VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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RESEARCH ON ENERGY AND EMISSION PERFORMANCE OF A DIESEL ENGINE FUELLED WITH HYDROTREATED VEGETABLE OIL AND BIOBUTANOL MIXTURES

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Abstract

The transportation industry is transforming the “Resource-efficient Europe” initiative to promote economic progress, increase competitiveness, and deliver high-quality mobility promotion services. This initiative encourages using locally sourced renewable biofuels, such as biobutanol-based fuel, to reduce ecological impact and increase renewable energy sources in overall energy consumption. Researchers in Lithuania explore second-generation biodiesel mixtures and biobutanol for further integration in the Lithuanian transport sector.

The quest for sustainable and environmentally friendly fuel alternatives for internal combustion engines has led to exploring second-generation biofuels, such as Hydrotreated Vegetable Oil (HVO) and biobutanol mixtures. This research evaluates the energy and ecological impacts of substituting conventional diesel with these biofuels in a compression ignition engine.

The experimental setup involved a 1.9 TDI engine type 1Z, operating at a constant speed of 2000 rpm under varying loads and exhaust gas recirculation (EGR) rates. Fuels tested included conventional diesel (D100), HVO100, and mixtures of HVO with 5%, 10%, and 20% biobutanol in percentage proportions by volume (HVOB5, HVOB10, and HVOB20). Key parameters studied are brake thermal efficiency (BTE), smoke emissions, NO_X, CO_2 emissions, and particulate number (PN). Theoretical investigations further analysed the correlation between energy and ecological indicators across different fuel compositions.

The research showed that using HVO100 and its mixtures with biobutanol greatly reduced the amount of smoke and CO_2 emissions compared to D100. The emissions went down even more as the biobutanol concentration increased in HVO. However, BTE showed a decrease with higher biobutanol concentration under constant load conditions. Specifically, HVOB20 demonstrated a reduction in *BTE* by approximately 1.4% compared to D100. NO_X emissions were lowest with HVO100, indicating a reduction in NO_X generation through increased EGR rates. Theoretical investigations underscored a strong correlation between ecological and energy parameters, highlighting the potential of biofuel mixtures to meet specified emission standards (Eur – Lex, 2019).

The usage of HVO and biobutanol in compression ignition engines presents a promising avenue for improving ecological indicators without significantly compromising energy efficiency. Nevertheless, the research identifies a need for further research into the long-term effects of these biofuels on engine reliability and performance. This research supports the transition towards alternative renewable fuels, reducing smoke emissions and CO_2 levels, thereby contributing to the global effort to combat climate change.

Reziumė

Transporto sektorius pertvarkomas pagal iniciatyvą „Tausiai išteklius naudojanti Europa“, kuria skatinama ekonominė pažanga, didinamas konkurencingumas ir plečiamos mobilumo paslaugos. Šia iniciatyva skatinama naudoti vietinės kilmės atsinaujinančius biodegalus, tokius kaip biobutanolio pagrindu pagamintus degalus, sumažinant transport priemonų poveikį aplinkai ir siekiant, kad kuo didesnę suvartojamos energijos dalį sudarytų iš atsinaujinančių šaltinių gaunama energija. Mokslininkai Lietuvoje tiria antros kartos biodyzelino mišinius ir biobutanolį, kad juos integruoti Lietuvos transporto sektoriuje.

Tvarių ir aplinką tausojančių vidaus degimo variklių alternatyviųjų degalų paieškos paskatino tyrinėti antros kartos biodegalus, tokius kaip hidrinti augaliniai aliejai (HVO) ir biobutanolio mišiniai. Šiame tyrime vertinamas įprasto dyzelino pakeitimo šiais biodegalais slėginio uždegimo variklyje energinis ir ekologinis poveikis.

Eksperimentuose naudotas 1,9 TDI 1Z tipo variklis, veikiantis pastoviu 2000 aps/min greičiu, esant įvairioms apkrovoms ir skirtingam išmetamųjų dujų recirkuliacijos (EGR) režimui. Tirti degalai buvo įprastinis dyzelinas (D100), HVO100 ir HVO mišiniai su 5 %, 10 % ir 20 % biobutanolio tūrio (HVOB5, HVOB10 ir HVOB20). Pagrindiniai ištirti parametrai yra: efektyvusis naudingumo koeficientas (BTE), dūmingumas, NOX, CO2 emisija ir kietųjų dalelių skaičius (PN). Atliekant teorinius tyrimus analizuotas ryšys tarp VDV ekologinių ir energinių rodiklių esant skirtingiems degalų mišiniams.

Tyrimas parodė, kad naudojant HVO100 ir jo mišinius su biobutanoliu dūmingumas ir CO_2 emisija mažesni, nei naudojant D100. Išmetamųjų teršalų kiekis mažėja, didinant biobutanolio koncentraciją HVO degaluose. *BTE* sumažėja esant didesnei biobutanolio koncentracijai ir pastovioms variklio apkrovos sąlygoms. HVOB20 parodė, kad *BTE* sumažėjo maždaug 1,4 %, palyginti su D100. NO_X emisija buvo mažiausia naudojant HVO100, tai rodo, kad padidinus EGR režimą susidaro mažiau azoto oksidų. Teorinių tyrimų rezultatai atskleidė stiprią ekologinių ir energinių parametrų koreliaciją ir parodė, kad biodegalų mišiniai turi didelį potencialą ir gali atitikti keliamus emisijos standartus (Eur – Lex, 2019).

HVO ir biobutanolio mišinių panaudojimas slėginio uždegimo vidaus degimo variklyje yra perspektyvus būdas pagerinti ekologinius rodiklius nesumažinant energinio efektyvumo. Tyrimo metu nustatyta, kad būtina toliau tirti ilgalaikį šių biodegalų poveikį variklio veikimo patikimumui. Šiuo tyrimu pagrindžiamas perėjimas prie atsinaujinančių alternatyviųjų degalų naudojimo, mažinant dūmingumą ir CO_2 išmetimą, taip prisidedant prie pasaulinių pastangų kovoti su klimato kaita.

Notations

Symbols

BMEP – Brake Mean Effective Pressure (bar) (liet. *vidutinis efektyvusis slėgis*);
BSFC_m – Brake Specific Fuel mass Consumption (g/kWh) (liet. *lyginamosios efektyvios degalų sąnaudos pagal masę*);
BSFC_V – Brake Specific Fuel volume Consumption (ml/kWh) (liet. *lyginamosios efektyvios degalų sąnaudos pagal tūrį*);
BTE – Brake Thermal Efficiency (liet. *efektyvusis naudingumo koeficientas*);
LHV_m – Lower Heating Value by mass (MJ/kg) (liet. *masės žemutinis šilumingumas*);
LHV_V – Lower Heating Value by volume (MJ/l) (liet. *tūrio žemutinis šilumingumas*);
M_B – Brake torque (Nm) (liet. *sukimo momentas*);
ROHR – Rate of Heat Release (liet. *šilumos išsiskyrimo intensyvumas*);
SOC – Start of Combustion (liet. *degimo pradžios momentas*);
SOI – Start of Injection (liet. *įpurškimo pradžios momentas*);
T_{ex} – Exhaust gas temeperature (liet. *išmetamųjų dujų temperatūra*);
λ – Air excess ratio (liet. *oro pertekliaus koeficientas*);
n – Rotational speed of the crankshaft (rpm) (liet. *variklio sukimosi dažnis*).

Abbreviations

AFR – Air–fuel ratio (liet. *oro ir degalų santykis*);
ATDC – After Top Dead Centre (liet. *po viršutinio galinio taško*);

BD20 – 20% *n*-butanol and 80% diesel by volume (liet. *20 % n-butanolio and 80 % dyzelino pagal tūrį*);
BTDC – Before Top Dead Centre (liet. *prieš viršutinį galinį tašką*);
BTL – Biomass to Liquids (liet. *biomasės į skyščius technologija*);
C/H – Carbon/Hydrogen ratio (liet. *anglies ir vandenilio santykis*);
CAD – Crank Angle Degree (liet. *alkūninio veleno pasisukimo kampas*);
CI – Compression Ignition (liet. *slėginis uždegimas*);
CO – Carbon monoxide (liet. *anglies monoksidas);*
CO_2 – Carbon dioxide (liet. *anglies dioksidas*);
D100 –100% conventional diesel fuel (liet. *įprastas dyzelinas*);
ECU – Electronic computer unit (liet. *variklio valdymo blokas*);
EGR – Exhaust Gas Recirculation (liet. *išmetamųjų dujų recirkuliacija*);
ES – European Union (liet. *Europos Sąjunga*);
GHG – Greenhouse gases (liet. *šiltnamio efektą sukeliančios dujos*);
HC – Hydrocarbons (liet. *nesudegę angliavandeniliai*);
HRR – Heat release rate (liet. *šilumos išsiskyrimo greitis*);
HVO – Hydrotreated vegetable oil (liet. *hidrintas augalinis aliejus*);
HVO100 – 100% hydrotreated vegetable oil (liet. *100 % hidrintas augalinis aliejus*);
HVOB10 – 90% hydrotreated vegetable oil, 10% biobutanol (liet. *mišinys iš* 90 *% hidrinto augalinis aliejaus, 10 % biobutanolio*);
HVOB20 – 80% hydrotreated vegetable oil, 20% biobutanol (liet. *mišinys iš* 80 *% hidrinto augalinis aliejaus, 20 % biobutanolio*);
HVOB5 – 95% hydrotreated vegetable oil, 5% biobutanol (liet. *mišinys iš* 95 *% hidrinto augalinio aliejaus, 5 % biobutanolio*);
LTC – Low Temperature Combustion (liet. *žemos temperatūros degimas*);
NO – Nitrogen monoxide (liet. *azoto monoksidas*);
NO_2 – Nitrogen dioxide (liet. *azoto dioksidas*);
NO_X – Nitrogen oxides (liet. *azoto oksidai*);
O_2 – Oxygen (liet. *deguonis*);
OBD – On-board diagnostics (liet. *įmontuojamoji diagnostikos įranga*);
PM – Particulate matter (liet. *kietosios dalelės*);
PN – Particulate number (liet. *kietųjų dalelių skaičius*);
$PODE_{3-4}$ – Polyoxymethylene dimethyl ethers (liet. *polioksimetileno dimetilo eteriai*);
p_{TC} – Turbocharger pressure (liet. *turbinos pripūtimo slėgis*);
RME – Rapeseed Oil Methyl Esters (liet. *rapsų metilo esteris*);
SB50 – 50% conventional diesel fuel, 50% *sec*-biobutanol (liet. 50 % įprastinis dyzelinas, 50% *sec*-biobutanolis);
TB50 – 50% conventional diesel fuel, 50% *tert*-biobutanol (liet. 50 % įprastinis dyzelinas, 50% *tert*-biobutanolis).

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Article 2. Valeika et al. (2022). Research of the impact of EGR rate on energy and environmental parameters of compression ignition internal combustion engine fuelled by hydrogenated vegetable oil (HVO) and biobutanol – Castor oil fuel mixtures (https://doi.org/10.1016/j.enconman.2022.116198) 82
Article 3. Valeika et al. (2023). Smoke Formation during Combustion of Biofuel Blends in the Internal Combustion Compression Ignition Engine (https://doi.org/10.3390/en16093682) 97

Article 4. Valeika et al. (2024). Compression ignition internal combustion engine energy parameter research using variable (HVO) biodiesel and biobutanol fuel blends (https://doi.org/10.3390/en17010262) 113 113

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Author's contribution to the publications

Publication[1]	Formal contribution[2]	Conceptualisation	Data curation	Formal analysis	Investigation	Methodology	Software	Validation	Visualisation	Writing – original draft	Writing – review & editing
Valeika et al., 2021	0.200	none	joint		sole	main			sole	joint	main
Valeika et al., 2022	0.333	joint	main	main	joint	main	main	joint	main	main	joint
Valeika et al., 2023	0.167	joint	joint	joint	main	main	joint	joint	main	main	joint
Valeika et al., 2024	0.167	main	joint		main	joint			joint	main	joint
Total or max[3]	0.867	main	main	main	sole	main	main	joint	sole	main	main

[1] The published articles have been used here with the permission of the relevant publishers.

[2] The formal contribution is calculated as a fraction – $1/N_{\text{authors}}$.

[3] The total sum of the formal contribution values or the highest contribution achieved (in the increasing order: none, joint, main, or sole) in the specified 10 of 14 roles (according to the CRediT taxonomy, https://credit.niso.org/).

Co-authors of all of the above-mentioned articles have no motive to use this published data to prepare other dissertations.

All the authors of the above-mentioned articles have agreed to the author's contribution statement.

Introduction

Problem Formulation

Following the European Climate Law (European, 2023) that aims to address climate change and environmental degradation, it is crucial to implement rigorous measures that involve legislative actions, technical advancements, and changes in fuel policies. The Climate Neutral Europe framework, as outlined in the European Green Deal Strategy (European, 2024), plays a crucial role in driving economic progress and improving competitiveness by efficiently utilising resources, specifically focusing on alternative renewable biofuels.

HVO and biobutanol fuel mixtures exhibit lower greenhouse gas (GHG) emissions than traditional fossil fuels. The use of these fuels contributes to global and regional goals of reducing CO_2 and other GHG emissions, thereby combating climate change. The European Environment Agency reported (Environment, 2021) that in 2019, transport accounted for 25% of the carbon dioxide emissions in the European Union, with motor travel contributing to 71.7% of this total. The European Commission has put out legal proposals to achieve integration among climate, energy, transport, and budgetary policy. European Green Deal strategy (European, 2023) aims to achieve carbon neutrality by focusing on a 55% reduction in carbon emissions by 2030 and a 90% reduction by 2040 compared to 1990 levels.

In summary, using HVO and biobutanol fuel mixtures in internal combustion engines is critical to achieving energy security, environmental sustainability, and economic development. As the transportation sector seeks to reduce its environmental impact, these renewable fuel mixtures offer a viable and efficient solution.

Relevance of the Dissertation

The transition towards sustainable and environmentally friendly transportation methods is a critical objective for mitigating the adverse effects of climate change and reducing environmental pollution. Within this context, the relevance of using fuel mixtures, specifically those combining HVO and biobutanol, in internal combustion engines emerges as a potent strategy in the quest for greener alternatives to conventional fossil fuels.

European Climate Law (European, 2023) sets a legally binding target of zero net GHG emissions by 2050 and identified several principal sources of environmental pollution, with energy production and transformation, the utilisation of fossil fuels, and emissions from road transport and equipment employing internal combustion processes being among the most significant contributors. In light of this, the shift towards biofuels, such as HVO and biobutanol, is not merely an alternative but a necessity for achieving a sustainable and less pollutive future.

Integrating biobutanol into HVO fuel blends presents a promising approach to entirely supplanting fossil diesel. This combination is particularly compelling because it constitutes a bio-based solution that aligns with the European Union's stringent environmental policy objectives (European, 2024).

Finally, HVO and biobutanol fuel mixtures are useful in internal combustion engines because they cut down on harmful exhaust emissions while still meeting global environmental policy goals. Advancing research in this area will be pivotal for realising the full potential of these biofuels, thereby contributing to a sustainable and eco-friendly transportation future.

Research Object

The research object of the dissertation is the energy and ecological characteristics of the compression ignition internal combustion engine operating with HVO-biobutanol mixtures.

Aim of the Dissertation

The dissertation aims to investigate the use of fuel mixtures of biological origin consisting of HVO and biobutanol in compression ignition internal combustion engines to determine energy and ecological characteristics.

Objectives of the Dissertation

The research concentrates on tackling the following precise and intricate elements to accomplish the established aim:

1. To investigate the HVO and biobutanol impact on the properties of fuel mixtures and combustion process in an engine.
2. To investigate the energy efficiency and emissions of a compression ignition engine running on HVO and biobutanol fuel mixtures.
3. To examine the influence of EGR and fuel injection time on the energy efficiency and ecological indicators of compression ignition internal combustion engines that use investigated fuel mixtures.
4. To evaluate the accuracy of experimental data from HVO and biobutanol fuel mixtures operating compression ignition engines.

Research Methodology

To investigate the *object*, the following *research methods* were chosen:

- *Classification* to summarise previous studies focused on the utilisation of biofuels in internal combustion engines by critically analysing their advantages and limitations.
- *Experience* in conducting an error analysis to identify the root causes of discrepancies that arose from using different biofuel mixtures in the internal combustion engine experiments.
- *Experimental* to explore the added value of utilising HVO and biobutanol fuel blends in enhancing the combustion efficiency, energy performance, and ecological sustainability of internal combustion engines.
- *Statistical* data was obtained from the experiment for analysing and evaluating the particular correlations associated with the usage of biofuels in compression ignition internal combustion engines.

Scientific Novelty of the Dissertation

The aspects of scientific novelty on the impact of employing different compositions of secondary generation biofuels, namely HVO-biobutanol (biobutanol concentration is till 20%, HVOB20), on the ecological and energy indicators of a compression ignition internal combustion engine are as follows:

1. The original methodology was implemented to investigate the properties of the fuel mixtures for the preparation of HVO and biobutanol mixtures.
2. The substantial impact of *SOI* of the structured mixtures of HVO and biobutanol on combustion efficiency and emissions was clarified.
3. The interaction between the biobutanol content of HVO fuel and EGR (up to 30%) has been shown not to increase NO_X emissions.
4. Pearson's correlation approach was used to examine the association between smoke and PN indicators in compression ignition engines.

Practical Value of the Research Findings

The significance of second-generation biofuels, such as HVO and biobutanol fuel mixtures, lies in their stability within fuel mixtures and their cost-effectiveness. These biofuels exhibit superior stability due to their refined production processes, which minimise the presence of impurities and ensure consistent fuel quality.

Increasing the EGR rate up to 30% increases emissions while reducing the negative impact on *BTE* and smoke emissions. Mixing biobutanol with HVO up to 10% achieves a balance between lower emissions and combustion efficiency. However, the use of biobutanol up to 20% results in a reduction of *BTE*.

To ensure optimum engine performance and efficiency, especially at various engine loads and EGR rates, it is necessary to adjust the cyclic fuel injection to compensate for the lower *LHV* of HVO and biobutanol mixtures compared to D100. HVO effectively reduces NO_X, CO_2 and particulate matter emissions by improving combustion processes compared to conventional fossil fuels. Biobutanol improves exhaust emissions by considering their impact on combustion process efficiency and emissions such as HC.

In conclusion, the use of the HVO and biobutanol fuel mixtures represents a sustainable path forward, harmonising environmental stewardship with economic pragmatism. Their stability in fuel mixtures ensures reliable engine performance, while their competitive pricing models, underpinned by advancements in production technologies and supportive policies, make them a viable alternative to traditional energy sources.

Defended Statements

1. The proposed biofuel mixtures, which meet fuel quality standards, are suitable for use in place of fossil fuels.
2. The decreased *LHV* of biobutanol results in an extended duration of injection, leading to longer combustion and lower *BTE*.
3. By increasing the EGR rate, the increase in smoke is effectively reduced by the addition of biobutanol in HVO fuel.
4. The analysed Pearson's correlation coefficients and the relations define the PN values from smoke emissions in a compression ignition engine.

Approval of the Research Findings

The main results of the dissertation were published in six articles on the research topic, four scientific journals indexed in the *Clarivate Analytics Web of Science* databases with an Impact Factor.
The author gave two presentations at two international scientific conferences:

- The 12th International Conference TRANSBALTICA XII: Transportation Science and Technology, 2021, Vilnius, Lithuania.
- The 12th International Scientific Conference Transport Problems 2020, 2020, Katowice, Poland.

Structure of the Dissertation

The dissertation is organised into three chapters. The First Chapter presents the potential of using HVO and biobutanol mixtures as an alternative to conventional diesel fuel. This chapter finishes by establishing the primary purpose and tasks of the current research.

The Second Chapter outlines the research methods used in the use of engine and traction benches. The chapter discusses the used fuel mixtures' physical-chemical properties.

The Third Chapter presents research on ecological and energy indicators to evaluate the impact of using HVO and biobutanol fuel mixtures on compression ignition in internal combustion engines. The energy indicators *BTE*, *BSFC*, and combustion parameters, such as *SOI*, *SOC*, and *ROHR*, as well as ecological indexes like smoke, Nox, CO_2, and PN, are contingent upon the particular fuel combination used.

The dissertation closes with general conclusions and recommendations of the research results. It also provides a list of references and copies of the author's four scientific publications by the dissertation theme. The dissertation consists of 136 pages, 21 figures, three tables, and 32 references cited in the dissertation.

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1

Analytical review of scientific publications considering the use of diesel and biodiesels

This chapter presents the use of HVO and biobutanol mixtures to replace fossil diesel. However, limited research poses questions about the combustion processes involved. Using EGR systems efficiently decreases nitrogen oxide emissions in mixtures with *n*-butanol blends.

This chapter formulates the main objective and tasks of the investigation. The main research results of this chapter were published in the author's publications (Valeika et al., 2022; Valeika et al., 2023; Valeika et al., 2024).

1.1. Engine energy and ecological parameters using various fuel mixtures

N-butanol is a biofuel derived from biomass and is considered a renewable energy source. According to previous research, butanol has emerged as a highly advanced alternative fuel option for utilisation in CI engines. Including *n*-butanol in diesel and bio-diesel mixtures resulted in a discernible influence on the combustion rate. However, a marginal variation was observed in the combustion temperature. The

introduction of *n*-butanol into the fuel led to a reduction in the size of soot particles. Adding *n*-butanol resulted in an extended ignition delay period and deceleration of the kinetic combustion phase, particularly noticeable under low-load conditions. The obtained results support the assertion that *n*-butanol-diesel mixtures while maintaining the same NO_X levels, exhibit a reduction in particulate matter and smoke emissions. However, it is important to note that the heat efficiency of these mixtures is lower when compared to conventional diesel fuel. Further investigations reveal that when the *i*-butanol concentration in diesel falls below 17.5%, the combustion flame exhibits a reciprocating propagation pattern. Conversely, when the *i*-butanol concentration exceeds 17.5%, the combustion flame demonstrates a motion characterised by intermittent jumps and crawls (Xiao et al., 2019). *N*-butanol and *i*-butanol properties are identical to those of biobutanol.

