of engine performance. In fact, the fuel mixture will be of good quality as the cetane number will be increased and the aromatics content will be reduced, which will result in reduced emissions of selected exhaust components and improved cold start performance.

The last, third option is to use only HVO as the fuel itself. This solution is considered primarily in terms of transport companies, public transport (city buses) or special-purpose vehicles (mines, biogas plants), power generators. This will allow the emission of toxic exhaust components from old vehicles to be reduced without modifying them. However, in order to achieve even more benefits of fuelling the engine with HVO fuel, due to the lower density and higher cetane number of HVO, it will be necessary to interfere with the injection system control (change of the fuel dose, fuel injection advance angle, injection duration and parameters related to the spurt of the injected fuel).

Based on the available literature, a comparative analysis of the elemental and chemical composition of diesel oil, HVO fuel and the mixture of diesel oil and HVO fuel, was carried out. The results of this analysis are presented in Table 2.

Table 2. Chemical composition of diesel oil, HVO fuel and the mixture of diesel oil and HVO fuel [6, 15, 20]

Name	Unit	Diesel oil	HVO	HVO-30
Diesel fuel	%	100	0	70
HVO	%	0	100	30
Coal	%	85,9	84,8	85,8
Hydrogen	%	13,5	15,2	14
C/H ratio	-	6,4	5,6	6,1
Sulphur	mg/kg	5	<3	3
Nitrogen	mg/kg	28	1,5	20
Aromatic compounds in total	%	18,9	0,2	13,6
Water	mg/kg	20	7	18

Table 3. Physical and chemical properties of diesel oil, HVO fuel and the mixture of diesel oil and HVO fuel [6, 15, 20]

Parameter	Unit	Diesel oil	HVO	HVO-30
Density at 15°C	kg/m^3	843	779,7	824
Viscosity at 40°C	mm^2/s	3,208	3,087	3,165
Flash point	°C	68	99	74
Cloud point	°C	-5	7	-6
Lubricity (HFRR)	µm	324	360	300
Heat of combustion	MJ/kg	45,99	47,27	46,35
Calorific value	MJ/kg	43,13	44,04	43,38
	MJ/l	36,35	34,34	35,75
Cetane number	-	54,6	>70	>65
Boiling point	°C	363	313	358

In the next stage of the work, the physicochemical properties of diesel oil, HVO fuel and the mixture of diesel oil and HVO fuel were analysed. The results of the comparative analysis are presented in Table 3.

Particular attention should be paid to the different value of the density of HVO fuel compared to diesel oil and the higher value of the cetane number of HVO fuel compared to the classic fuel for compression ignition engines, i.e. diesel oil.

Injector contamination

One of the problems of supplying internal combustion engines with hydrocarbon fuels is contamination of the injection system. The tendency to deposit formation is related to the chemical composition of the fuel. The amount of carbon deposits increases when the fuel contains unsaturated hydrocarbons, high molecular weight components, sulphur compounds and organic acids. The quality of fuels available on the market and the operating conditions of the engine have a large impact on the coking of the injectors. This, in turn, may result in a loss of power and a reduction in the durability of the engine [6]. Coking of the surface at the junction of the needle tip and the sprayer seat reduces or blocks the fuel flow through the injector, changes the range and structure of the injected fuel stream. Based on the literature data, Figure 2 shows the results concerning the average contamination of the injectors for three fuels: diesel oil, a mixture of 30% HVO and 70% Diesel oil, and 100% HVO. The CEC F-098-08 test method used is designed to evaluate the contamination of modern multi-hole injectors of the high-pressure diesel fuel supply system as a standard test for fuel quality evaluation.

Fig. 2. Results of the injector contamination test [6, 10, 20]