Biodiesel, a first-generation biofuel, is largely acknowledged as the predominant biofuel. The composition mostly comprises methyl or ethyl esters of fatty acids, typically known as Fatty Acid Methyl Esters (FAME) or Fatty Acid Ethyl Esters (FAEE). The second generation biofuels are only generated from waste biomass or non-food ingredients. Biohydrocarbons represent a distinct classification of biocomponents used in biofuels as an additive. The synthesis of these compounds necessitates the application of catalytic oil hydrogenation technology. This method involves the removal of oxygen and unsaturated bonds from triglyceride structures, commonly referred to as HVO. The resultant composition primarily comprises liquid paraffinic hydrocarbons. Algae is the major source from which the third-generation biofuels are predominantly derived. HVO significantly reduces carbon dioxide emissions by approximately 90% compared to regular diesel. Furthermore, HVO demonstrates a decrease in particulate matter emissions by approximately 30% and a reduction in nitric oxide emissions by approximately 9% compared to conventional diesel fuel. Its primary manufacturing source is vegetable waste, including residual portions of vegetables and fruits and outdated margarine. HVO has the potential to be commercially available in two forms: pure HVO100 or as a blend with regular diesel fuel, with varying ratios such as HVO30, HVO50, and so on. In its unadulterated state, it reduces around 90% of CO_2 emissions, as supported by references (Bharathiraja et al., 2017; Vijayan et al., 2018).

The evaluation of emissions involved conducting experiments on mixtures of HVO and *i*-butanol. The findings indicated a minor drop in NO_X emissions and a significant reduction in particulate matter compared to traditional diesel fuel. The examination demonstrated that diesel-*i*-butanol mixtures (with *i*-butanol comprising 30% of the diesel fuel by volume) exhibited higher NO_X emissions compared to conventional diesel fuel but lower levels of NO_X emissions than HVO-*i*-butanol mixtures (with *i*-butanol comprising 30% of the HVO fuel) (Xia

et al., 2019). The disparities in NO_X emissions between conventional diesel and HVO are substantial. However, introducing *i*-butanol into HVO did not result in any notable or consistent alterations in NO_X levels. Consequently, conducting a statistical evaluation of the obtained findings proves challenging. An observed correlation exists between the rise in oxygen concentration in biodiesel and a subsequent decrease in CO emissions. The experimental verification of this phenomenon was attempted by Sayin et al. (2013) and Gumus et al. (2012). The researchers employed various fuel types in their research, including traditional diesel, pure biodiesel, and different combinations of diesel and biodiesel, denoted as B100, B50, B20, and B5, where the numerical values represent the percentage of biodiesel included in the diesel fuel. CO emissions were seen to reduce by 38.18%, 30.90%, 20.66%, and 13.55% at different engine loads when utilising B100, B50, B20, and B5 fuels, respectively, compared to conventional diesel. The findings of the research were derived from the observation that an increased oxygen concentration in the utilised fuels enhanced both the combustion process and its overall efficiency. Gharehghani et al. (2017) reported comparable findings. The average reduction in CO emissions was seen when utilising several biodiesel mixtures (B25, B50, B75, and B100), representing the percentage of biodiesel content in diesel. CO emissions reductions were 5.2%, 11.2%, 22.5%, and 27% for B25, B50, B75, and B100, respectively. The results are further supported by increased oxygen content in the utilised fuel mixtures and a reduced duration of the combustion process. The presence of oxygen in biodiesel leads to the oxidation of carbon molecules, resulting in a decrease in CO emissions. The consideration of fundamental fuel qualities, including viscosity and density, is crucial to attaining thorough combustion, resulting in the production of CO_2. Additionally, the engine configuration and speed, air-to-fuel ratio, and *SOI* must be duly acknowledged. Using traditional fossil fuels derived from hydrocarbons hinders the targeted decrease in CO_2 emissions (Pillay et al., 2012).

Using biodiesel considerably reduces environmental pollution with particulate matter; hence, its adoption as a substitute for fossil diesel is extremely welcome. Even if RME is the major kind of biodiesel in Lithuania (Rimkus et al., 2019; Zavadskas et al., 2019), trying out the second-generation biodiesel mixtures BTL (Dimitriou et al., 2018; Gardezi et al., 2013), HVO (Aatola et al., 2008; Bortel et al., 2019), and other mixtures with biobutanol be sensible. When investing in and improving the technology for the manufacture of second-generation biofuels, the progress of the process towards increased commercial use is observed. This allows ceasing the use of first-generation biofuels altogether and transitioning to second-generation biofuels. The biofuel business is unlikely to experience major changes in the foreseeable future. The usage of first- and second-generation biofuels will continue to trend, increasing the volume of the

second-generation biofuels in line with the established environmental and economic policy.

The studies demonstrated that mixtures of diesel and alcohol lower particulate matter emissions (Rimkus et al., 2019). Ignition delays no longer occur when employing *n*-butanol and diesel mixtures compared with conventional diesel. Mixes of HVO and *n*-butanol (30%) lower particulate matter emissions more than conventional diesel and HVO (Zöldy, 2019).

Conventional diesel and HVO were used to examine the size of PM and their quantities. When utilising HVO, smaller particulate matter (below 50 nm) was created, and PM emissions were similarly decreased. Other experiments demonstrated that particulate matter emissions decreased with increasing advanced injection timing; nonetheless, greater quantities of PM were created in the application of pre-injection (pilot injection) than with the single injection strategy (Huang et al., 2019).

The usage of *i*-butanol and diesel mixtures was seen to yield a substantial decrease in soot emissions when compared to conventional diesel, maintaining the same EGR rate. The reduction in soot emissions reached around 90% at a 30% EGR flow rate, as reported in reference (Kumar & Saravanan, 2016).

Studies show that BD20 fuels increase cylinder pressure, heat release rate, ignition delay, and combustion efficiency, while adding $PODE_{3-4}$ shortens ignition delay, increases heat release, and improves combustion efficiency (Huang et al., 2019). Diesel-butanol blends have lower *BTE* at light load and slightly higher TB50, with lower calorific value and higher thermal efficiency. Diesel *BTE* increases more than butanol blends as the load increases due to increased cylinder temperature. However, butanol blends have higher *BTE* at 1.2 MPa loads than D100, the highest TB50 (Pan et al., 2020).

After comparing the HRR of the fuels tested under different operating conditions, it was found that butanol delays the ignition time. At a *BMEP* of 1.2 MPa, the heat release time of butanol blends is very close to diesel. Also, the maximum HRR of the SB50 is about 1.5 times that of the D100 (Pan et al., 2020).

1.2. Publications on the influence of exhaust gas recirculation on reducing pollution when an engine is fuelled with various fuel mixtures

Experiments were conducted to investigate the effects of various EGR settings on the combustion characteristics and emissions of diesel and *n*-butanol mixtures. EGR affects particulate matter emissions. It is insignificant at below 10%. As EGR rates increase, soot emissions decrease due to decreased total combustion temperature and extended ignition delay. This phenomenon, known as EGR High

Flow Low-Temperature Combustion (LTC), effectively inhibits the production of nitrogen oxides and soot (Han et al., 2010).

When conventional diesel is blended with butanol, increasing the EGR rate initially decreases the total particulate concentration of all evaluated fuel blends. As the EGR rate continues to increase, the particulate concentration begins to increase. The total mass concentration of particles begins to increase, and the geometric diameter of the particles gradually changes and increases. Compared with D100, BD20 had a smaller particle formation concentration peak and a smaller particle geometric diameter.

The influence of the λ and EGR on the initiation of combustion was found to have negligible effects on both HVO and conventional diesel fuels. Notwithstanding this lack of sensitivity, minor modifications in the premixed, experimental combustion stage and its subsequent impact on mixture conditions give rise to significant emission variations. The research revealed that when employing high rates of EGR at 30% and 40%, the introduction of *n*-butanol into diesel fuel at varying concentrations (ranging from 0% to 50%) had a significant impact on the particle emission properties of the diesel engine. This effect was observed across different EGR conditions and led to a notable reduction of approximately 74% in the overall concentrations of *n*-butanol/diesel PM compared to conventional diesel fuel. An investigation was conducted to compare the effects of *n*-butanol and *2*-butanol blended with diesel fuel at a volume ratio of 20% on engine performance, focusing on the influence of fuel characteristics and oxygenated structures. The research found that when EGR rates varied from 0% to 62%, butanol-diesel mixtures resulted in the lowest levels of soot emissions. This effect was most pronounced at higher EGR flow rates, specifically those over 40% (Huang et al., 2016).

Using biodiesel in conjunction with 10% and 20% EGR resulted in mean reductions of NO_X emissions by 14.4% and 27.6%, respectively, compared to scenarios where EGR was not employed. When subjected to high EGR rates, conventional diesel fuel blended with varying proportions of butanol and pentanol demonstrates favourable outcomes in terms of decreasing total hydrocarbon content (THC). There was no discernible variation in NOx levels since all fuels exhibited equivalent emissions at a consistent EGR rate. B10P20 and B20P10 fuel mixtures have been found to effectively mitigate both soot emissions and CO emissions at varying EGR rates compared to conventional diesel. In summary, B20P10 fuel has better combustion and emission characteristics, especially when using a higher EGR rate (Liang et al., 2021). When the EGR rate surpasses 30%, the ignition delay of B20P10 and B30 is observed to be shorter compared to that of D100. This phenomenon is attributed to the presence of oxygen in biodiesel, which enhances its combustion efficiency, particularly at elevated EGR flow rates. High levels of EGR flow concurrently reduce NOx emissions and soot.

However, it also leads to an increase in CO emissions and total hydrocarbons. According to previous research, diesel engines may find three-component mixes with medium EGR flow more appropriate, considering the EGR rate and fuel attributes (Liang et al., 2021).

1.3. Conclusions of the First Chapter and formulation of the dissertation tasks

1. The use of HVO and biobutanol fuel mixtures (fuel additives) has great potential to expand the use of biofuels and become a suitable substitute for fossil diesel. Furthermore, it is important to note that the fuel mixture consists entirely of biological components, aligning it with the policy objectives set forth by the European Union climate law. However, the limited scope of research in this area generates some inquiries regarding the examination of the combustion process of these fuels. The existing studies have predominantly concentrated on summarising fuel consumption patterns and their environmental impact. A thorough evaluation of the energy-environmental aspects and combustion process analysis provide stronger evidence for using these fuels in compression ignition engines without requiring further modifications to the engine structure.
2. The shift towards substituting fossil fuels with renewable energy sources is the paramount aspect of a comprehensive strategy for achieving sustainable transportation. Currently, biofuels account for a mere 4% of the global energy consumption in the transportation sector. The HVO and biobutanol fuel mixtures, derived from abundant, sustainable, and economical sources, are viable substitutes for fossil fuels. This is a kind of biofuel that may be used in the transportation system to meet sustainability requirements.

Based on the literature survey, the following tasks were formulated:

1. To investigate the HVO and biobutanol impact on the properties of fuel mixtures and combustion process in an engine.
2. To investigate the energy efficiency and emissions of a compression ignition engine running on HVO and biobutanol fuel mixtures.
3. To examine the influence of EGR and fuel injection time on the energy efficiency and ecological indicators of compression ignition internal combustion engines that use investigated fuel mixtures.
4. To evaluate the accuracy of experimental data from HVO and biobutanol fuel mixtures operating compression ignition engines.

2

Research methodology of hydrotreated vegetable oil and biobutanol mixtures as fuels of compression ignition engines

This chapter presents the research methodologies using engine and traction benches. The chapter presents the physical-chemical characteristics of fuel and fuel blends consisting of diesel, HVO and biobutanol. Additionally, a research methodology is introduced to delineate the sequence of research activities. The text provides detailed explanations of the engine and the traction stand, together with the recorded parameters and their level of precision. The methodologies of combustion analysis and Pearson's correlation coefficient computation are described. The main research results of this chapter were published in the author's publications (Valeika et al., 2021; Valeika et al., 2022; Valeika et al., 2023; Valeika et al., 2024).

2.1. Nomenclature of the research methodologies of testing biobutanol and hydrotreated vegetable oil fuel mixtures influence on compression ignition engine

The experimental research aimed to ascertain the impact of biofuel mixtures listed above on the energy and ecological indicators of the compression ignition internal combustion engine. Figure 2.1 displays the research scheme.

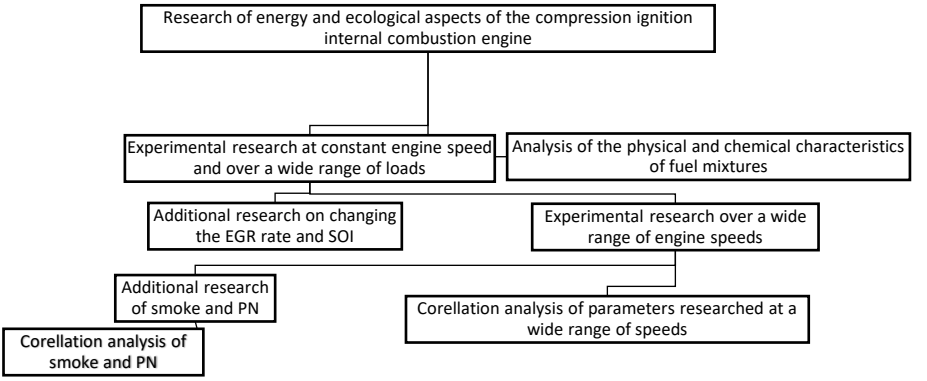


Fig. 2.1. Scheme of HVO and biobutanol fuel mixture research methodology (compiled by the author)

The experimental studies were conducted in these phases:

1. To research the physical-chemical properties of HVO and biobutanol fuel mixtures.
2. The energy and ecological indicators of a stationary compression ignition internal combustion engine were examined at a constant engine speed of 2000 rpm, across a wide range of loads, using the intended fuel mixtures.
3. The EGR rate and start of injection (*SOI*) parameters were adjusted under the specified conditions.
4. A traction stand was used to analyse the energy and ecological parameters of the engine at various engine speeds.
5. Smoke determination was tested according to Regulation EB 595/2009 methodology; PN and smoke measurements were conducted using the intended fuel mixtures.

The thorough analysis of the HVO and biobutanol fuel blends, as described earlier, offers valuable insights into their viability as environmentally friendly substitutes in compression ignition engines. These discoveries provide

opportunities for future refinement of biofuel mixtures to improve engine efficiency and minimise ecological consequences.

2.2. Analysis of physical-chemical properties of biobutanol and hydrotreated vegetable oil fuel mixtures

Experimental tests were performed using conventional diesel (D100), pure hydrogenated vegetable oil (HVO100), mixtures of hydrogenated vegetable oil and biobutanol (Table 2.1) in different proportions: 95% hydrotreated vegetable oil and 5% biobutanol, 90% hydrotreated vegetable oil and 10% biobutanol, and 80% hydrotreated vegetable oil and 20% biobutanol by volume (referred to as HVOB5, HVOB10, and HVOB20, respectively). Castor oil additive, accounting for 5% of the total volume of biobutanol, was incorporated into biobutanol mixtures to enhance lubricity. Physical and chemical characteristics of pure fuels and fuel mixtures were analysed, and the findings were reported (Table 2.1). To achieve the desired fuel qualities, HVO and biobutanol fuels used in the experiments were blended immediately prior to their use. To mitigate the potential influence of temperature variations on density, the fuels and components used in the experiment were uniformly stored at identical temperatures prior to testing.

Table 2.1. Properties of 100% conventional diesel, HVO, biobutanol, castor oil, and fuel mixtures used in experiments

Parameter	Diesel	HVO	Biobutanol	Castor oil	HVOB5	HVOB10	HVOB20
Density at 15° C, kg/m^3	830.4	780.0	810.0	964.0	780.4	782.4	786.4
Cetane number	51	70	18	28	67.3	64.6	59.3
Carbon (% mass)	86.20	84.55	65.00	73.60	83.55	82.55	80.57
Hydrogen	13.80	15.45	13.50	11.55	15.34	15.24	15.03
Oxygen	0	0	21.50	14.85	1.11	2.21	4.40
Kinematic Viscosity, 40° C,mm^2/s	3.5	3.289	2.27	128	3.23	3.18	3.08
AFR	14.79	15.18	11.30	11.91	14.98	14.77	14.38
LHV_m, MJ/kg	43.10	44.10	33.00	41.30	43.54	42.98	41.87
LHV_v, MJ/l	36.09	34.17	26.73	39.81	33.98	33.63	32.93

Prior to and during the experimentation, the fuels and their respective mixes were consistently agitated to prevent stratification caused by varying densities and to uphold the uniformity of the mixture. According to the fuel quality standard EN ISO 3104:1996 the upper and lower limits for the kinematic viscosity at 40° C are set as 3 and 5 mm^2/s, respectively. The viscosity of the HVOB20 fuel combination is precisely 3.08 mm^2/s. Increasing the concentration of biobutanol by more than 20 per cent in HVO fuels exceeds the minimum limits of EN ISO 3104:1996 Table 2.3. describes the equipment and performance conditions used for the experiments provided below.

Table 2.2 provides information on compression ignition internal combustion engines, including their models and the specific conditions under which experiments are conducted. The research was conducted at the Laboratory of Transport Engineering and Logistics of VILNIUS TECH. A stationary research bench was used in the laboratory, as depicted in Figure 2.2.

Table 2.2. The sequence of experimental research on internal combustion engines and the test conditions

Test No	Engine model	Test mode	Used fuels and fuel mixtures
1	1.9 TDI VW-Audi 1Z 66 kW (4000 rpm) 182 Nm (2000 rpm)	Constant crankshaft speed, n = 2000 rpm, engine loads of 30 Nm, 60 Nm, 90 Nm and 120 Nm	D100 HVO100 HVOB5 HVOB10 HVOB20
2		Constant crankshaft speed, n = 2000, engine loads of 30 Nm, 60 Nm, 90 Nm and 120 Nm, at different EGR rates: 0%, 10%, 20%, 30%	
3	1.9 TDI ALH (Skoda Octavia) 66 kW (4000 rpm) 210 Nm (1900 rpm)	Smoke measurement, particulate concentration measurement	
4		External speed characteristic: torque/power – engine speed (n =1400 – 4600 rpm)	

The engine crankshaft was connected to the load stand KI-5543. Fuel consumption was measured using a fuel scale, and exhaust emissions were measured using an AVL DiCom 4000 gas analyser and smoke meter. Smoke measurement was performed by evaluating the decrease in light intensity caused by scattering and absorption processes. The characteristics of the equipment are presented in Table 2.3.

The numerical analysis of the combustion process was conducted using AVL BOOST software. The rate of heat release during combustion was calculated using pressures in the cylinder measured during tests, air and fuel consumption, properties of the fuel used, and engine parameters. The following combustion process indicators were set: start of combustion, in-cylinder temperature, in-cylinder temperature rise, and in-cylinder pressure rise. The mentioned combustion process parameters helped to analyse environmental and energy indicators using conventional diesel, hydrotreated vegetable oil, and hydrotreated vegetable oil and biobutanol mixtures.

Table 2.3. The laboratory equipment data used in bench experiments

Equipment	Accuracy of measurement	Purpose of use
Load bench *KI-5543*	1.2 Nm	Brake torque
Scale SK-500	1.0 g	Fuel consumption
Air mass meter BOSCH HFM 5	≤2%	Air mass
VAG-COM diagnostic equipment	–	Fuel injection timing, the start of injection (*SOI*)
Piezo pressure sensor AVL GH13P	± 0.11 (%FCO)	In-cylinder pressure
Encoder A58M- F	0.1758 crank angle degrees (CAD)	Crankshaft position
Oscilloscope AVL DiSTEST DPM 800	–	In-cylinder pressure and CAD transmit
Delta OHM HD 2304.0, sensor TP704-2BAI	± 0.0002 MPa	Intake pressure
K type thermocouple	± 0.5%	Intake air and the exhaust gas temperature
AVL DiCom 4000 gas analyser	CO_2, 0.1% vol.; CO, 0.01% vol.; HC, 1 ppm; NO_x, 1 ppm; smoke, 0.01 m^{-1}	CO_2, CO, HC, NO_x, smoke absorption coefficient

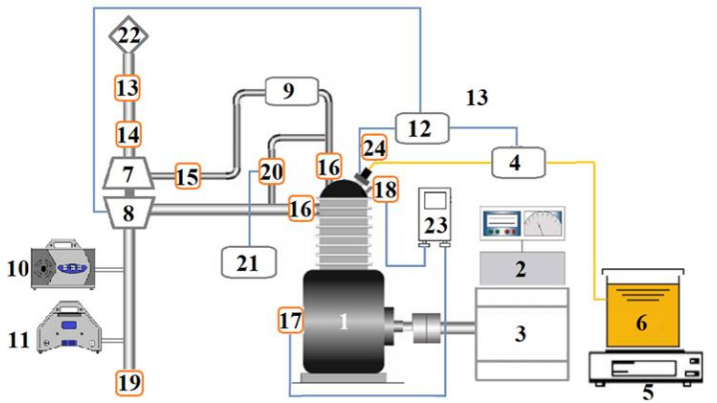


Fig. 2.2. Experiment engine test scheme: 1 – engine, 2 – measurement output gauges, 3 – engine load unit, 4 – high-pressure fuel pump, 5 – scales, 6 – fuel tank, 7 – compressor, 8 – turbocharger, 9 – intercooler, 10 – exhaust gas analyser, 11 – smoke analyser, 12 – ECU, 13 – air mass meter, 14 –intake air temperature sensor, 15 – pressure sensor, 16 – temperature sensor, 17 – crankshaft position sensor, 18 – in-cylinder pressure sensor, 19 – exhaust pipe, 20 – EGR valve, 21 – EGR controller, 22 – air filter, 23 – oscilloscope, 24 – injector

The VILNIUS TECH car traction stand MAHA LPS 2000 was used to widen the area of research and assess the energy and ecological characteristics of the engine throughout a wide range of engine rotated speeds. The research scheme is depicted in Figure 2.3, the car traction stand is equipped with an electromagnetic brake, measuring a maximum 6 kN attractive force and 260 kW maximum brake power. The measurement error is ± 2%.

The numerical analysis of the combustion process was conducted using AVL BOOST software. The rate of heat release during combustion was calculated using pressures in the cylinder measured during tests, air and fuel consumption, properties of the fuel used, and engine parameters. The following combustion process indicators were set: the start of combustion, in-cylinder temperature, in-cylinder temperature rise, and in-cylinder pressure rise. The mentioned combustion process parameters helped to analyse environmental and energy indicators using conventional diesel, hydrotreated vegetable oil, and hydrotreated vegetable oil and biobutanol mixtures.

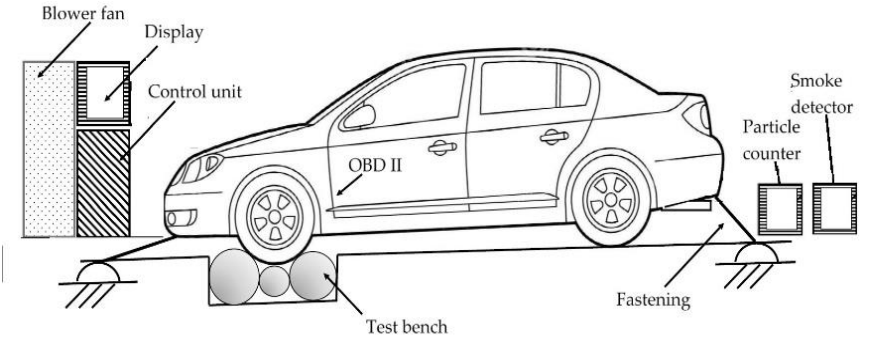


Fig. 2.3. Car traction stand with particle counter and smoke detector equipment (compiled by the author)

During the experimental tests, using ROSS-TECH VCDS car diagnostic equipment, data reading was performed when connected to the OBDII link of the electronic control unit to evaluate the following parameters: fuel consumption, turbocharger pressure, and fuel injection time. This diagnostic equipment was used to capture data at approximately every 2.5-second intervals.

Upon analysing the data from the engine's ECU, it was observed that the recorded data points were transmitted in distinct blocks and lacked precise synchronisation in time. These data points include engine speed (rpm), cyclic fuel quantity (mg/cycl), cyclic air mass (mg/cycl), fuel injection timing (BTDC), turbocharger pressure (mbar), and fuel injection timing (mg/cycl).

During the research, the P-Trak ultrafine particle counter 8525 was additionally used in the car traction stand (their description is given in (Rimkus

et al., 2019)) to measure the concentration of particles with an aerodynamic diameter of 0.02–1 μm in the range of 0–500,000 units/cm^3. Particulate matter concentration was measured with the engine working at idle speed prior to the smoke measurement.

The estimation of diesel car emissions was conducted through the use of two distinct methodologies, namely, the measurement of exhaust gas smoke and the assessment of particulate matter concentration. The smoke detector CET2200C was used to measure smoke by determining the light absorption coefficient. This coefficient indicates the extent to which light emitted from the meter source is absorbed by the smoke emitted from the vehicle. The measurement limits of the smoke meter range from 0 to 99.99 m^{-1}, with an accuracy of 0.01 m^{-1}.

2.3. Combustion analysis methodology

AVL BURN program was used for combustion analysis (*Theory "AVL BOOST VERSION 2011,"* 2011). The heat release rate was obtained from measured cylinder pressure curves. Using the AVL BOOST combustion model, in-cylinder pressure and temperature were calculated based on the heat release rate determined during the analysis. The BOOST tool was based on the algorithms used in the *BOOST* cylinder to fulfil this task.

The first law of thermodynamics for high-pressure cycle states that the change of the internal energy in the cylinder is equal to the sum of piston work, fuel heat input, wall heat losses and the enthalpy flow due to blow-by:

$$\frac{d(m_c \cdot u)}{d\alpha} = -p_c \cdot \frac{dV}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum \frac{dQ_w}{d\alpha} - h_{BB} \cdot \frac{dm_{BB}}{d\alpha} + \sum \frac{dm_i}{d\alpha} \cdot h_i - \sum \frac{dm_e}{d\alpha} \cdot h - q_{ev} \cdot f \cdot \frac{dm_{ev}}{dt}. \quad (2.1)$$

The variation of the mass in the cylinder calculated from the sum of the in-flowing and out-flowing masses, is shown in equation (2.2)

$$\sum(dm_c)/(d\alpha) = \sum(dm_i)/(d\alpha) - \sum(dm_e)/(d\alpha) - (dm_{BB})/(d\alpha) + (dm_{ev})/(dt), \quad (2.2)$$

where: $(d(m_c \cdot u))/d\alpha$ – change of the internal energy in the cylinder; $-p_c \cdot (dV/d\alpha)$ – piston work; $dQ_f/d\alpha$ – fuel heat input; $\sum(dQ_w/d\alpha)$ – wall heat losses; $h_{BB} \cdot (dm_{BB}/d\alpha)$ – enthalpy flow due to blow-by; m_c – mass in the cylinder; u – LHV; p_c – cylinder pressure; V – cylinder volume; Q_F – fuel energy; Q_w – wall heat loss; α – crank angle; h_{BB} – enthalpy of blow-by; $dm_{BB}/d\alpha$ – blow-by mass flow; d_{mi} – mass element flowing into the cylinder; d_{me} – mass element flowing out of the cylinder;

h_i – enthalpy of the in-flowing mass; h_e – enthalpy of the mass leaving the cylinder; q_{ev} – evaporation heat of the fuel; f – fraction of evaporation heat from the cylinder charge; m_{ev} – evaporating fuel.

The rate of heat release was only calculated during the high-pressure phase with all valves closed, so typically, from the intake valve closed to the exhaust valve opened.

2.4. Theoretical investigation of research errors

The primary objective of managing measurement results is to get the most precise measurement outcome and assess its margin of error. The precision of the measurement is contingent upon the quantity of experimental data, the characteristics of the distribution of measurement errors, the methodology used for measurement, the intricacy of the computation, and the desired expeditiousness in presenting the outcomes.

The standard deviation is the square root of the variance and so computed by:

$$s_y = \sqrt{\frac{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}{n-1}}. \tag{2.3}$$

Note that $y_i - \bar{y}$ is the deviation of the i th value from the sample mean, so the numerator is the sum of squared deviations (JCGM, 2008).

The standard error of a statistic quantifies the level of accuracy associated with the statistic. The standard error of the mean quantifies the level of accuracy in estimating the mean. The standard error of a difference in means quantifies the level of accuracy in estimating the difference between means. A lower standard error indicates a higher level of precision in the estimate. The standard error of the mean (SEM) is computed as:

$$SEM = \frac{S_y}{\sqrt{n}}. \tag{2.4}$$

The SEM is often denoted S_y to indicate that it is a standard deviation of the mean $\bar{y}$.

In this case, uncertainties are used as an SEM indicator (JCGM, 2008). Uncertainty refers to the discrepancy in estimating a parameter, such as the average of a sample, the disparity in averages between two experimental treatments, or the anticipated outcome given a certain alteration in the circumstances (JCGM, 2008). Uncertainty is quantified using either the variance

or its square root, known as the standard deviation. The standard deviation of a statistic is usually referred to as a standard error.

2.5. Methodology for the calculation of the Pearson's correlation coefficient

Several coefficients are appropriate under different circumstances. Among them, one the Pearson's product-moment correlation coefficient is used the most frequently.

The Pearson's correlation coefficient measures linear relationships between two variables. The σ_X and σ_Y are the standard deviations of two random variables, X and Y, respectively. Then, the Pearson's product-moment correlation coefficient between the variables (Bowerman & O'Connell, 1997) is as follows:

$$\rho_{X,Y} = \left(\operatorname{cov}\left(X,Y\right)\right)/\left(\sigma_X \sigma_Y\right) = \left(E\left(\left(X - E\left(X\right)\right)\left(Y - E\left(Y\right)\right)\right)\right)/\left(\sigma_X \sigma_Y\right), \quad (2.5)$$

where $E(X, Y)$ denotes the expected value of the variable and cov(X, Y) means covariance.

The interval data comes from paired observations, and the variables are normally distributed (Weisberg, 2014). The data does not contain any extreme values which are apt to affect the result.

The covariance matrix of linear regression is calculated by:

$$\begin{bmatrix} Cov\left(\beta_0,\beta_0\right) & Cov\left(\beta_0,\beta_1\right) \\ Cov\left(\beta_1,\beta_0\right) & Cov\left(\beta_1,\beta_1\right) \end{bmatrix} = \sigma^2 \frac{1}{SXX} \begin{bmatrix} \sum x_i^2 / n & \bar{x} \\ \bar{x} & 1 \end{bmatrix}. \quad (2.6)$$

The correlation between any two parameters is:

$$\rho\left(\beta_i,\beta_j\right) = \left(Cov\left(\beta_i,\beta_j\right)\right)/\left(\sqrt{Cov\left(\beta_i,\beta_i\right)}\sqrt{Cov\left(\beta_j,\beta_i\right)}\right). \quad (2.7)$$

For a particular value x_p, the 100(1-α)% confidence interval for the mean value of y at $x = x_p$ is:

$$\hat{y} \pm t_{\left(\alpha/2,n^*-1\right)} = S_t \sqrt{1 + (1/n) + (x_P - x)^2 / SXX)}. \quad (2.8)$$

Assuming the pair of variables (X, Y) follows the bivariate normal distribution. Examine the correlation between the two variables using a confidence ellipse (Press, 1992). The confidence ellipse is centred on ($\bar{X}$,$\bar{Y}$), and the major semiaxis a and minor semiaxis b equal:

$$a = c\sqrt{(\sigma_X^2 + \sigma_Y^2 + \sqrt{\left(\sigma_X^2 - \sigma_Y^2\right)^2 + 4r^2\sigma_X^2\sigma_Y^2}) / 2}; \quad (2.9)$$

$$b = c\sqrt{(\sigma_X^2 + \sigma_Y^2 - \sqrt{\left(\sigma_X^2 - \sigma_Y^2\right)^2 + 4r^2\sigma_X^2\sigma_Y^2}) / 2}. \quad (2.10)$$

For a given confidence level of (1-α), the constant c is:
1) Confidence ellipse for the population mean:

$$c = \sqrt{((2(n-1)/n(n-2))\left(\alpha^{(2/(2-n)} - 1\right)}; \quad (2.11)$$

2) Confidence ellipse for prediction:

$$c = \sqrt{(2(n+1)(n-1))/(n(n-2))\left(\alpha^{(2/(2-n))} - 1\right)}. \quad (2.12)$$

The inclination angle of the ellipse is:

$$\beta = (1/2)\arctan(2r\sqrt{\sigma_X^2\sigma_Y^2}) / (\sigma_X^2 - \sigma_Y^2). \quad (2.13)$$

Calculations have been conducted according to Formula (2.5–2.13), and the results are shown in Figures 3.13–3.15. Overall, Pearson's product-moment correlation coefficient is a reliable statistical tool used to evaluate linear correlations between variables. Its effectiveness is backed by extensive computations and graphical representations. The findings provide a strong basis for comprehending the complex relationships between paired observations and allow for precise predictions using confidence ellipses.

2.6. Conclusions of the Second Chapter

1. The precise ratios of HVO and biobutanol fuel blends were carefully chosen based on their favourable physical-chemical characteristics. The careful selection of this approach serves as the foundation for the research's goal to enhance engine efficiency and minimise ecological consequences. This showcases the potential of these biofuel blends as feasible substitutes for sustainable energy solutions.
2. Experimental research of HVO and biobutanol fuel mixtures involved selecting, classifying, and approving techniques for energy, combustion, and ecology changes in compression ignition engines.

3. The obtained experimental results confirmed the reliability and validity of the theoretical investigation data.
4. Pearson's correlation method was used to estimate the parameters of the test results and to establish the interdependence between them, allowing the approximation of continuous data on engine performance by quantifying linear correlations.

3

Experimental results of a compression ignition engine fuelled with hydrotreated vegetable oil and biobutanol fuel mixtures

This chapter presents an analysis of ecological and energy indicators conducted to investigate the effects of employing HVO and biobutanol fuel mixtures on compression ignition in internal combustion engines. The start of injection was regulated by ECU, according to the provided engine manufacturer's algorithm. Energy indicators *BTE, BSFC* and combustion characteristics, including *SOI, SOC, ROHR* and the ecological factors, including smoke, NOx, CO_2, and PN, depend on the specific fuel mixture used. The correlation parameters for engine parameters using various fuel mixtures have been reported. The main research results of this chapter were published in the author's publications (Valeika et al., 2021; Valeika et al., 2022; Valeika et al., 2023; Valeika et al., 2024).

3.1. Compression ignition engine energy and ecological indicators

The tests were performed at the Laboratory of Transport Engineering and Logistics of Vilnius Gediminas Technical University (VILNIUS TECH) in 2020–2022. The Investigation methodology is presented in the Second Chapter. The first part of this subsection researched and described combustion and energy indicators of CI. The second part detailed results and description of ecologic characteristics research on CI engines

During research, the engine speed and load remained constant. Variations were observed in ecological and energy indicators, as observed in experimental research conducted on a CI engine fuelled by several mixtures, namely, conventional diesel D100, HVO100, HVOB5, HVOB10, and HVOB20. Experimental trials were performed under the condition of a consistent rotated speed of the crankshaft, denoted as n = 2000 rpm. Engine loads of 30 Nm, 60 Nm, 90 Nm, and 120 Nm were deliberately chosen to replicate engine speeds approximately equivalent to 50 km/h, 80 km/h, 100 km/h, and 110 km/h, respectively. Additionally, different rates of EGR were employed, specifically 0%, 10%, 20%, and 30%.

3.1.1. Research on the combustion and energy characteristics of the compression ignition engine

The research compares ignition timing and ignition delay between D100 and HVOB20 fuels, focusing on the difference in brake mean effective pressure and exhaust gas recirculation rate (Fig. 3.1). Indicators of the combustion process were determined based on the experimental data and using the AVL BOOST program. D100 fuel had 2.4 CAD BTDC ignition timing, and HVOB20 had 0.2 CAD BTDC timing, resulting in a 2.2 CAD delay.

The start of injection was regulated by ECU, according to the provided engine manufacturer's algorithm. The start of combustion values varied between D100 and HVOB20. HVOB20 had a significantly higher combustion delay than D100 due to the elevated cetane number. The biobutanol ratio increased ignition delay values, with HVOB20 showing the highest value at approximately 4.2 CAD ATDC. *SOI* values for D100 and HVOB20 increased with an EGR rate from 0% to 30%, resulting in varying ignition timings. HVO100 usage reduced delay time by 1.3 CAD, while delay values showed mild incremental tendencies as the EGR rate increased.

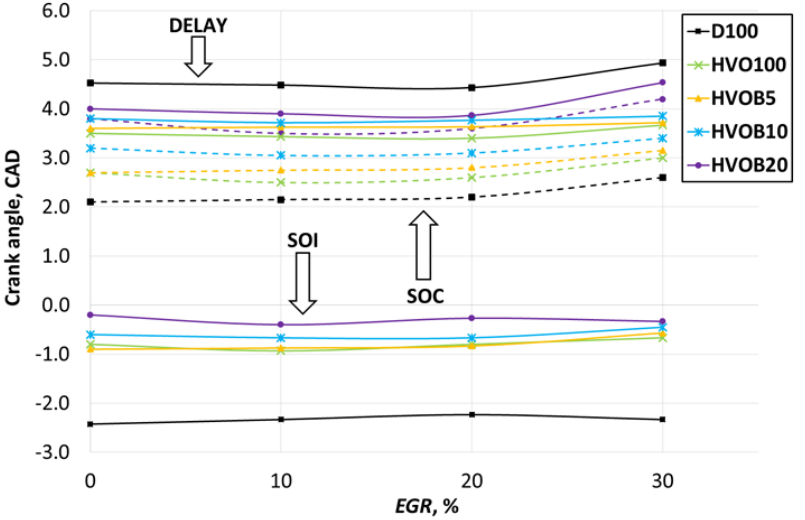


Fig. 3.1. *SOI*, *SOC* and combustion delay depending on fuel composition at different EGR rates

The shown *ROHR* values were compared to those of conventional diesel (Fig. 3.2). When the EGR rate was increased to 30%, more intense *ROHR* changes were as follows: during the premixed combustion phase, the use of EGR at a rate of 30% resulted in comparison to the absence of EGR (0%). The *ROHR* in D100 had a 16% drop, whereas it decreased 13% in HVO100. In HVOB5, it declined by 2%; in HVOB10, it decreased by 20%; and in HVOB20, it decreased by 21%. The variation in *ROHR* values during the controlled combustion phase reduced as the EGR rate increased to 30%. Specifically, in D100, the value fell by 4.8%. Similarly, HVO100 declined by 12%, HVOB5 by 10%, HVOB10 by 7%, and HVOB20 by 4.6%.

At EGR 0% and engine load 0.4 MPa (Fig. 3.3), the *BTE* value decreased by approximately 1.4%, with a *BTE* value ranging from ~0.301 to ~0.297 when HVOB20 was used and compared to D100. When the EGR rate in HVO fuel varied from 0% to 30%, it affected *BTE* in engine load variations. When EGR was set to 0%, HVO100 had a 0.2 to 0.4% higher *BTE* than D100. However, the trend in *BTE* decreases when transitioning from a 5% biobutanol concentration to a 20% concentration. For comparison, EGR 30% and EGR 0% *BTE* values decrease by 4% with HVOB20 compared to D100.

This situation can be explained by lower HVO and biobutanol $LHV_{\_V}$ values (MJ/l) (Table 2.1): D100 36.09 MJ/l, and with HVO100 ~5%, HVOB5 ~6%, HVOB10 ~7%, and HVOB20 ~9% less compared to D100. $LHV_{\_V}$ difference compared to $LHV_{\_m}$ was determined by fuel density, which was ~ 7.5%, ~7.0%, ~6.5%, and ~6.0% lower for HVO100, HVOB5, HVOB10, and HVOB20,

respectively, compared to D100. Caused by lower $LHV_{\_V}$ under different engine loads and with changing EGR rates, $BSFC_{\_V}$ values of HVO100, HVO and biobutanol blends were in all cases higher compared to D100.

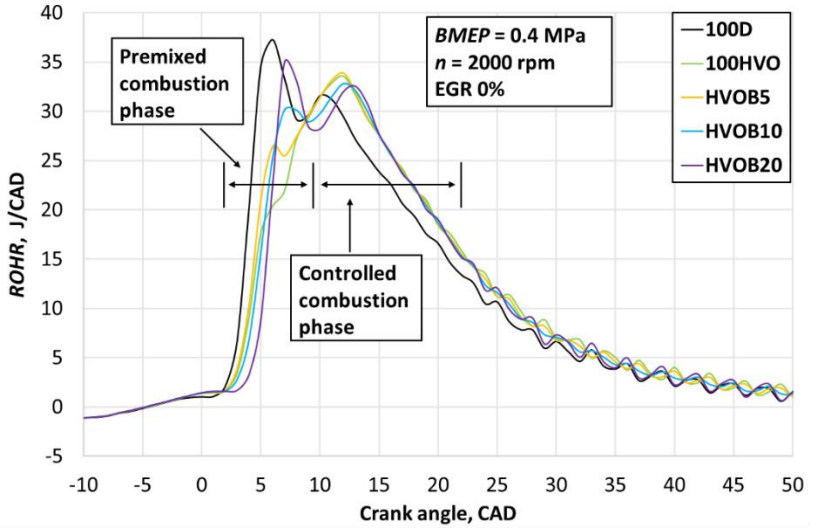


Fig. 3.2. *ROHR* depending on fuel composition

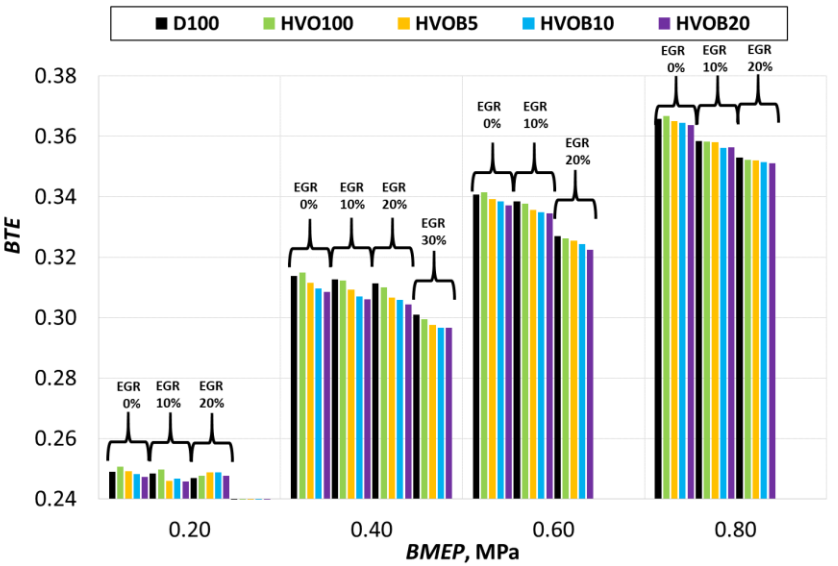


Fig. 3.3. Dependence of brake thermal efficiency on fuel composition and the engine load at different EGR rates

The research findings indicate that the $BSFC\_m$ of the CI engine is consistently lower when using HVO100 fuel compared to D100 fuel, regardless of the engine load and EGR rate. This is seen in Figure 3.4. The inclusion of biobutanol (increased from 10% to 20%) in HVO resulted in a greater $BSFC\_m$ compared to D100. The findings from the fuel research (Table 2.1) indicate that the lower heating value of HVO100 by mass (MJ/kg), referred to as LHV_m, was 2.3% more than that of D100. Lower LHV_m values corresponded to greater $BSFC$_m values. The LHV_m of the HVOB5 fuel mix was just 1% higher, whereas the LHV_m value of HVOB20 was 2.8% lower compared to D100. When analysing the relationship between the change in $BSFC\_m$ and D100, it was noted that the consumption of HVO100 fuel reduced by about 2.5% at *BMEP* 0.4 MPa and EGR 0%, however, for HVOB20, it rose by approximately 5% (from ~266 g/kWh to ~279 g/kWh). When the EGR rate was set at 30%, the $BSFC\_m$ of HVO100 fuel was reduced by about 2%. When HVOB5 fuel was used, the $BSFC\_m$ was the same as that of D100 fuel. However, when HVOB20 fuel was used, the $BSFC\_m$ rose by approximately 4.5% (from ~277 g/kWh to ~290 g/kWh) compared to conventional diesel. At *BMEP* of 0.4 MPa, the $BSFC\_m$ values showed an increase when comparing the values of EGR at 30% and EGR at 0%. The D100 value rose by 4%. Additionally, when using HVO100 fuel, the increase was 5%, and when using HVOB20 fuel, the increase was 4%. The alteration in $BSFC$_m was influenced by both LHV_m and the braking thermal efficiency of the engine running cycle (Fig. 3.3), which is contingent upon the combustion process.