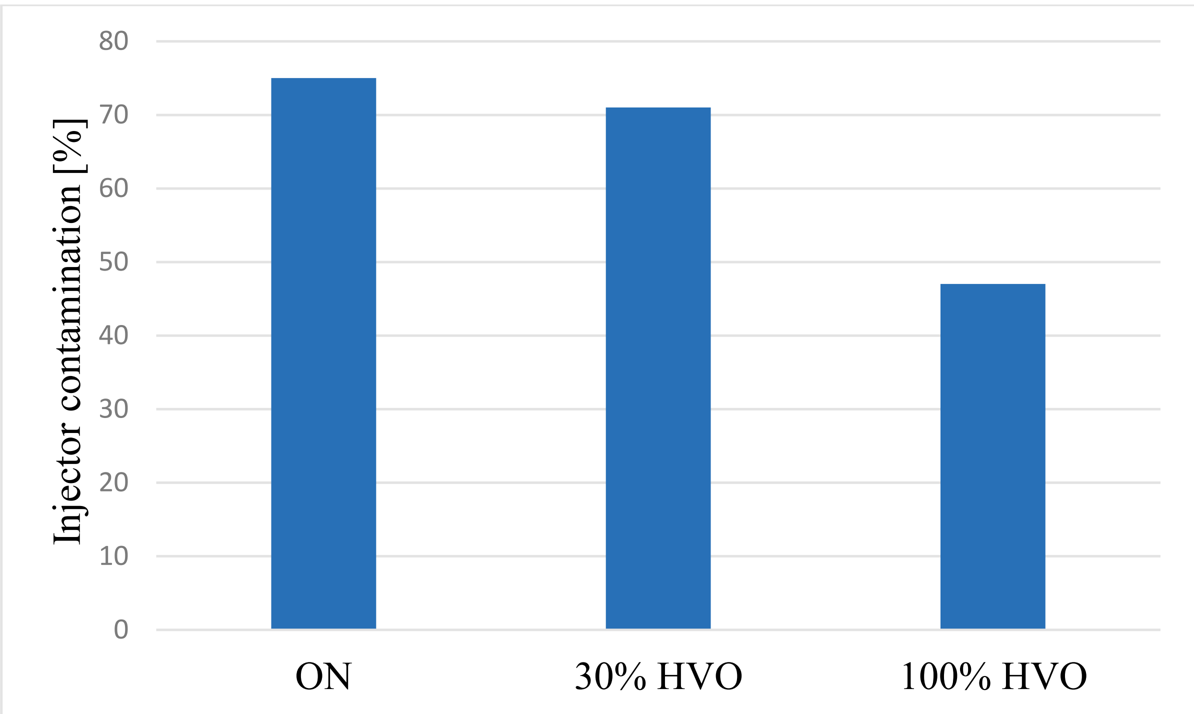
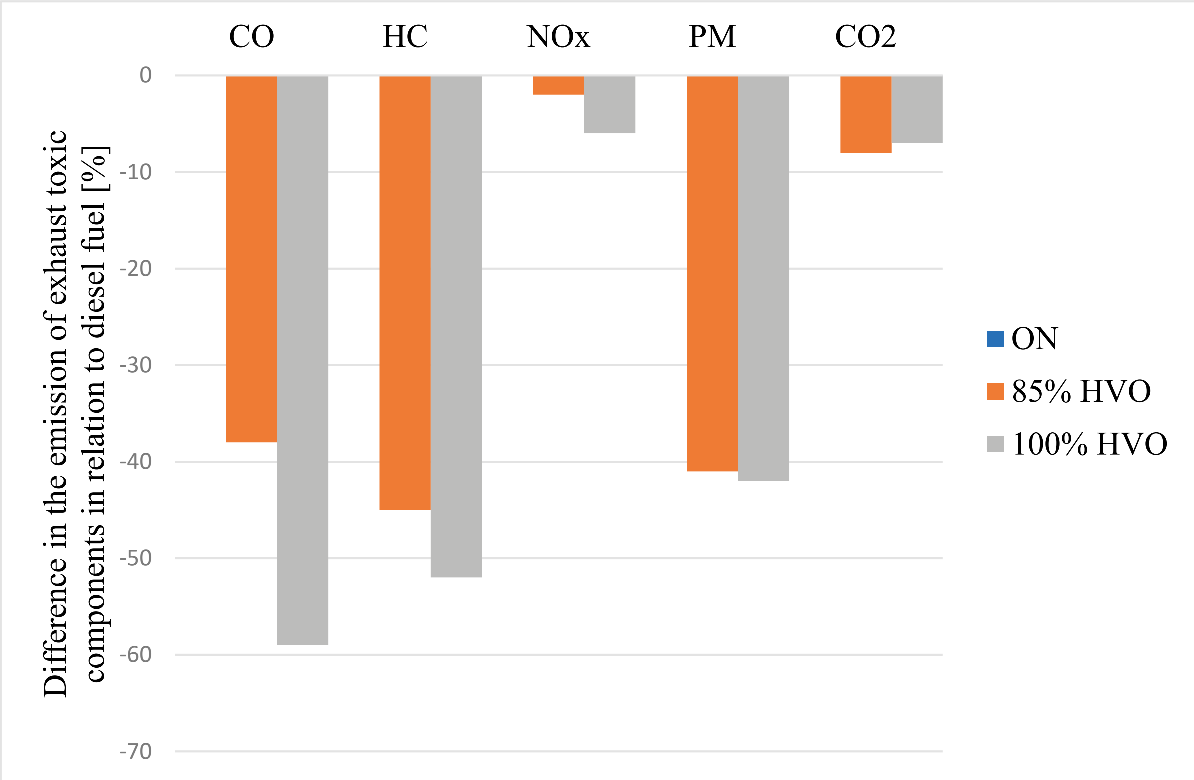