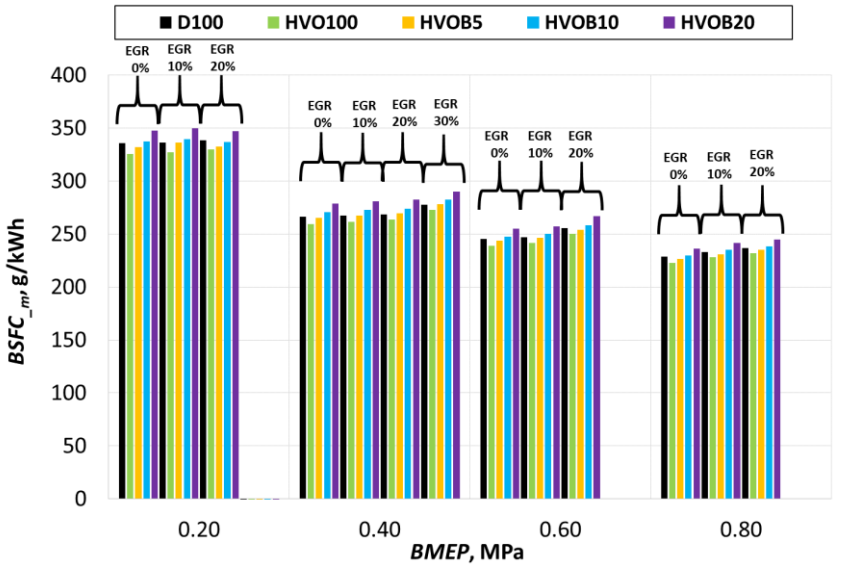


Fig. 3.4. Dependence of *BSFC* by mass on fuel composition and the engine load at different EGR rates

The car traction stand data shows that over the entire engine speed range, replacing conventional diesel with HVO and biobutanol mixtures results in a reduction in engine power (Fig. 3.5) up to 20% (with 20% biobutanol). To maintain the manufacturer's rated power, the cyclic injection volume should be increased according to the formula:

$$V_{cycl(mix)} = \frac{BTE_{mix} \cdot V_{cycl(D100)} \cdot LHV_{V(D100)}}{LHV_{V(mix)} \cdot BTE_{D100}}, \quad (3.1)$$

where: BTE_{mix} – fuel mixture brake thermal efficiency; $V_{cycl(D100)}$ – conventional diesel cyclic fuel injection volume, ml; $LHV_{V(D100)}$ – conventional diesel lower heating value by volume, MJ/l; $LHV_{V(mix)}$ – fuel mixture lower heating value by volume, MJ/l; BTE_{D100} – conventional diesel brake thermal efficiency.

Analysing a broad spectrum of engine rotated speed, it was discovered that the *BTE* value of HVO100 exhibited an approximate increase of 26% compared to D100, within the engine speed range of 1500 rpm to 4500 rpm (Fig. 3.5). At 1500 rpm, an increase in biobutanol concentration in HVO fuel improved *BTE* by 19% to 22% compared to D100.

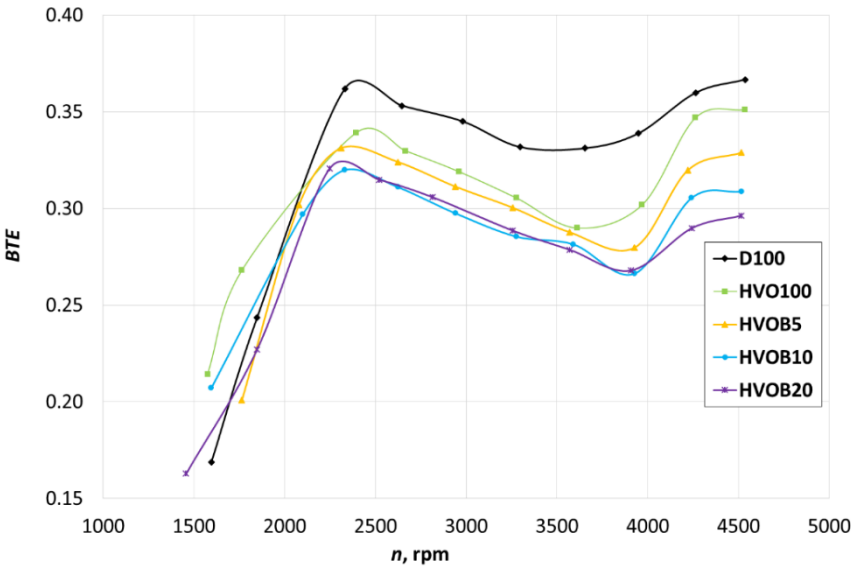


Fig. 3.5. Dependence of brake thermal efficiency on fuel composition at different engine speeds

However, a 20% biobutanol concentration resulted in a 3.5% decrease in *BTE* value compared to D100. The influence of biobutanol on *BTE* decreased as engine speed rose. At 4500rpm, the *BTE* of D100 decreased by 4.4%. Increasing biobutanol concentration in HVO from 5% to 20% resulted in a noticeable decrease in *BTE* value. HVOB20 also showed a 20% decrease in *BTE* value. The incorporation of hydrogenated vegetable oil and different mixtures of HVO and biobutanol, along with an increase in engine rpm, demonstrates a noticeable negative effect of biobutanol on *BTE*.

3.1.2. Research on the ecologic characteristics of the compression ignition engine

The use of HVO100 and mixtures of HVO and biobutanol resulted in a progressive reduction in smoke levels, as depicted in Fig. 3.6. Based on the analysis of the EGR impact, the usage of HVO100 and HVO/biobutanol fuel mixtures exhibited reduced smoke emissions in comparison to D100 under similar load and EGR conditions. The experiment revealed that when the EGR rate was raised from 0% to 30% under a consistent engine load *BMEP*, there was a noticeable rise in smoke emissions.

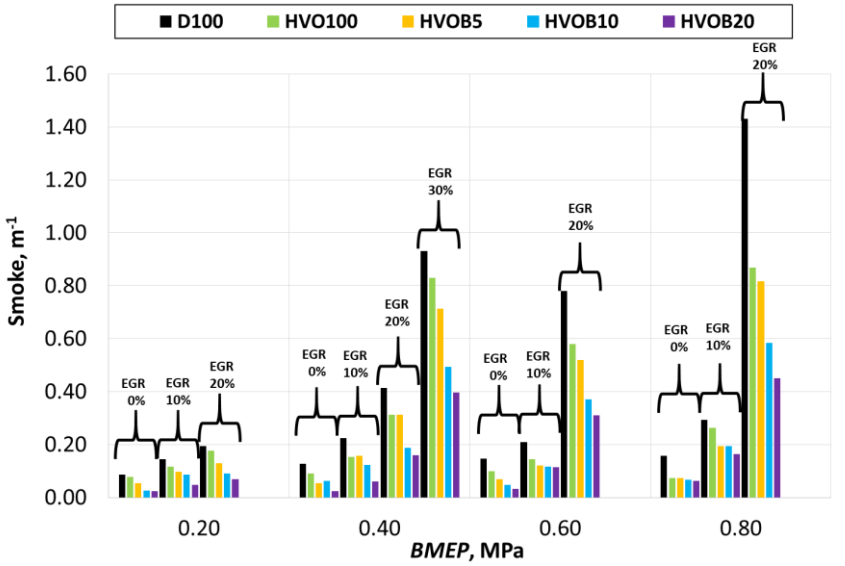


Fig. 3.6. Dependence of smoke on fuel composition and engine load at different EGR rates

This is attributed to a reduction in O_2 levels and an increase in CO_2 and H_2O vapour within the cylinder. At a consistent engine load of 0.4 MPa and EGR off, the smoke emissions of HVO100 exhibited a reduction of around 29% (from ~0.13m^{-1} to ~0.02m^{-1}) compared to D100. Similarly, HVOB20 showcased a substantial decrease of almost 80%.

The EGR rate significantly impacts Smoke emissions at a pressure of 0.4 MPa. An increase in EGR rate results in a six-fold increase in smoke emissions when using conventional diesel. However, when using hydrotreated vegetable oil and biobutanol mixtures, smoke output decreases by approximately 57% (from ~0.93m^{-1} to ~0.4m^{-1}, when BMEP 0.4 MPa, EGR 30%), compared to D100. This suggests that HVO and biobutanol mixtures improve smoke reduction performance when combined with a lower EGR rate, while a greater EGR rate reduces the beneficial effects of biobutanol on smoke reduction.

The experimental research found that D100 had the highest levels of NO_X emissions, while HVO100 had the lowest levels (Fig. 3.7). When biobutanol concentration in HVO fuels was increased, NO_X emissions increased across all engine loads and EGR rates, but NO_X emissions were not higher than with D100. Comparing NO_X emissions between HVO100 and mixtures with biobutanol and D100 at a *BMEP* of 0.4 MPa and an EGR rate of 0%, HVO100 showed a 7% (from ~3.32 g/kWh to ~3.08 g/kWh) reduction in NO_X emissions.

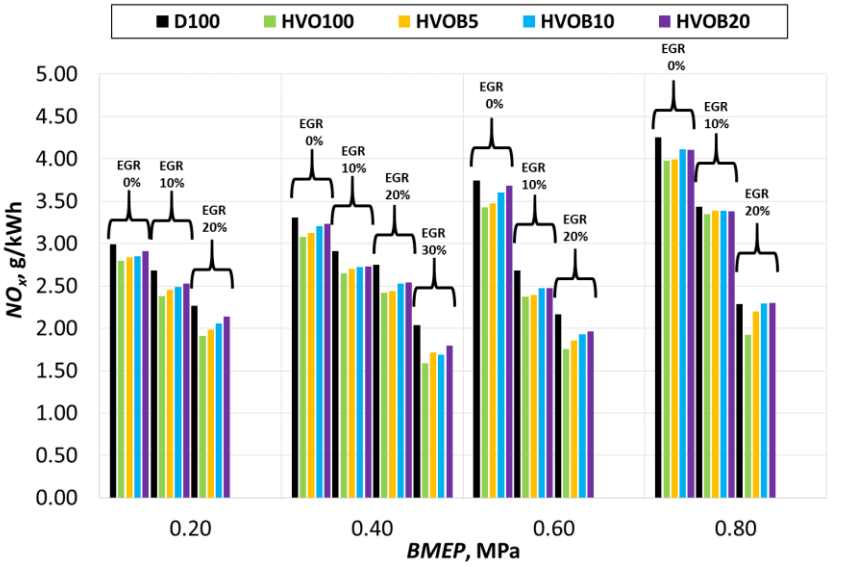


Fig. 3.7. Dependence of NO_x emissions on fuel composition and engine load at different EGR rates

The reduction of nitrogen oxide emissions is achieved by increasing the EGR rate (Fig. 3.7), which involves reintroducing carbon dioxide, water vapour, and other combustion byproducts into the cylinder. This process decreases combustion intensity and temperature, reducing nitrogen oxide generation. At an EGR level of 30%, HVO100 and HVOB20 fuels showed a 22% and 12% NO_X emission reduction, respectively.

CO_2 is a significant environmental parameter contributing to the greenhouse effect and is formed through the combustion of hydro-carbons used as fuel. The carbon content in the fuel and the quantity consumed influence CO_2 emissions. The research found that substituting D100 with HVO100 resulted in a variation in engine load and reduced CO_2 emissions by 2 to 3% when the EGR rate was set at 0% (Fig 3.8). Increasing the concentration of biobutanol in HVO from 5% to 20% also decreased CO_2 emissions, with HVOB20 exhibiting a decrease from 2.4% to 6.4% compared to D100.

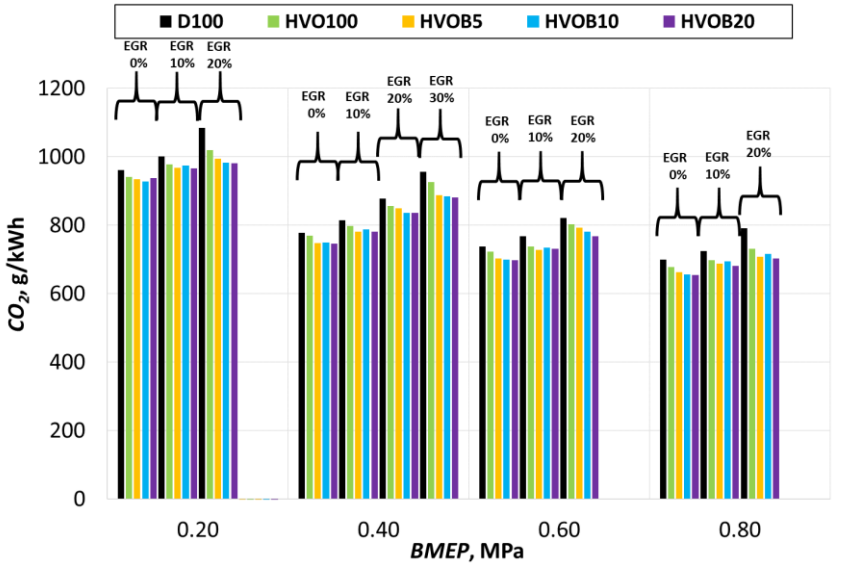


Fig. 3.8. Dependence of CO_2 emissions on fuel composition and engine load at different EGR rates

Under conditions of a consistent engine load, where the *BMEP* is maintained at 0.4 MPa, and the EGR is set at 30%, it was observed that the CO_2 emissions in HVO100 were reduced by around 3.2%. Similarly, in HVOB20, the CO_2 emissions decreased by approximately 7.8% (from ~955 g/kWh to ~880 g/kWh) compared to D100. The findings from the CO_2 investigation indicate that including a maximum of 20% of HVO in fuel leads to a reduction in CO_2

emissions. Despite the observed reduction in CO_2 values when using HVO100 and HVO biobutanol mixtures, a rise in CO_2 emissions occurs when the EGR rate is raised from 0% to 30%. This is attributed to a drop in the engine's *BTE* (Fig. 3.3) and an increase in $BSFC_{\_m}$ (Fig. 3.4).

The experimental research findings demonstrated that across various engine loads and varying EGR rates, the HC emissions in HVO100 were consistently lower than those in D100 (Fig. 3.9). This may be attributed to the decreased C/H ratio and reduced fuel mass consumption of HVO100. Introducing biobutanol into HVO at an EGR rate of 0% resulted in an elevation in HC emissions across all engine loads. The use of the HVOB20 fuel mix resulted in elevated HC emissions in comparison to traditional diesel fuel. Lower fuel viscosity may be linked to HC emissions.

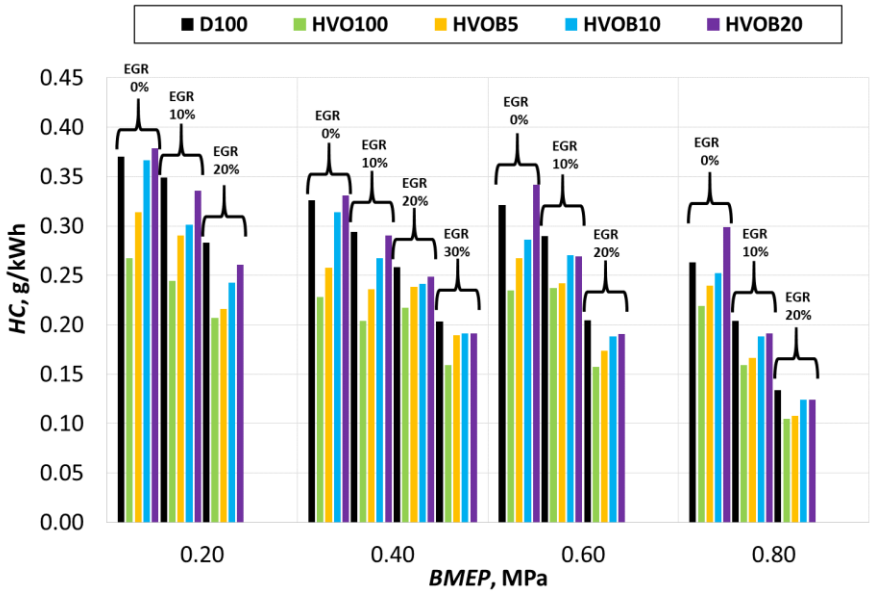


Fig. 3.9. Dependence of HC emissions on fuel composition and engine load at different EGR rates

When elevating the EGR rate from 10% to 30%, the emission of HC decreases due to the improved evaporation of fuel, resulting from its injection of higher temperature. When HVO100 is used instead of D100, HC emissions are consistently reduced. Nevertheless, the introduction of biobutanol into HVO and raising the biobutanol content to 20% leads to an increase in HC emissions across all engine loads, albeit the emissions remain below those of D100. Under a constant engine load of 0.4 MPa and EGR off, the emissions of HC) from

HVO100 fall by about 30% (from ~0.33 g/kWh to ~0.23 g/kWh) compared to D100. However, while using HVOB20, the HC emissions are around 1.6% higher than those of D100. When examining the impact of EGR on HC emissions at a BMEP of 0.4 MPa, it was seen that raising the EGR rate resulted in a drop in HC emissions. Specifically, when comparing an EGR rate of 30% to an EGR rate of 0%, the following reductions were observed: D100 reduced by 13%, HVO100 decreased by 0.5%, and HVOB20 decreased by 17%.

The findings derived from the research provide a basis for substantiating the potential of second-generation biofuels, considering their impact on smoke emissions and particulate matter concentration. Upon analysing the data on smoke levels (Fig. 3.10), a clear reduction in smoke was observed in comparison to regular diesel.

The presence of oxygen in biobutanol initiated the enhancement of the combustion process. However, the inclusion of biobutanol at concentrations of up to 5% did not significantly impact smoke values. An intriguing phenomenon was observed when evaluating smoke emissions using diesel fuel after experiments involving bio-fuel mixtures.

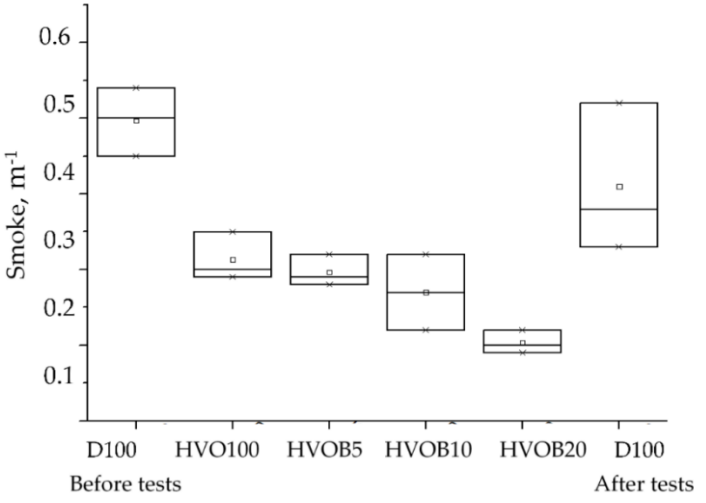


Fig. 3.10. Scattering of smoke readings using different biofuel mixtures

The use of biofuel mixtures facilitates the purification of the exhaust system by decreasing smoke emissions. Overall, the use of biofuel mixtures significantly reduces smoke in vehicles. Specifically, the impact of fuelling diesel (D100 After Tests) in comparison to D100 exhibited a reduction of 18%.

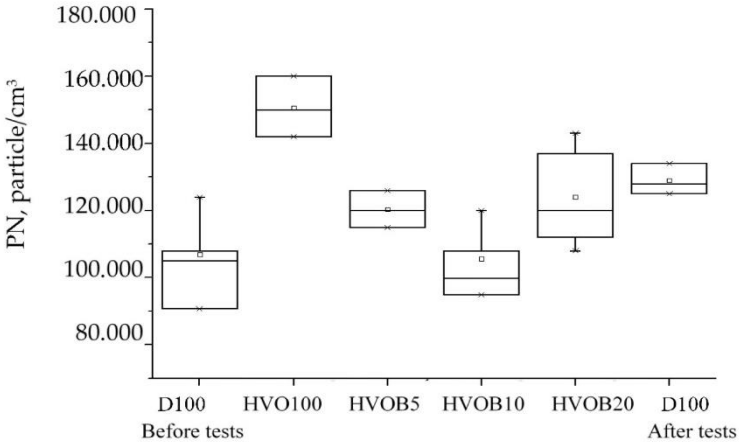


Fig. 3.11. Scattering of PN readings using different biofuel mixtures

The analysis of the overall concentration of PN, ranging from 0.02 to 1 μm, yields contrasting findings compared to the assessment of smoke. The fuel that yielded the greatest PN value was HVO 100 (Fig. 3.11). However, the presence of biobutanol reduces the concentration of particles, leading to two primary hypotheses. HVO's physical properties are enhanced by the addition of biobutanol to its chemical reactions, resulting in a reactive fuel additive with volatile and efficient evaporation characteristics. This makes it suitable for stable mixes with reduced stratification tendencies, as supported by HVOB20 findings indicating the greatest particle dispersion per cubic centimetre. However, diesel and biofuel mixtures do not show significant differences in particle concentrations. Therefore, increasing biobutanol content increases particle dispersion and potentially generates minute particles.

3.2. Assessment of errors in results from experiments and a theoretical perspective

Analysis of errors (Figs. 3.12.–3.14., 3.15.–3.18.) demonstrated a relationship between the concentration of biobutanol in HVO mixtures and the errors in energy and ecological parameters, except for smoke during engine testing.

As a result of the enhanced evaporation of biobutanol, there was an increase in the formation of PN, leading to a corresponding rise in errors of ~14%. As the concentration of biobutanol increased, there was a corresponding increase in the occurrence of larger HC errors, respectively, ~5%, ~7% and ~14%. Similarly, the

inaccuracies in exhaust gas temperature rose as the absolute value of this parameter grew.

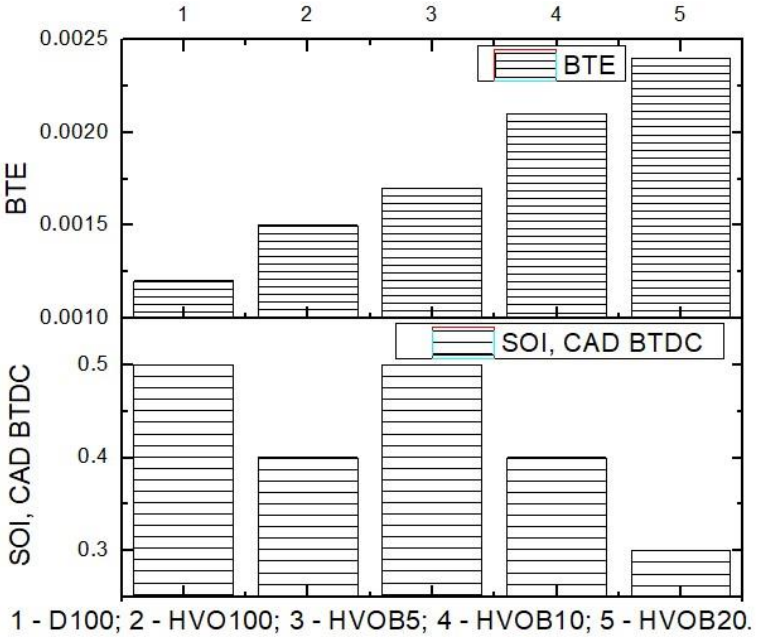


Fig. 3.12. Results of the theoretical research: *SOI* and *BTE*

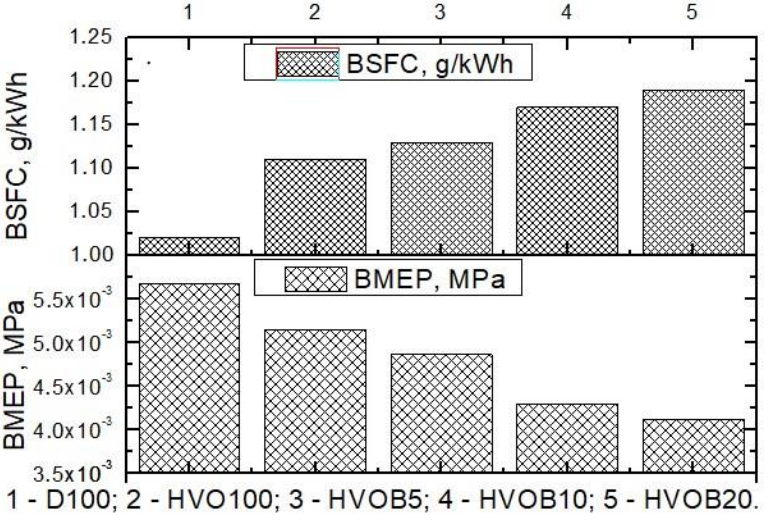


Fig. 3.13. Results of the theoretical research: energy indicators (*BMEP* and *BSFC*)

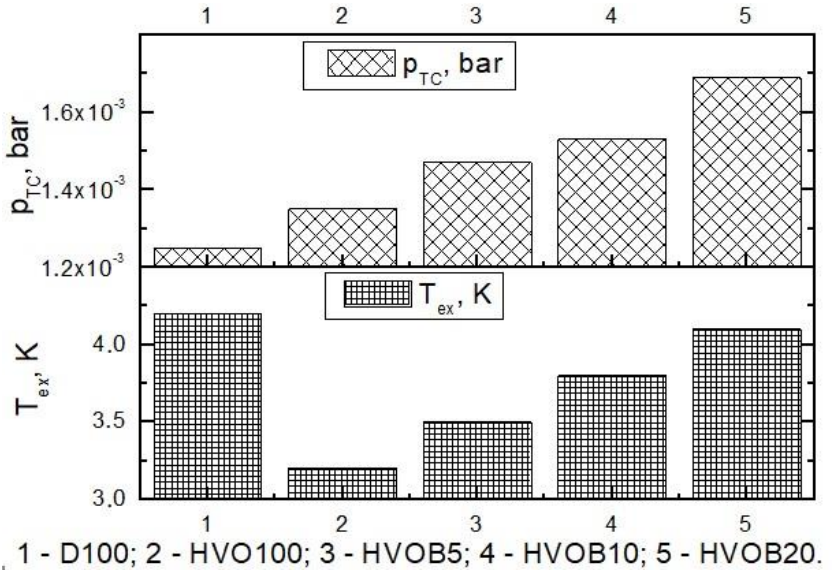


Fig. 3.14. Results of the theoretical research: T_{ex} and p_{TC}

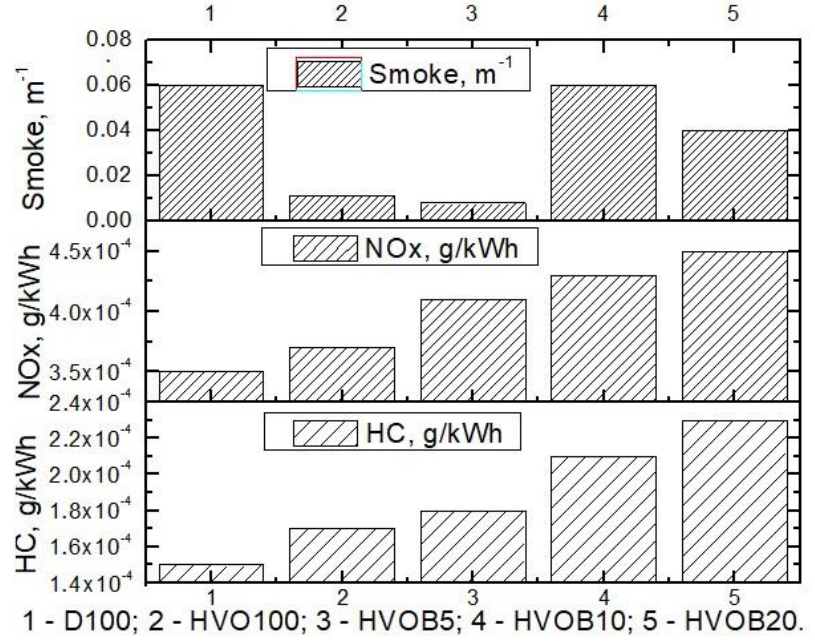


Fig. 3.15. Results of the theoretical research: environmental indicators (HC, NO_X, Smoke)

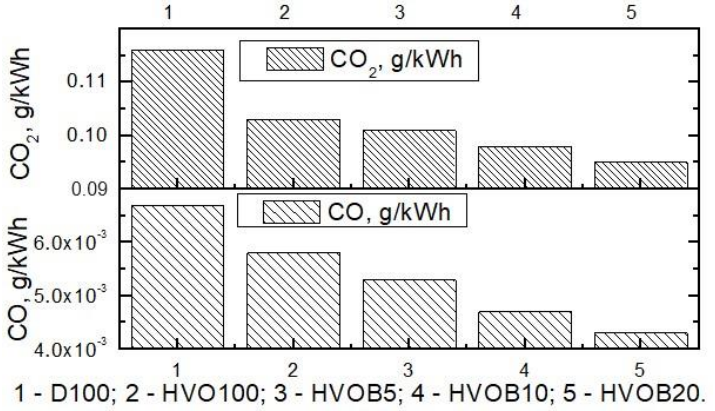


Fig. 3.16. Results of the theoretical research: environmental indicators (CO, CO_2)

The evaluation of NO_X errors demonstrates a correlation between rising biobutanol content and greater temperature trends. The improved combustion process in biobutanol is attributed to the extra oxygen it contains. This extra oxygen enhances both *BTE* and p_{TC} errors by ~11% and ~5%. However, it simultaneously decreases CO_2 errors, respectively, by ~2%, ~7%, and ~12%, and CO errors, respectively, by ~7%, ~9%, and ~13%. As the absolute values of the parameter grow, the decreased calorific value of bio-butanol leads to an increase in $BSFC_m$ errors increased by ~6%. Similarly, mistakes in the *BMEP* indicator exhibit a contrasting pattern.

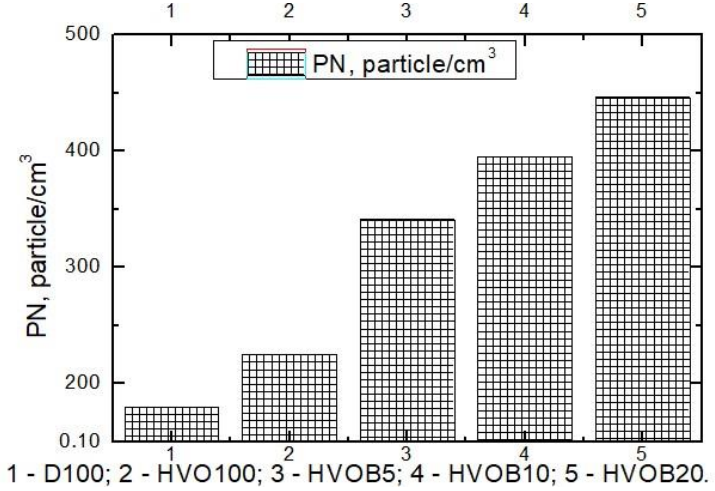


Fig. 3.17. Results of the theoretical research: environmental indicators (PN concentration on the car traction stand)

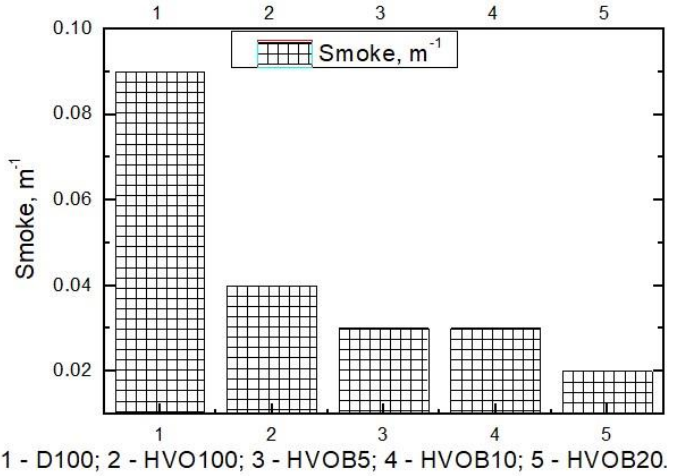


Fig. 3.18. Results of the theoretical research: environmental indicators (smoke)

During the evaluation on the traction bench, a noticeable diminishing tendency was observed as the content of biobutanol increased. However, this inclination was not detected while assessing smoke errors on the engine bench stand. No discernible patterns of change were seen in the errors of other indicators (*P*, *SOI*) when the biobutanol concentration increased.

3.3. Establishing the correlation between compression ignition engine parameters

The experimental researchshowed that fuel mixtures of HVO and biobutanol may have a substantial effect on engine performance and emissions, with clear relationships identified across several factors. These results emphasise the capacity of these biofuels to function as sustainable substitutes, providing opportunities to decrease environmental harm and comply with emission requirements.

The results were separated into parts:

1. Correlation between ecological and energy engine values; then there was the wide engine speed range.
2. Correlation between the smoke and Particular Number values.

The experiment analysed the interdependence characteristics of different fuel sources using biofuels and their mixtures and conventional diesel fuel as a benchmark for comparative comparison. Correlation dependencies were used to evaluate the effects of biobutanol concentrations on the strength of dependency,

allowing for a more accurate of the patterns of co-variation and correlations between variables. The dependencies are visually represented in Fig. 3.19 and Fig. 3.20. Upon careful examination of Fig. 3.21. (a and b), it is evident that various fuel types lead to the creation of unique inter-parameter connection patterns that are similar to those found before.

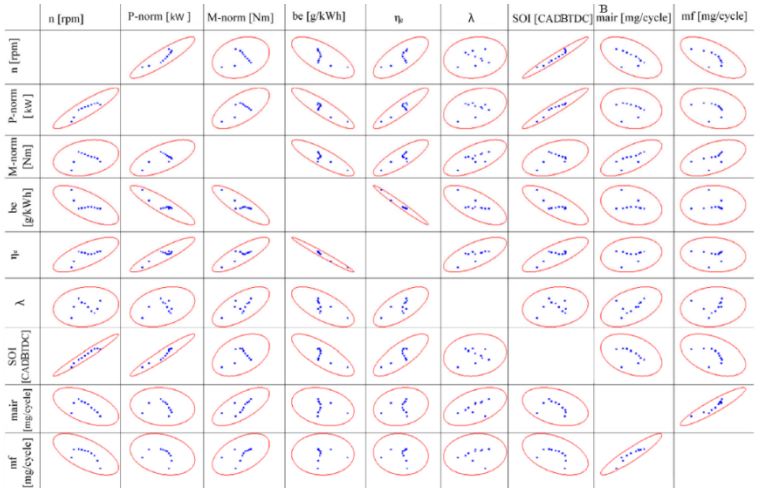


Fig. 3.19. Correlation parameters of engine parameters using D100 fuel

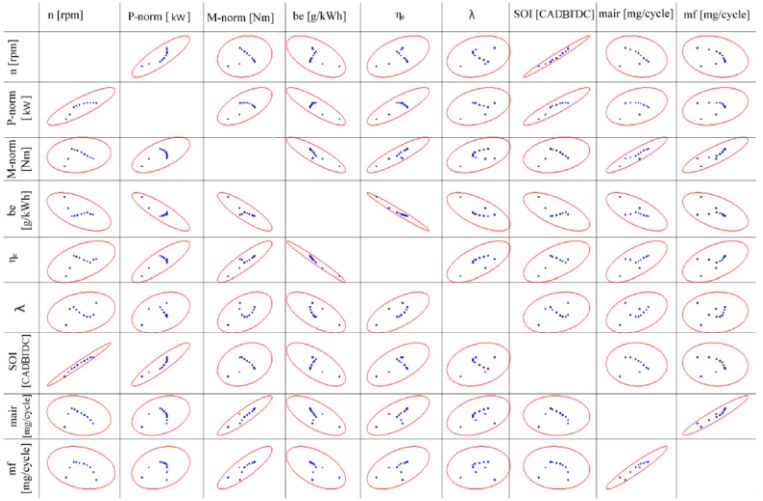
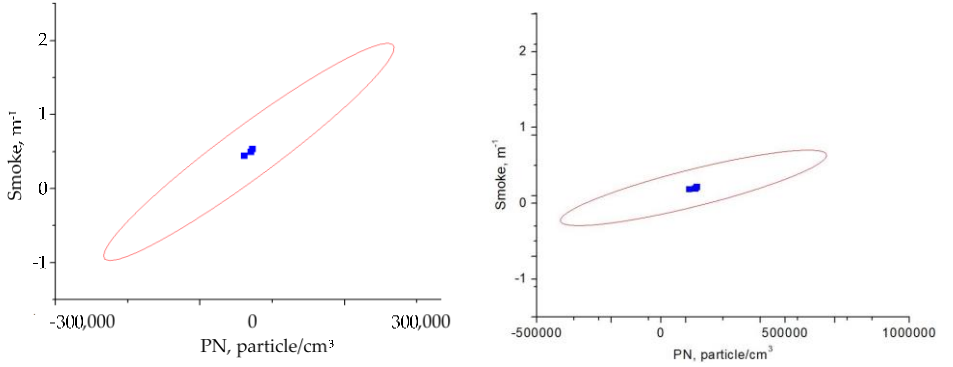


Fig. 3.20. Correlation parameters of engine parameters using HVOB20 fuel

The efficiency ratio is a crucial factor in determining the efficiency of a vehicle. It is closely linked to factors, such as rotated speed, power, engine speed, power and *SOI*, fuel consumption, and the reciprocal impacts of fuel and air masses. A strong correlation exists between engine rotated speed, power and *SOI*. Biofuels, either in their pure form or mixed with other substances, show a significant correlation between engine load, fuel quantity, and air quantity.

A robust correlation dependency was seen when comparing based on Pearson's correlation coefficients. Significant correlation values were found between D100 (Fig. 3.21.a), HVOB5, and HVOB20 (Fig. 3.21.b), indicating a close relationship. However, HVO100 fuel exhibited a somewhat weaker but still notable correlation.



a) b)

Fig. 3.21. Correlation between smoke and PN parameters using different fuels: a) D100; b) HVOB20

However, the differences between different biofuels were below 10%, indicating autonomous correlations regardless of the biofuel classification. The combination of HVO-biobutanol fuel mixtures has the potential to decrease smoke emissions. The legislation prohibits operating vehicles exceeding permissible smoke emission limits, particularly for older diesel vehicles with EURO 4 and lower emissions standards (Eur – Lex, 2019). Following the implementation of new EURO 6B and anticipated EURO 7 regulations, particle concentration and actual PN have significant importance.

3.4. Conclusions of the Third Chapter

1. The observed levels of smoke were the highest when using D100. The use of HVO100, due to the reduced C/H ratio, led to a significant

reduction of smoke by around 40%. The addition of biobutanol further enhanced these reductions.

2. At a higher EGR rate (30%), the NO_X emission was significantly reduced (~35%) and the increase in the biobutanol concentration in the mixture did not have a significant effect on the increasing NO_X emission, since the high amount of recirculated CO_2 gas significantly lowered the combustion temperature and inhibited the combustion-improving effect of the oxygen in the biobutanol.
3. When EGR 0% from HVO100, HC emissions decreased by ~30% compared to D100; from HVOB5 – by ~21%; and from HVOB10 – by ~3.7%. With HVOB20, they were ~1.6% higher compared to D100. The rise in CO and HC emissions resulted from the introduction of biobutanol, which reduced the viscosity of the fuel mixture. This led to fuel droplets reaching the periphery of the combustion chamber, where they were inappropriately mixed with air and did not burn properly.
4. The addition of biobutanol to HVO fuel mixtures increases PN and HC errors by approximately ~14%, respectively, due to increased evaporation. This increases NO_X, *BTE*, and p_{TC} errors by around ~11% and ~5%, respectively. However, CO_2 and CO errors decrease. As the amount of biobutanol in HVO fuel mixtures rises, the lower heating values fall. This causes $BSFC_{\_m}$ errors to rise by about 6%.
5. Increasing the concentration of biobutanol does not have an impact on the strength of the relationship between smoke and PN indicators. Replacing diesel with biofuels, the correlation between smoke and PN indicators decreases by 45% based on the evaluation of Pearson's correlation coefficient.

General conclusions

1. Replacement of D100 with HVO100 and biobutanol mixtures delayed *SOI* because of differences in fuel density, viscosity, and compressibility. Biobutanol's longer ignition delay is due to lower cetane number, higher latent heat of vaporisation, and auto-ignition temperature, resulting in higher maximum *ROHR* in the premixed combustion phase. However, due to a ~20% shorter HVO100 ignition delay, mixtures with biobutanol HVOB5, HVOB10 and HVOB20 had *ROHR*, which was, respectively, ~29%, ~19%, and ~5.5% lower in premixed combustion phase compared with D100 (~37 J/CAD). During the controlled combustion phase, the maximum *ROHR* increased by 6%, 8%, 5%, and 3%, respectively, due to the reduced LHV_{V} value and longer injection timing compared to D100 (~32 J/CAD).
2. *BSFC* using HVO100 was lower by ~2.5%; LHV_{m} was 2.3% higher compared to D100. Adding biobutanol to HVO, the fuel mixture's LHV_{m} decreases, and $BSFC\_{m}$ with HVOB20 is higher by ~ 5% (from ~266 g/kWh to ~279 g/kWh) compared to D100. When assessing the $BSFC\_{V}$ change, HVO100 increased by ~ 5% (from ~318 ml/kWh to ~335 ml/kWh), and HVOB20 – by ~12% compared to D100 due to LHV_{V} of HVO100, which is ~5% less compared to D100. HVO100 *BTE* was 0.2–0.4% higher as the concentration of biobutanol in HVO fuel increased (from 5% to 20%), and the *BTE* values decreased by 0.1–0.4%

compared with D100. Increasing the EGR rate decreased the *BTE* of all fuels; however, increasing the biobutanol concentration from 10% to 20% at EGR 30% stopped the decrease in *BTE*.

3. The substitution of D100 with HVO100 decreased smoke by approximately 11%. Furthermore, the addition of 5%, 10%, and 20% biobutanol to HVO reduced smoke by about 57% (from ~0.93m^{-1} to ~0.4m^{-1}), respectively, compared to D100. Reduction may be attributed to a decreased C/H ratio of the HVO and biobutanol rise in oxygen concentration within the mixture. Raising the engine load demonstrated the positive effect of biobutanol on reducing smoke emissions. Raising the EGR 30% rate resulted in a smoke rise by ~40% due to the lower combustion temperature and lower AFR.
4. The higher cetane number of HVO reduces *ROHR* intensity and combustion temperature, reducing NO_X emissions by 17–20% over the entire engine load range, comparing HVO100 to D100. Adding up to 20% of biobutanol to HVO lowers the cetane number of the fuel mixture, increases the oxygen concentration and increases the intensity of *ROHR* and the combustion temperature. At EGR 30%, the addition of biobutanol to HVO by 5%, 10%, and 20% increased NO_X emissions, respectively, by 6%, 4%, and 12% compared to HVO100 (~1.62 g/kWh), but the values were lower than that for D100 (~2.05 g/kWh).
5. Replacing D100 with HVO100 reduced CO_2 emissions by up to 3% and HC by ~30%. CO_2 emissions for HVOB20 were lower by up to 6.4%, and HC was ~1.6% higher compared to D100; this was impacted by decreased C/H ratio, which was 6.25 in D100, and 5.47 in HVO100 (12.5% lower compared to D100). The rise in HC emissions resulted from the introduction of biobutanol, which reduced the viscosity of the fuel mixture. This led to fuel droplets reaching the periphery of the combustion chamber, where they were inappropriately mixed with air and did not burn properly. When increasing EGR rate is up to 30%, CO_2 emissions increase because of increasing *BSFC* values. HC emissions decreased by 13% with D100 and with HVOB20 – by 17% (up to 0.19 g/kWh). Although EGR reduces the combustion temperature and worsens combustion, the oxygen in biobutanol maintains the combustion improvement effect (increases the combustion temperature), thus reducing HC emissions.
6. Pearson's correlation coefficients show a strong correlation (0.87 …0.99 when biofuel mixtures were used) between smoke and PN indicators in the tested compression ignition engines. After the use of biofuels, the dependence of the correlation between smoke and PN decreased by 45% compared to conventional diesel.