Fig. 3. The difference in the emission of exhaust toxic components in relation to clean diesel fuel [6, 9]



Based on the analysis performed, it can be concluded that the engine fuelling with HVO biofuel shows less contamination of the injectors than in the case of the engine fuelling with diesel oil. Lower contamination of the injectors can also be observed when using a 30% HVO biofuel additive to diesel oil.

Emission of toxic exhaust components

Toxic components of the exhausts may constitute a few percent of the exhausts volume, and taking into account also carbon dioxide, even several percent of the exhaust gas volume. The emission of toxic components depends on the type of fuel and the method of its combustion in the engine. In the case of compression-ignition engines, the main problem is the emission of carbon oxides, hydrocarbons, nitrogen oxides, solid particles and carbon dioxide. The use of biofuel has an impact on the emission of these toxic components of exhaust gases. Figure 3 shows the percentage difference between the emissions of selected toxic components of exhaust gases when the engine is fuelled with 100% HVO and the mixture of 85% HVO and 15% ON with regard to the fuel running on pure diesel oil.Based on the analysis performed, it can be concluded that the engine fuelling with HVO biofuel shows less contamination of the injectors than in the case of the engine fuelling with diesel oil.

The results presented in Figure 3 show that the use of HVO biofuel significantly reduces the emission of particulate matter, carbon monoxide and hydrocarbons compared to fuelling the engine with diesel oil. This applies to both the HVO biofuel and the mixture in the volume ratio of 85% HVO and 15% diesel oil. Emission of nitrogen oxides with the use of HVO biofuel and a mixture of 85% HVO and 15% diesel oil is comparable to the emission of nitrogen oxides with the use of diesel fuel. This is a great advantage of this fuel, considering the comparison of HVO biofuel with FAME biofuel. The use of FAME usually increases NOx emissions due to its elemental composition, which includes oxygen [13].

Conclusions

Based on the comprehensive evaluation of HVO fuel compared to 1st generation biofuels, the following conclusions can be drawn:

- we use waste (non-food) raw materials for the production of HVO biofuel,
- HVO biofuels show a higher quality in relation to the first generation biofuels (good chemical stability, possibility of long-term storage). This makes it easier to accept by the automotive industry,
- the use of HVO biofuel reduces CO2 emissions compared to the first generation biofuels,
- during the production of HVO biofuel, no waste is generated for which there is little demand (e.g. glycerin in the case of FAME biofuel).

Based on the literature analysis of the tests results of toxic substances emissions when fuelling a compression-ignition engine with HVO fuel and mixtures of diesel oil and HVO fuel, the following conclusions can be drawn:

- The use of Hydro-treated Vegetable Oil (HVO) enables the reduction of CO, HC and NOx as well as particulate emissions without the need for changes to the engine or its control systems.
- With the standard (factory) settings of the fuel injection times of the tested engines, the use of 100% HVO led to a reduction of NOx emissions by approx. 6-8% compared to diesel fuel. This is a significant difference compared to FAME biofuels. The use of FAME biofuel increases the emission of nitrogen oxides compared to diesel fuel.
- The results of the research on HVO fuels carried out so far suggest that by optimizing the fuel injection parameters for HVO, even more significant reductions in the emission of toxic exhaust components can be achieved.
- Thanks to the analysis of the research conducted to date on the fuelling of the combustion engine with HVO fuel, it can be concluded that the results of all tests indicate a reduction of both exhaust smoke and nitrogen oxides. Importantly, this applies to both, the tests of the emis-

sion of toxic components of engine exhaust gases from a passenger vehicle as well as tests carried out on high-power engines and other applications [20].

- Series-manufactured engines must pass the exhaust emission type-approval tests using specified reference fuel type as defined in the regulations. The reference fuels correspond to the average market quality of fuel. This means that by using the standard engine management settings, one can only partially reduce the exhausts emissions (based only on the better quality of HVO fuel). Nevertheless, reducing the emission of toxic components (as a result of better fuel quality) is a benefit for society and the environment. On the other hand, the full benefits of better fuel quality and fuel-optimized engines can be achieved with dedicated vehicle fleets. Examples include city buses, non-road equipment operating in mines, and forklifts operating in confined spaces where the reduction of local emissions is particularly important.

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