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A Study of Energy and Environmental Parameters of a Diesel Engine Running on Hydrogenated Vegetable Oil (HVO) with Addition of Biobutanol and Castor Oil

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Abstract: The article analyses energy and environmental operating parameters of a compression ignition internal combustion engine running on HVO-biobutanol and castor oil fuel blends, also comparing them with parameters of an engine running on convection diesel. Since biobutanol is known for poor lubrication characteristics, it was mixed with 5% of castor oil. The obtained blend of biobutanol and castor oil was mixed with HVO at 2/95, 10/90, and 20/80 v/v and fed to the compression ignition internal combustion engine. The presented physicochemical indicators justified the use of the said fuel blends. Constant engine crankshaft speed of 2000 rpm and a variable load expressed as BMEP of 0.1–0.9 MPa was selected in the research. When using the biobutanol–castor oil additive (hereafter simply biobutanol additive) in HVO, an increase in the rate of heat release (ROHR) and the convergence of its value to that of to conventional diesel fuel was observed. A decrease in BTE values was also observed with increasing biobutanol concentration in the blend. Increasing concentration of biobutanol in blends led to an increase in BSFC both in terms of volume and mass; HC and NO_x emissions grew as well, but smoke emissions declined, and no material changes in CO and CO_2 emissions were observed.

Keywords: hydrogenated vegetable oil (HVO); biobutanol; combustion; pollutant emissions; engine efficiency; mechanical engineering

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1. Introduction

Environmental problems have led to the development of second-generation biofuel production from non-food biomass. The said lignocellulose raw materials are their by-products, such as sugar cane flour, cereal straw, deforestation waste, municipal waste, and vegetative grasses, also fast-growing forests [1]. In order to reduce particulate matter emissions from diesel engines, it is important to develop new fuels, new injection strategies, and highly performing after-treatment devices, i.e., diesel particulate filters [2,3]. Devices that measure particulate matter emitted by cars are currently being renovated [4,5]. The European Union regularly updates permitted pollutant emissions and their limit values [4]. Some countries try to switch from diesel to electric cars as soon as possible due to stricter restrictions on emissions imposed by legislation [6,7].

The EU White Paper and the Europe 2020 Strategy laid down therein provides for the flagship initiative "Resource-Efficient Europe" and the energy efficiency plan of 2011, the main aim of which is to create conditions for promoting European economic progress, increasing competitiveness, providing high-quality mobility services, and making much more efficient use of resources [8–10]. This is the way to increase competitiveness and

provide high-quality services and to use resources much more efficiently [11]. This means that the transport sector must use more renewable biofuels of local origin and reduce negative impact on the environment [12]. Moreover, fuels containing biobutanol would be in line with these aims, as their further processing into fuels would increase the share of renewable energy sources in the total energy consumption [13,14]. The use of biodiesel allows significant reduction in environmental pollution with particulate matter [15,16]; thus, its use as a substitute for fossil diesel is very welcome [17]. Even though RME is the dominant type of biodiesel in Lithuania [18,19], trying out second-generation bio-diesel blends (biomass to liquid (BTL) [20,21], hydrogenated vegetable oils (HVO) [22,23], and other blends with biobutanol would be rational. When investing in and improving the technology for the production of second-generation biofuels, the progress of the process towards increasing commercial use can be observed. This would allow stopping the use of first-generation biofuels altogether, switching to second-generation biofuels. The biofuel industry is unlikely to undergo radical changes in the near future. The use of first- and second-generation biofuels will continue to trend, increasing the amounts of second-generation biofuels in line with the established environmental and economic policy [24,25].

Butanol can be of petroleum origin, which is labelled i-bubanol (iso-butanol), and of biological origin (also labelled n-butanol or 1-butanol). N-butanol is one of the most effective additives for reducing NO_X in diesel during combustion [26]. Additionally, a reduction in soot emissions has been observed when mixing diesel with n-butanol [27]. Increasing n-butanol volume in diesel increases NO_X emissions [28]. Exhaust Gas Recirculation (EGR) systems help to reduce NO_X emissions [29,30]. Tests have been performed with diesel and n-butanol blends using different EGR parameters and analysing exhaust gases [31–33]. Cetane number and stability of biodiesel (methyl esters of vegetable oils) are lower compared with HVO (hydrotreated vegetable oil). When adding n-butanol and ethanol to diesel in tests of fuel blends in diesel engines [34], n-butanol showed better results due to a higher cetane number, density, and viscosity. The assessment of homogeneity of the blends revealed that n-butanol mixes with diesel without any additional solvents, unlike ethanol [35,36]. The conducted tests revealed that blends of diesel and alcohol reduce particulate matter emissions [18,37,38]. Ignition delays no longer occur when using n-butanol and diesel blends compared with pure diesel. Using blends of HVO and n-butanol or n-butanol blends (of 30%) reduces particulate matter emissions compared with pure diesel and HVO [13,39].

The use of HVO and n-butanol blends can be concluded to render the best results, including the cetane number, start of combustion, and oxygen content [40–42].

In the assessment of emissions, results of tests of HVO–i-butanol blends revealed a slight decrease in NO_x and a high reduction in particulate matter compared with conventional diesel [43]. The analysis of conventional diesel, diesel–i-butanol, and HVO–i-butanol mixtures revealed higher NO_X emissions in diesel–i-butanol blends (with i-butanol accounting for 30% in diesel) compared with conventional diesel but lower NO_X emissions than that of HVO–i-butanol (with i-butanol accounting for 30% in HVO) [44]. Differences in NO_X emissions of pure diesel and HVO are sufficient, and adding i-butanol in HVO did not lead to any significant and consistent changes in NO_X; thus, statistical assessment of the results received is complicated [45,46]. The increase of oxygen concentration in biodiesel leads to lower CO emissions [47]. Sayin et al. and Gumus et al. tried to prove this phenomenon experimentally [48,49]. The researchers used conventional diesel, pure biodiesel, and blends of diesel and biodiesel: B100, B50, B20, B5 (the figures mean percentage biodiesel content in diesel). At various engine loads, CO emissions decreased by 38.18, 30.90, 20.66, and 13.55%, respectively, using B100, B50, B20, B5 compared with conventional diesel. The results of the research were based on the fact that a higher oxygen content in the used fuels improved the combustion process and its completeness. Gharehghani et al. presented similar results [50]. CO emissions using B25, B50, B75, and B100 (the figures mean percentage biodiesel content in diesel) decreased by an average of 5.2, 11.2, 22.5, and 27%, respectively. Higher oxygen content in the fuel blends used and shorter combustion

process also confirm the results obtained. Oxygen contained in biodiesel oxidises with carbon molecules thus reduced CO emissions [26]. Basic fuel properties, such as viscosity and density, become important in order to achieve complete combustion, which would generate CO_2; also, the structure of the engine, engine speed, air-to-fuel ratio, and start of injection (SOI) must be taken into account. The use of conventional fossil hydrocarbon-based fuels would not allow achieving a reduction in CO_2 emissions [51]. Many research reports show that CO_2 emissions decrease using biodiesel compared with diesel. This is due to the low carbon content in biodiesel [52,53].

The conducted research with biodiesel with added alcohol demonstrated a decrease in HC emissions. HC emissions decreased by adding 15% and 20% of n-butanol and pentanol compared with biodiesel without alcohol. This is said to come as a result of increased oxygen content in fuels. On the other hand, the addition of alcohols led to fuel droplets of a larger diameter, resulting in ignition delay, which may increase HC generation during combustion. It has been argued that alcohol as an additive in biodiesel must be considered comprehensively [27].

Pirjola and a team of other researchers presented research results stating that a change in engine load and speed demonstrates the dependence of emissions on the said parameters. The highest content of pollutants is achieved with the engine idling, while the lowest pollutant levels are reached at the engine load of 50%. A further increase of engine load leads to increasing pollutant emissions [43].

Conventional diesel and HVO were used in the analysis of the size of particulate matter (PM) and their amount. When using HVO, smaller particulate matter (below 50 nm) was generated, and PM emissions were also lower [43,54]. Other studies revealed that particulate matter emissions decreased with increasing duration of the pre-injection interval; however, higher volumes of PM have been generated in application of pre-injection ratio compared with the single injection condition. Research of a different nature allowed stating that mixing n-butanol in diesel increased the duration of the ignition delay phase, leading to a better mixing of air and fuel blend during the ignition delay phase and lower PM emissions during combustion [32].

N-butanol had an impact on the combustion speed in diesel and bio-diesel blends, while the combustion temperature differed slightly. Having added N-butanol to the fuel resulted in a smaller diameter of soot particles [55]. N-butanol increased the duration of the ignition delay and slowed down the combustion phase, which was especially evident at low loads. The results achieved allow stating that with NO_x staying the same, n-butanol–diesel blends reduce particulate matter content and smoke, but heat efficiency also decreases compared with pure diesel [33]. More detailed studies show that during combustion, when the i-butanol ratio in diesel is below 17.5%, the combustion flame propagates back and forth, while with i-butanol ratio above 17.5%, the combustion flame propagates in a jumping-crawling motion [56].

When using HVO–n-butanol and i-butanol blends, no significant changes were observed in the heat release rate at low and high engine loads; thus, the obtained results of fuel blends can be compared based on the measurement uncertainty [39]. The results received when using blends of diesel and n-butanol revealed that brake thermal efficiency (BTE) decreased significantly at low engine loads, but an increase of about 7.08% was observed at high engine loads [57]. The comparison of diesel and HVO-brake-specific fuel consumption (BSFC) revealed that HVO fuel consumption decreased by 1% at low rotational speed, which is an insignificant result; meanwhile, BSFC increased when using a diesel with n-butanol and i-butanol blend [38]. A 10% i-butanol content (in the diesel–i-butanol blend) demonstrated an increase in BTE (brake thermal efficiency) and a decrease in BSFC (brake-specific fuel consumption), which is assumed to be due to decreased injection pressure [58]. Additionally, when using this fuel blend, exhaust gas temperature (EGT) was lower compared with that of conventional diesel [59].

In summary, biobutanol and HVO blends can be said to be very promising and can completely replace fossil diesel. In addition, such a fuel mix is 100% biological; thus, it is

in line with EU policy objectives. However, a relatively small field of research on these fuels raises a number of questions about the analysis of its combustion process, as the conducted research has mostly focused on summarizing characteristics of fuel consumption and environmental properties. A comprehensive assessment of both energy-environmental and the combustion process analysis would allow for a better substantiation of the use of such fuels in compression ignition engines, without any additional modifications in the engine structure and with biobutanol concentration ranging from 0% to 20% in terms of volume in fuel blends with HVO.

2. Equipment, Methodology, and Fuel

Tests were conducted using the 1.9 TDI diesel engine (type 1Z) equipped with an electronic control unit BOSCH VP37. Test engine had a rotary fuel pump and a turbocharger. Selected technical data of the 1.9 TDI engine are shown in Figure 1.

Parameter	Value
• Power	• 66 kW (4000 rpm)
• Torque	• 182 Nm (2000-2500 rpm)
• Piston diameter, mm	• 79.5 mm
• Piston stroke, mm	• 95.5 mm
• Copression ratio	• 19.5
• Displacement	• 1896 cm^3
• Number of cylinders	• 4/OHC
• Fuel injection	• Direct (single)
• Nozzle type	• Hole-type
• Nozzle opening pressure	• 190 bar
• Nozzle and holder assembly	• Two spring
• Cooling system	• Liquid cooling

Figure 1. The main parameters of the test engine (1.9 TDI type: 1Z).

Figure 2 presents fundamental data of the measurement equipment used in this research.

Configuration of the test stand is shown in Figure 3. The engine crankshaft was coupled with the eddy current brake. Fuel consumption was measured with the fuel scale and emissions sampled with the AVL DiCom 4000 gas analyser and smoke opacity meter. Smoke measurement is performed by determining the extinction of a light beam by scattering and absorption.

Experimental tests were conducted at a constant crankshaft rotation speed of n = 2000 rpm. These revolutions were set closest to the most economical operating mode of a laboratory engine (1.9 TDI, type 1Z). During the tests, engine loads of 30 Nm, 60 Nm, 90 Nm, and 120 Nm were selected, simulating engine speeds of ~50 km/h, ~80 km/h, ~100 km/h, and ~110 km/h at the said loads.

Equipment	Accuracy of measurement	Purpose of use
• Load bench *KI-5543* • Scale SK-500 • Air mass meter BOSCH HFM 5	• 1.2 Nm • 1.0 g • ≤2%	• brake torque • fuel consumption • air mass
• VAG-COM diagnostic equipment	• -	• Fuel injection timing, the start of injection (SOI)
• Piezo pressure sensor AVL GH13P	• ±0.11 (%FCO)	• In-cylinder pressure
• Encoder A58M- F	• 0.1758 crank angle degrees (CAD)	• Crankshaft position
• Oscilloscope AVL DiSTEST DPM 800	• -	• in-cylinder pressure and CAD transmit
• Delta OHM HD 2304.0, sensor TP704-2BAI	• ±0.0002 MPa	• intake air pressure
• K type thermo couple	• ±0.5%	• intake air and the exhaust gas temperature
• AVL DiCom 4000 gas analyser	• CO_2, 0.1% vol.; CO, 0.01% vol.; HC, 1 ppm; NOx, 1 ppm; smoke, 0.01 m^{-1}	• CO_2, CO, HC, NO_x, smoke absorption coefficient

Figure 2. Laboratory equipment.

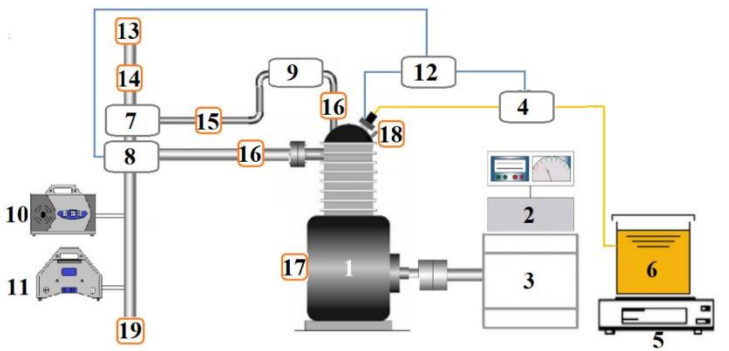


Figure 3. Engine test equipment. 1–engine, 2–measurement output gauges, 3–engine load unit, 4–high pressure pump, 5–scales, 6–fuel tank, 7–compressor, 8–turbocharger, 9–intercooler, 10–exhaust gas analyser, 11–smoke analyser, 12–electronic control unit, 13–air mass meter, 14–intake air temperature sensor, 15–pressure sensor, 16–temperature sensor, 17–crankshaft position sensor, 18–in-cylinder pressure sensor, 19–exhaust pipe.

Experimental tests were conducted with the engine running on conventional diesel fuel (labelled D100), hydrotreated vegetable oil (labelled HVO100), hydrotreated vegetable oil, and biobutanol blends of 95/5, 90/10 and 80/20 (% vol/% vol) (labelled HVOB5, HVOB10, and HVOB20). An amount of 5% of castor oil was added to fuel blends with biobutanol for better lubrication. Selected physicochemical properties of base fuels were tested and the results are listed in Table 1.

Table 1. Properties of 100% pure diesel, hydrotreated vegetable oil, biobutanol, and castor oil.

Parameter	Diesel	Hydrotreated Vegetable Oil	Biobutanol	Castor Oil
Density at 15 °C, kg/m^3	830.4	780.0	810.0	964.0
Carbon content, % m/m	86.20	84.55	65.00	73.60
Hydrogen content, % m/m	13.80	15.45	13.50	11.55
Oxygen content, % m/m	0	0	21.50	14.85
Stoichiometric AFR	14.79	15.18	11.30	11.91
Cetane number	51	70	18	28
Lower heating value, MJ/kg	43.1	44.1	33.0	41.3
Lower heating value, MJ/l	36.09	34.17	26.73	39.81
Purity, %	N/A	N/A	99.5	100
Manufacturer, country	Orlean Lietuva, Lithuania	Neste, Finland	Carl Roth GmbH, Germany	Biochemlit, Lithuania

In order to maintain the accuracy of the tests, the fuels used and their additives were kept at the same temperature to avoid differences in temperature and density that can be affected by temperature. Fuel blends (hydrotreated vegetable oil and biobutanol) were mixed on the day of the study just before use. They were stored at the same temperature and mixed to avoid delamination of components and to maintain homogeneity of the blend for different densities. The properties of fuel blends used during tests are presented in Table 2.

Table 2. Properties of fuel mixtures.

Properties	HVOB5	HVOB10	HVOB20
Density at 15 °C, kg/m^3	780.4	782.4	786.4
Carbon content, % m/m	83.55	82.55	80.57
Hydrogen content, % m/m	15.34	15.24	15.03
Oxygen content, % m/m	1.11	2.21	4.40
Stoichiometric AFR	14.98	14.77	14.38
Cetane number	67.3	64.6	59.3
Lower heating value, MJ/kg	43.54	42.98	41.87
Lower heating value, MJ/l	33.98	33.63	32.93

The numerical analysis of the combustion process was conducted using AVL FIRE software. The rate of heat release (ROHR) during combustion was calculated using cylinder pressures measured during tests, air and fuel consumption, properties of the fuel used, and engine parameters. The following combustion process indicators were set: start of combustion (SOC), in-cylinder temperature, in-cylinder temperature rise, and in-cylinder pressure rise. The said combustion process parameters helped to establish environmental and energy indicators using conventional diesel, hydrotreated vegetable oil, and hydrotreated vegetable oil and biobutanol blends.

3. Research Results and Discussion

Graphs illustrating changes in environmental and energy indicators are presented based on the results of the experimental research of CI engine running on conventional diesel D100, HVO100, and HVOB5, HVOB10, HVOB20 blends. The discussion of the said indicators and trends of their changes are presented based on the properties of the fuel used, the numerical analysis of the combustion process, and conclusions of other researchers.

3.1. Combustion Indicators

Experimental research was conducted at a constant engine crankshaft speed of n = 2000 rpm and three different engine loads (M_B = 30 Nm, M_B = 60 Nm, M_B = 90 Nm, and M_B = 120 Nm), which correspond to the brake mean effective pressure $BMEP$ = 0.2 MPa, $BMEP$ = 0.4 MPa, $BMEP$ = 0.6 MPa, $BMEP$ = 0.8 MPa.

Figure 4 illustrates the rate of heat release. According to the presented graph, under the same brake mean effective pressure of fuels and their blends, the start of combustion (SOC) varies: D100 ~0.7 CAD ATDC; HVO100 ~0.3 CAD BTDC; HVOB5, HVOB10, and HVOB20 ~0.1 CAD BTDC. The start of injection (SOI) in this mode of engine operation was set at ~4 CAD BTDC. The duration of the ignition delay phase of the said fuels also differed: D100 ~4.7 CAD ATDC; HVO100 ~3.7 CAD ATDC (which is 1 CAD less compared with D100); HVOB5, HVOB10, and HVOB20 ~3.9 CAD ATDC (which is 0.8 CAD less compared with D100). The analysis of combustion duration (CD) revealed that the longest combustion duration was with pure diesel: D100 ~50.7 CAD; HVO100 ~4.2 CAD less compared with D100; and CD decreased respectively when adding biobutanol: HVOB5- ~4.3 CAD less, HVOB10- ~3.9 CAD less, and HVOB20- ~5.2 CAD less. The maximum ROHR value was achieved in premixed combustion phase when using pure diesel at 5 CAD ATDC–35.0 J/CAD. When using hydrotreated vegetable oil (HVO), the maximum ROHR value was at 3 CAD ATDC–21.5 J/CAD (a decline of ~39%), while having added in HVO biobutanol at 5, 10, and 20%, the maximum ROHR decreased respectively in the premixed combustion phase at 4 CAD ATDC by ~28, ~21, and ~10% when comparing with pure diesel. When using pure diesel (D100), the maximum ROHR value in the controlled combustion phase was 32.4 J/CAD at 10 CAD ATDC. When using HVO, the maximum ROHR value in this phase was ~34 J/CAD at 9 CAD ATDC (an increase of ~4.9%). Having added biobutanol to HVO, the value of ROHR in the controlled combustion phase was the following: HVOB5–an increase of ~5.9% at 9 CAD ATDC; HVOB10–an increase of ~6.8% at 10 CAD ATDC; HVOB20–an increase of ~5.4% at 9 CAD ATDC; and the said ROHR value was compared with pure diesel. A growth in the controlled combustion phase when increasing biobutanol concentration improved soot oxidation but had a negative impact on the energy efficiency of the engine [60]. ROHR significantly decreasing in the premixed combustion phase reduced the intensity of NO_x generation [61].

The maximum temperature rise value can be achieved with conventional diesel ~53° K/CAD, at 4 CAD ATDC) (Figure 5). When using HVO100, the maximum temperature rise decreased by ~22% at 8 CAD ATDC compared with conventional diesel. Additionally, HVOB5 dropped by ~24% 8 CAD ATDC, HVOB10 by ~19% at 4 CAD ATDC, and HVOB20 by ~4% at 4 CAD ATDC. With increasing biobutanol concentration in HVO, a difference in the temperature rise in the premix combustion phase was observed to decrease compared with conventional diesel and came close to the value of the reference fuel. These trends are in line with previously published works by the authors [12,62].

The assessment of the in-cylinder temperature graph (Figure 6) revealed that when increasing biobutanol concentration in HVO, the in-cylinder temperature in the controlled combustion phase also increased. The highest temperature of HVO100 was 1392 K, D100–1400 K, and HVOB20–1424 K. With increasing biobutanol concentration in HVO, the combustion process was also longer. This is why the temperature and the pressure of turbo-compressor increased during compression, emitting more energy along with exhaust gases, but resulting in better soot combustion.

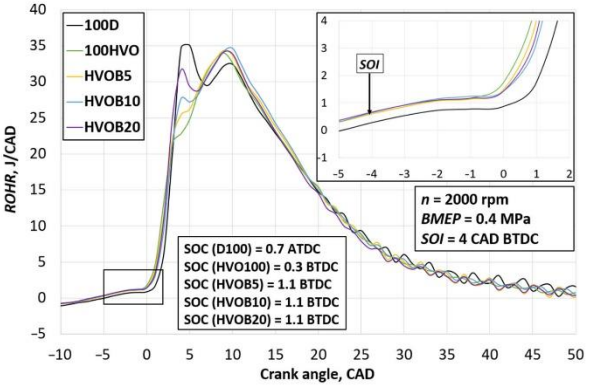


Figure 4. Rate of heat release in-cylinder depending on fuel composition.

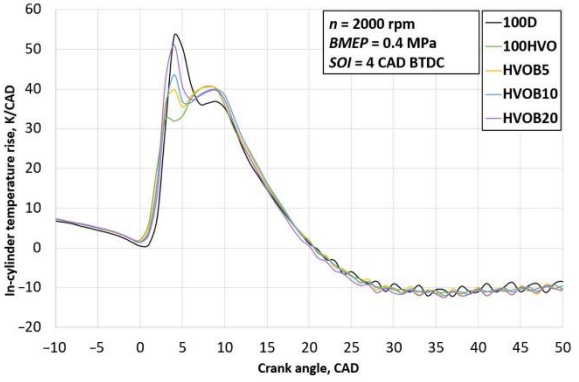


Figure 5. Temperature rise in-cylinder depending on fuel composition.

The highest in-cylinder pressure rise in the premix combustion phase was reached when using pure diesel: ~0.21 MPa/CAD, (Figure 7). The pressure rise of HVO100 in the premix combustion phase declined by ~48%, with HVOB5 decreasing by ~30%, HVOB10 by ~30%, and HVOB20 by ~11%. The greatest in-cylinder pressure rise was reached with D100, HVOB10, and HVOB20 fuel blends at 4 CAD ATDC, with HVO100 and HVOB5 fuel blend at 3 CAD ATDC. When increasing biobutanol concentration in HVO, the pressure rise also increased, but the result was not higher than that of conventional diesel.

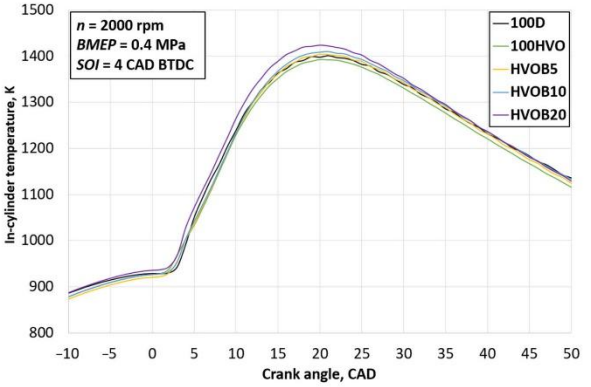


Figure 6. In-cylinder temperature depending on fuel composition.

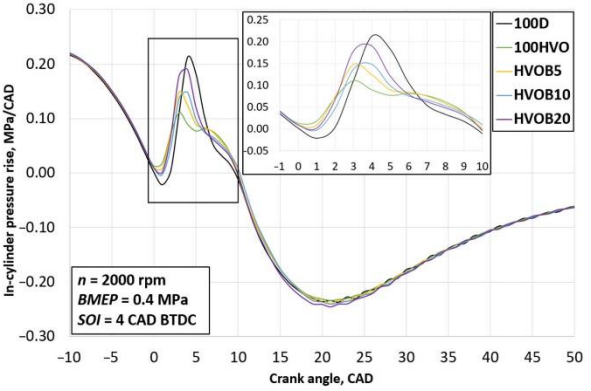


Figure 7. Pressure rise in-cylinder depending on fuel composition.

Figure 8 illustrates the in-cylinder pressure graph. When using conventional diesel (D100), the highest in-cylinder combustion pressure was ~7.68 MPa. When using HVO100, the maximum combustion pressure decreased to ~7.59 MPa. When increasing biobutanol concentration in HVO, the maximum combustion pressure of HVOB20 fuel blend increased to ~7.78 MPa (~1.3% more compared with conventional diesel). When using diesel, the highest combustion pressure was reached at ~9 CAD ATDC, and when using HVO and its blends with biobutanol it was 1 CAD later.

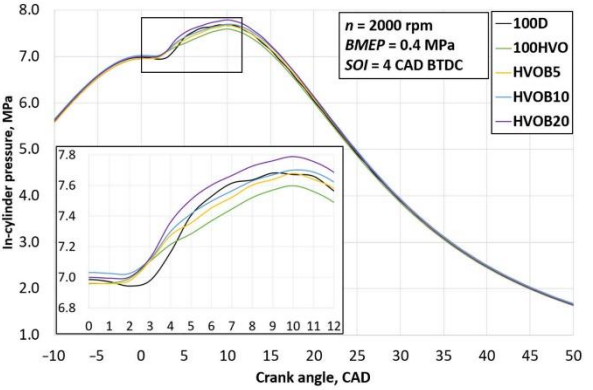


Figure 8. In-cylinder pressure depending on fuel composition.

Figure 9 presents the dependence of the temperature of emissions on the engine load measured in the experimental research. The temperature of emissions of D100 and HVO100 fuels was observed to be almost the same at changing engine loads (*BMEP* = 0.2 MPa; 0.4 MPa, 0.6 MPa, and 0.8 MPa). Increasing the biobutanol concentration in HVO from 5% to 20% decreased the temperature of exhaust emissions in the range of 0.5% to 1.5%. Exhaust temperature depends on LHV value—with decreasing LHV, exhaust temperature also decreases (to supply the same amount of fuel in the cylinders per cycle) [61]. Having added biobutanol to HVO in the research, the value of LHV decreased compared with HVO100 (Tables 1 and 2); however, more fuel was supplied (Figure 11) because the engine generated equal power. Having performed similar fuel tests, Yilmaz et al. concluded that blends of biodiesel and n-butanol rendered lower exhaust gas temperatures because of lower density of n-butanol and cetane number compared with diesel or biodiesel. Moreover, n-butanol mixed into fuel blends increases the oxygen content of the fuel, which improves and speeds up the combustion process, which lowers the exhaust gas temperature [63]. This is confirmed by ROHR (Figure 4), which shows that by increasing the concentration of biobutanol in the mixture, energy is released more intensively during the premixed combustion phase and that the amount of energy released decreases during the controlled combustion phase and later controlled combustion phase.

Figure 10 illustrates the dependence of the turbocharger pressure on engine load. Turbocharger pressure of D100 and HVO blends with biobutanol (HVOB5, HVOB10, and HVOB20) increased or decreased by no more than 0.5% at the designated engine loads. When using HVO fuel, this indicator increased and was about 1% higher in all engine modes compared with D100. The trend of a change in the turbocharger pressure was found to be similar to that of BTE of the engine (Figure 13), while values of brake thermal efficiency of HVOB5, HVOB10, and HVOB20 were determined to be similar to those of D100. The value of brake thermal efficiency of HVO100 was about 0.5% higher compared with conventional diesel. Energy efficiency of the engine running on HVOB5, HVOB10, and HVOB20 blends and the amount of energy emitted to the exhaust and cooling system was similar to that of D100.

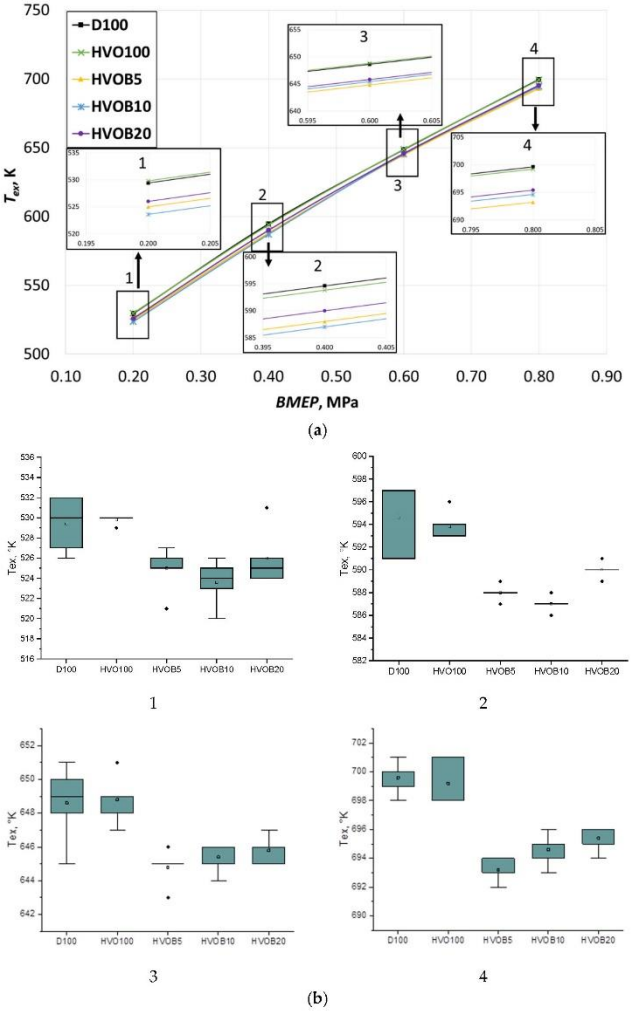


Figure 9. Dependence of exhaust temperature on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

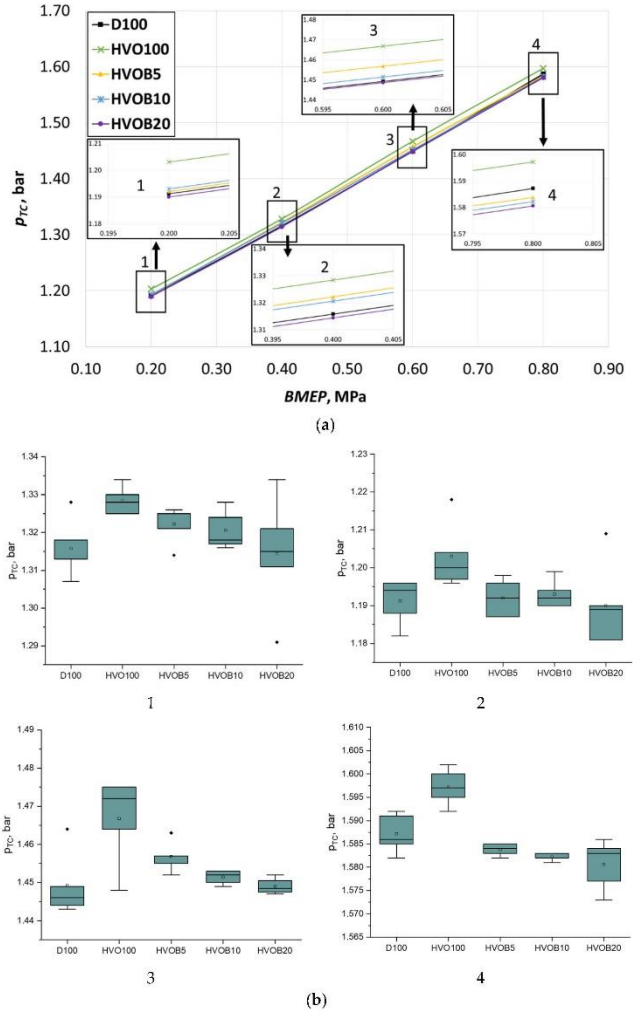


Figure 10. Dependence of turbocharger pressure on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

3.2. Energy Indicators

Figure 11 illustrates the dependence of brake specific fuel mass consumption on fuel composition (*BSFC_m*) and the engine load. The conducted research determined the brake specific fuel mass consumption (*BSFC* by mass) of the compression ignition engine and revealed that at different engine loads, comparative HVO100 consumption in terms of mass was about 2.3–2.8% lower compared with D100, while consumption of HVOB5 *BSFC* was lower by 0.8–1% compared with D100. The results of the fuel study (Tables 1 and 2) revealed that compared with conventional diesel, the density of HVO100 was 7.5% lower, but its lower heating value (LHV) was 2.3% higher than that of D100. The assessment of HVOB5 fuel density revealed that its density was 7.0% lower and that the lower heating value (*LHV*) was 1% higher compared with that of D100. Higher *LHV* resulted in lower values of *BSFC* by mass. However, it was also observed that when increasing the concentration of biobutanol in HVO (from 10% to 20%), *BSFC* by mass also started increasing: HVOB10 by 0.5–0.6% and HVOB20 by 3.2–3.4% compared with D100. According to the obtained fuel study results (Tables 1 and 2), HVOB10 density was 6.5% lower compared with conventional diesel, and lower heating value (*LHV*) was 0.3% lower than that of D100. The analysis of HVOB20 fuel blend revealed that its density was 6.0% lower, and that *LHV* was 2.8% lower compared with that of D100.

Huang et al. obtained similar research results when assessing *BSFC*, when *BSFC* by mass values increased in 70% conventional diesel and 30% n-butanol fuel blends. This can be explained by lower density of n-butanol and lower cetane number compared with diesel [64]. Xiao et al. conclude that in blends of biodiesel and n-butanol (adding up to 30% of n-butanol by mass), *BSFC* results are higher than those of conventional diesel because of a lower calorific value of biodiesel and n-butanol [65]. In the analysed case, the cetane number in biobutanol was 2.5 times lower than that of conventional diesel and 4 times lower than that of HVO (Table 1), while the cetane number of fuel mixtures HVOB10 and HVOB20 was lower than that of D100 (Table 2).

Dependence of brake specific fuel volume consumption (*BSFC_v*) and the engine load is presented in Figure 12. The results presented in this figure look absolutely different compared with Figure 11; however, the assessment of *LHV* in terms of volume (MJ/l), which are presented in Tables 1 and 2, revealed that these values (MJ/l) have tended to decrease: HVO100 about 5%, HVOB5 6%, HVOB10 7%, and HVOB20 9% lower compared with conventional diesel. Figure 12 illustrates this trend. Decreasing *LHV* value (MJ/l) in fuels or their blends leads to increasing brake specific fuel volume consumption. The greatest difference in *BSFC_v* was observed using HVOB20, where an increase was consistent at different engine loads: 9% compared with D100.

Another analysed energy indicator parameter was brake thermal efficiency—*BTE* (Figure 13). The comparison of HVO100 and D100 fuels at different loads revealed an increase in BTE of 0.1–0.6%. With increasing biobutanol concentration in HVO (from 5% to 20%), BTE value starts decreasing compared with D100: HVOB5 0.1–0.2%, HVOB10 0.2–0.3%, and HVOB20 0.3–0.4%. A decrease in BTE with blends with HVO and biobutanol was minor (1% difference in *BTE* was not achieved compared with D100). The obtained research results allow concluding that biobutanol additive of up to 20% by volume in HVO does not have any material impact on energy efficiency of the combustion process.

A decrease in *LHV* of fuel blends can be explained by the fact that the addition of n-butanol allows reducing fuel viscosity, improving injection and providing more oxygen in the combustion cylinder to improve chemical energy of fuel by turning it into useful engine work [66]. Studies conducted by other researchers rendered different results. Pan et al. used blends of biodiesel and 2-butanol in a CI engine in their research and discovered that *BTE* decreased at low engine loads but increased by about 7.08% at high engine loads [57].

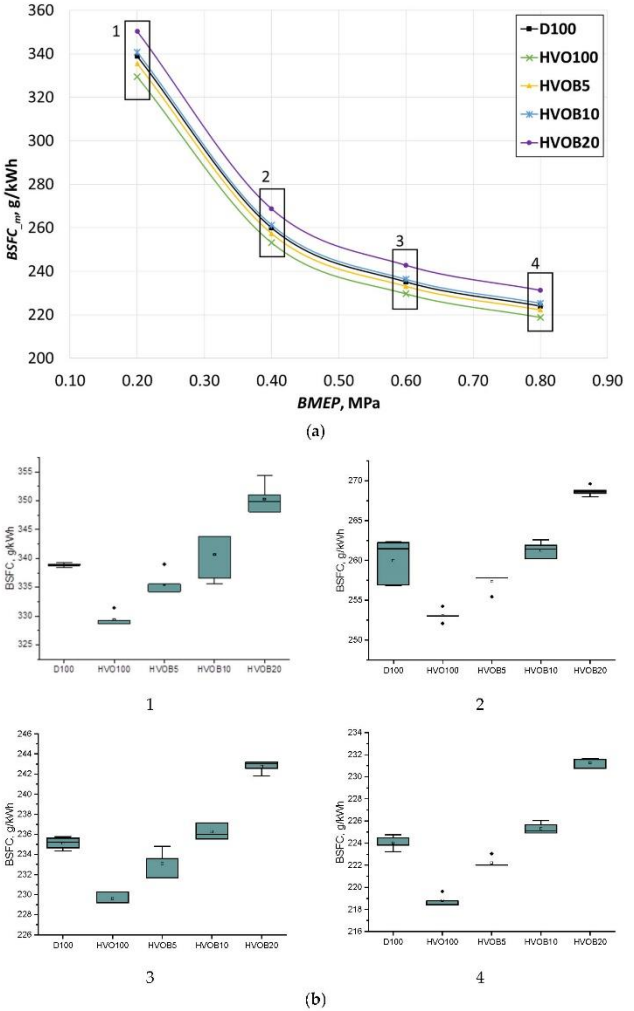


Figure 11. Dependence of BSFC by mass on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

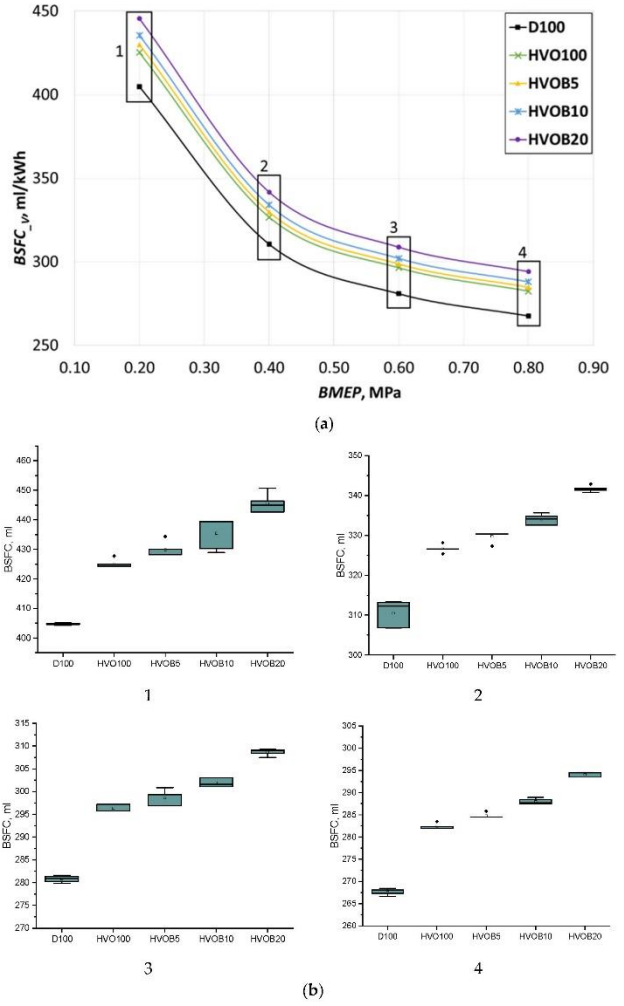


Figure 12. Dependence of BSFC by volume on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

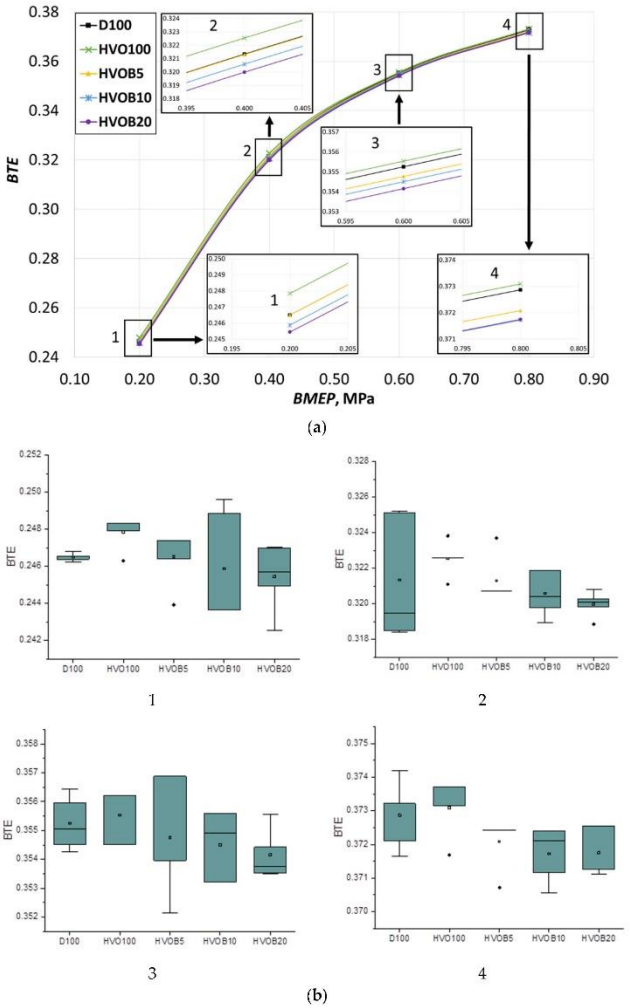


Figure 13. Dependence of brake thermal efficiency on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

3.3. Environmental Indicators

One of the key environmental indicators found during the research was carbon dioxide (CO_2) content in the exhaust gas. Carbon dioxide is an environmental parameter emitted in complete combustion process when oxygen for a complete combustion process is enough. CO_2 content can also increase with increasing content of carbon in fuel molecules [67]. The substitution of conventional diesel by HVO100 reduces CO_2 emissions by 3.5–6.7% (Figure 14). The use of HVO and biobutanol fuel blends (with biobutanol concentration of 5–20%) did not result in any material changes in CO_2 emissions; CO_2 values of fuel blends were close to HVO100: 3.3–6.8%. The assessment of the obtained CO_2 research results allows stating that biobutanol additive of up to 20% by volume in HVO does not have any significant impact on CO_2 emissions.

Bandbafha et al. explained a reduction in carbon dioxide compared with conventional diesel. They say that biodiesel has a lower elemental carbon to hydrogen ratio (C/H) than conventional diesel, so CO_2 emissions from air combustion will be lower than those of diesel [61].

Figure 15 presents the results of the study of carbon monoxide (CO). The obtained results revealed a significant difference in CO at BMEP of 0.2–0.6 MPa when comparing HVO100, HVO, and biobutanol fuel blends with D100. Having increased the engine load (BMEP 0.8 MPa), CO values became the same. The HVO100 CO value at BMEP 0.2 MPa was 50% lower, and at BMEP 0.6 MPa it was 6% lower compared with D100. An increase of biobutanol concentration in HVO (from 5% to 20%) led to a decrease in CO value at BMEP 0.2 MPa: HVOB5 was 51%, and HVOB20 was 51%, compared with D100. Having increased engine load to BMEP 0.4 MPa, CO values of HVO100, HVOB5, HVOB10, and HVOB20 became the same. With the engine running at BMEP 0.8 MPa, CO values of all fuels used and their blends were the same. CO emissions are affected by different engine operating conditions. The engine load has been proven to have a significant effect on CO emissions. Higher load values are associated with reduced CO emissions [68]. The cylinder temperature was also experimentally proven to increase when moving from low to high loads, which allows for a better combustion and thus reduces CO emissions [69].

Studies of physicochemical properties of fuels (Table 1) revealed the ratio of masses of carbon and hydrogen C/H was 6.25, fuel HVO100 was 5.47 (12.5% lower), and HVOB20 was 5.36 (14.2% lower). CO reduction in the use of pure HVO and blends of HVO with biobutanol can be explained by a lower C/H ratio. Researchers Bandbafha et al. concluded that CO emissions decreased using biodiesel due to a lower carbon-to-hydrogen ratio compared with diesel. CO can also decrease due to a higher oxygen content in the fuel mixture [26].

The composition of fuel and fuel blends (Tables 1 and 2) allowed determining that stoichiometric air–fuel ratio (AFR) for D100 was 14.79 kg, HVO100 was 15.18 kg (2.6% more), and HVOB20 was 14.38 kg (2.8% less). Having added biobutanol and castor oil in HVO, air-to-fuel ratio decreased. The said reduction of AFR was due to oxygen (O_2) content in biobutanol and castor oil (O_2).

The use of HVO100 and blends of HVO and biobutanol led to a gradual decrease in smoke (Figure 16). The obtained research results revealed that HVO100 smoke value was 22–33% lower compared with D100, while smoke values of HVO and biobutanol blends had a tendency to decrease: HVOB5 from 39% to 45%, HVOB10 from 45% to 55%, and HVOB20 from 50% to 64%, compared with conventional diesel. Researchers Imdadulas and others used n-butanol and biodiesel mixtures at different proportions and observed a decrease in smoke compared with conventional diesel [35]. Additionally, researchers Imtenan et al. confirmed that oxygen contained in alcohols, such as n-butanol, used in combination with biodiesel reduces smoke emissions [69].

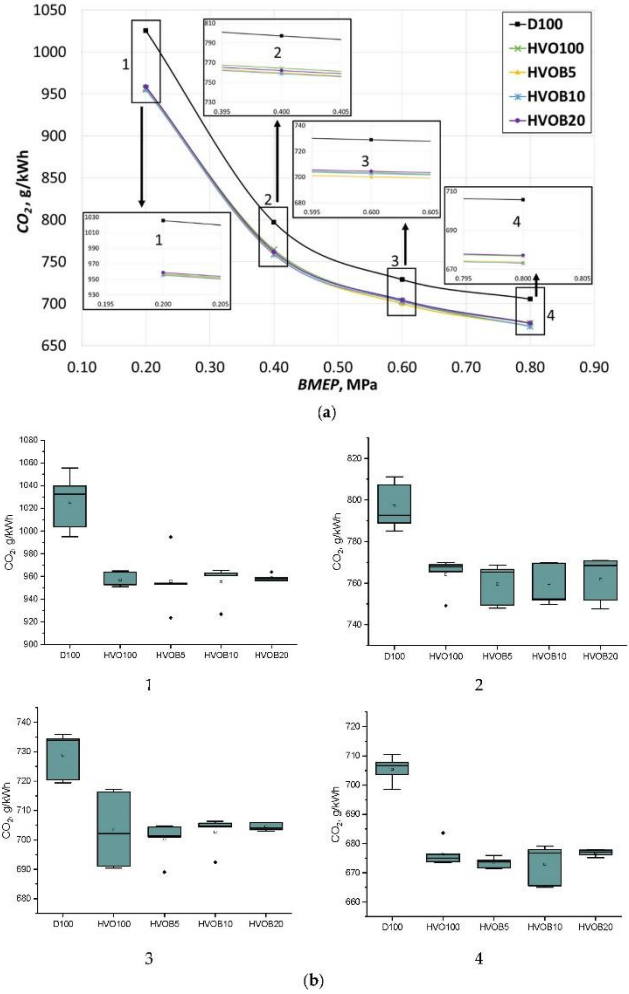


Figure 14. Dependence of CO_2 emissions on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

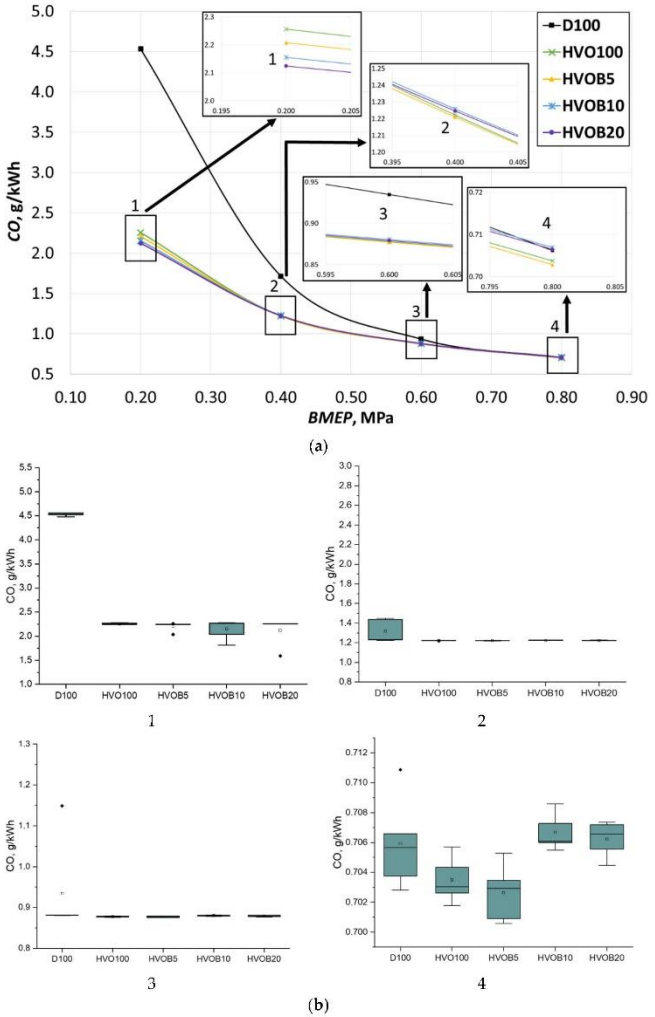


Figure 15. Dependence of CO emissions on fuel composition and engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

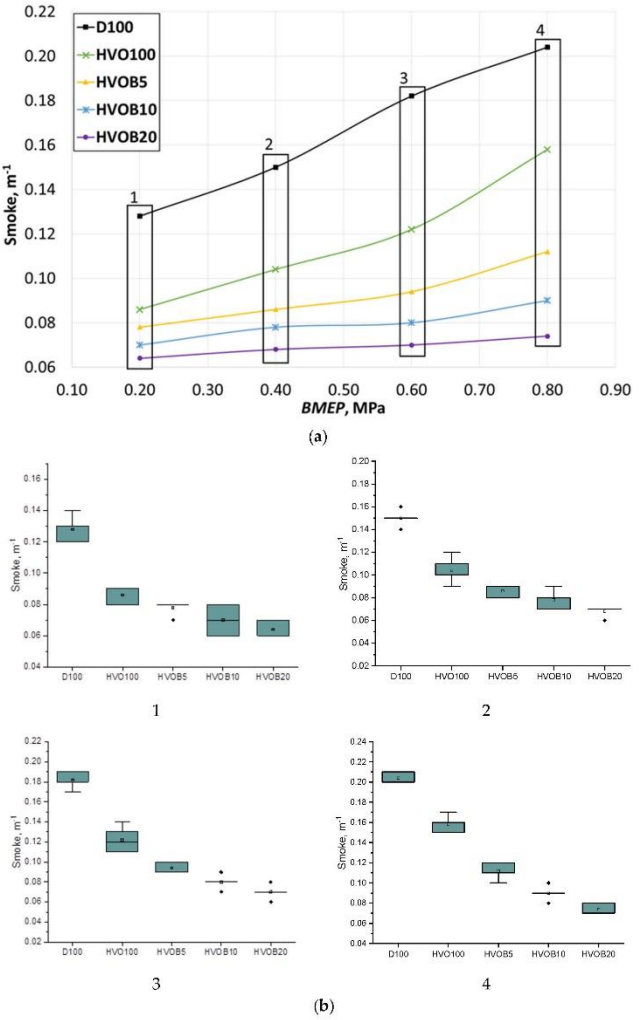


Figure 16. Dependence of smoke on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

In a compression ignition engine, the air intake system operates with excess air, resulting in unburnt hydrocarbons (HC) and thus low emission concentrations [70]. Figure 17 shows the results of studies of unburnt hydrocarbon (HC) at different engine loads. The obtained results revealed that the concentration of HVO100 is 36–43% lower depending on the engine load compared with conventional diesel. However, having added biobutanol to HVO, HC concentration increased steadily depending on biobutanol concentration. With biobutanol concentration of 5% (HVOB5) it was 28–34%, while adding biobutanol 10% (HVOB10) HC concentration it was 6–8% lower compared with D100. However, increasing the concentration of biobutanol in HVO fuel to 20% resulted in a higher concentration of unburned hydrocarbons than in conventional diesel: 12–39%.

Hosseinzadeh et al. explained the increase in HC concentration having added biobutanol. Studies revealed that adding alcohol in biodiesel resulted in lower HC emissions. HC emissions also decreased mixing in biodiesel 15% and 20% of n-butanol compared with biodiesel without alcohols. This was due to increased oxygen content in the fuel. On the other hand, the addition of alcohols resulted in an increase in the diameter of fuel droplets, which in turn led to an increase in the ignition delay, which can increase HC formation during combustion. The use of alcohols as additives in biodiesel needs to be assessed comprehensively [26].

HC emissions can also be associated with a lower fuel viscosity. Farayedhi et al. say that lower viscosity fuels create smaller droplets in the injection process. These smaller fuel droplets reach the cylinder walls due to a weaker mixing of fuel and air mixture near the walls, which causes a quenching effect, thus increasing the emission of unburned fuel (HC) [71].

Combustion temperature and oxygen unused during combustion have the greatest impact on the formation of nitrogen oxides (NO_X). In experimental studies, NO_X emissions were the highest in D100 and the lowest in HVO100 (Figure 18). Increasing biobutanol concentration in HVO fuel leads to a steady decrease in NO_X emissions at all engine load modes compared with D100. The comparison of NO_X emissions of HVO100 and D100 revealed that having substituted the fuel with HVO100, NO_X emissions decreased by 17–20% (Figure 18). The decrease in NO_X emissions can be explained by lower ROHR intensity (Figure 4) and a smaller temperature rise (Figure 5). Vojtisek et al., having conducted similar studies, also state that NO_X emissions were similar when comparing HVO with n-butanol and i-butanol blends with pure HVO, but in both cases they were lower than that of pure diesel [39].

Mixtures of HVO and biobutanol used in the study contain oxygen (Table 2). When increasing the volume of biobutanol, oxygen concentration increases as well. The comparison of NO_X emissions in HVO and biobutanol blends with D100 revealed that NO_x emissions increased when increasing the biobutanol volume from 5% to 20% in HVO fuels. In HVOB5, NO_X emissions decreased by 16–18% compared with D100, in HVOB10 by 14–17%, and in HVOB20 by 13–14%. Addition of oxygen to the fuel also demonstrated conflicting results. Having conducted research with biodiesel and n-butanol (with n-butanol accounting for 30% in the volume of biodiesel), Prabu et al. state that NO_X emissions decreased compared with diesels without alcohols. This phenomenon can be justified by a decrease in the combustion temperature [72]. However, results of research conducted by Imdadulas et al. [35] revealed that using oxygen additives, such as n-butanol in biodiesel, rendered an opposite effect, with no reduction in NO_X emissions. These conclusions were justified by the fact that alcohols used as an additive in biodiesel reduced the cetane number.

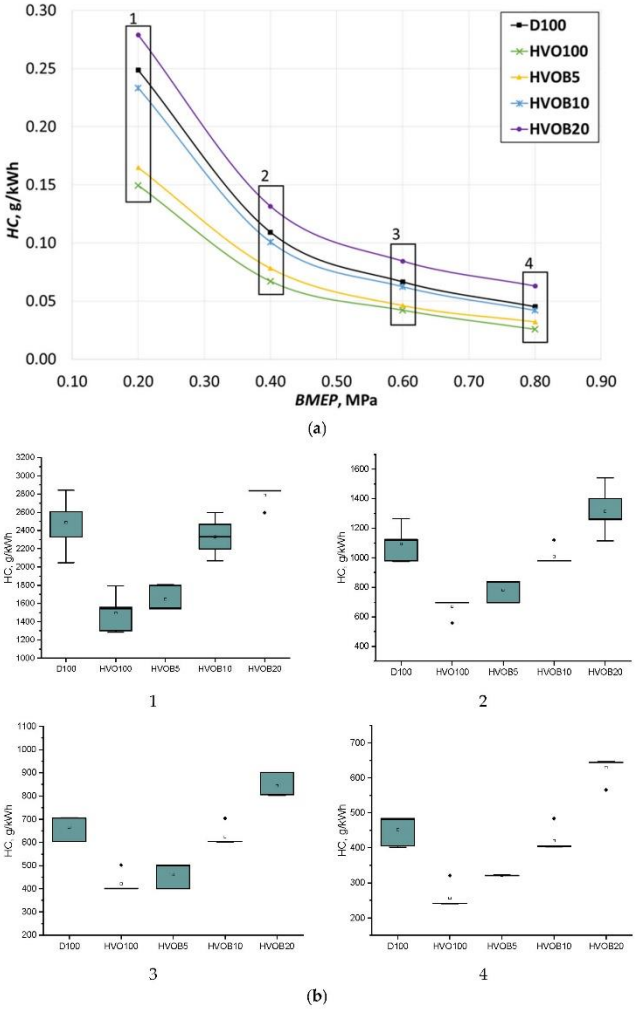


Figure 17. Dependence of HC emission on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

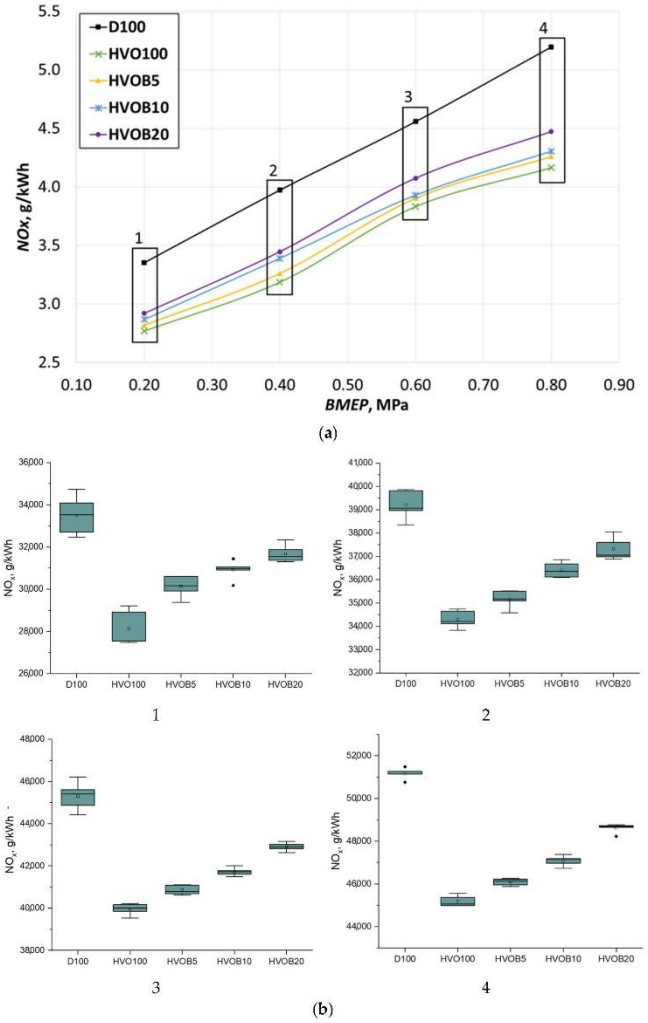


Figure 18. Dependence of NO_X emission on fuel composition and the engine load: (**a**) summary of results; (**b**) accuracy and errors of measurements.

4. Conclusions

Experimental studies and numerical analysis of the combustion process of pure conventional diesel (D100), hydrotreated vegetable oil (HVO100), and hydrotreated vegetable oil and biobutanol mixtures (HVOB5, HVOB10, and HVOB20) with different engine loads have resulted in the following conclusions:

1. Comparing fuels HVOB5, HVOB10, and HVOB20 with D100, LHV (MJ/l) values decrease by ~5.85%, 6.81%, and 8.75%, respectively. When using hydrotreated vegetable oil and biobutanol mixtures, due to the oxygen in the biobutanol, the other stoichiometric AFR parameter was: HVOB5 ~1.28% higher compared with D100 (HVO100 stoichiometric AFR parameter was ~2.64% higher compared with D100, so in this case HVOB5 fuel mixture is stoichiometric and AFR is ~1.32% higher compared with HVO100), and HVOB10 and HVOB20 are lower (0.14% and 2.77%) compared with D100.), and HVOB10 ~0.14% and HVOB20 ~2.77% lower compared with D100.
2. The ignition delay phase duration of the mentioned fuels and their mixtures at the brake mean effective pressure value of 0.4 MPa was different: D100 ~4.7 CAD ATDC, HVO100 ~3.7 CAD ATDC (which is 1 CAD less compared with D100), HVOB5, HVOB10, and HVOB20 ~3.9 CAD ATDC (which is 0.8 CAD less compared with the D100). Comparing the maximum ROHR at premixed combustion phase, value D100 at 5 CAD ATDC-35.0 J/CAD with hydrotreated vegetable oil (HVO), the maximum ROHR value at 3 CAD ATDC was 21.5 J/CAD lower (reduction ~39%). The maximum ROHR at 4 CAD ATDC value was reduced by adding 5%, 10%, and 20% of HVO addative in the premixed combustion phase respectively, compared with pure diesel by ~28%, ~21%, and ~10%. Comparing the maximum ROHR value at controlled combustion phase using D100 32.4 J/CAD at 10 CAD ATDC with HVO-34 J/CAD at 9 CAD ATDC was an increase in HVOB5 ~5.9% at 9 CAD ATDC, an increase in increase ~4.9%). The HVOB10 at 10 CAD ATDC and HVOB20 increases of ~6.8% and ~5.4% compared with D100 at 9 CAD ATDC. Comparing the maximum ROHR at controlled combustion value phase using D100 32.4 J/CAD at 10 CAD ATDC with HVO-34 J/CAD at 9 CAD ATDC was increased ~4.9%. The ROHR value of controlled combustion phase when biobutanol was added to HVO was an increases using the fuel mixtures HVOB5 ~5.9% at 9 CAD ATDC, HVOB10 ~6.8% at 10 CAD ATDC and HVOB20 ~5.4% at 9 CAD ATDC compared with D100.
3. As the concentration of biobutanol in HVO fuel increases, the temperature rise in premix combustion phase difference decreases and approaches the value of D100 fuel. The maximum temperature rise value was reached with D100 ~53° K/CAD, at 4 CAD ATDC). Using HVO100, the maximum fuel temperature rise is reduced by ~22% at 8 CAD ATDC compared with conventional diesel. Decreases respectively: HVOB5 ~24% 8 CAD ATDC, HVOB10 ~19% 4 CAD ATDC, and HVOB20 ~4% at 4 CAD ATDC. The same trend of the results was obtained according to the in-cylinder pressure rise indicator. As the concentration of biobutanol in HVO fuel increases, the pressure rise increases, but the value does not reach higher than D100: the maximum in-cylinder pressure rise during the premix combustion phase was achieved using pure diesel ~0.21 MPa/CAD. HVO100 fuel premix combustion phase pressure rise is reduced by ~48%. HVOB5 ~30%, HVOB10 ~30%, HVOB20 ~11%.
4. Regarding brake specific fuel mass consumption on fuel composition (BSFC_m) and the engine load, at different engine loads, the HVO100's relative fuel mass consumption by mass is less than 2.3–2.8% compared with D100, and the value of the fuel mixture HVOB5 BSFC by mass is less than 0.8–1% compared with D100. However, the density of HVO100 is 7.5% lower compared with conventional diesel, but the lower heating value (LHV) is 2.3% higher than that of D100, and when evaluating the HVOB5 fuel mixture, the density is 7.0% lower, and the lower heating value (LHV) is 1% higher compared with the D100. The higher LHV value results in lower BSFC by mass values. Additionally, with increasing biobutanol concentration in HVO fuel (from 10% to 20%), BSFC by mass starts to increase: HVOB10 by 0.5–0.6% and

HVOB20 by 3.2–3.4% increase compared with D100. The density of HVOB10 is 6.5% lower compared with conventional diesel, and the lower heating value (LHV) is 0.3% lower than D100; the density of HVOB20 fuel mixture is 6.0% lower, and the LHV value is 2.8% lower compared with D100. Estimation of brake specific consumption by volume gave different results, but there is a dependence on LHV by volume (MJ/l). As the value of LHV by volume (MJ/l) decreased in fuels and their mixtures, the brake specific fuel volume consumption increased: HVO100 about 5%, HVOB5 6%, HVOB10 7%, HVOB20 9% less compared with D100.

5. Based on the results of the research, it can be stated that biobutanol, as an additive up to 20% by volume, in HVO fuels does not significantly affect the energy efficiency of the combustion process. The increase in BTE was 0.1–0.6% at different loads comparing HVO100 and D100. As the concentration of biobutanol in HVO fuel increases (from 5% to 20%), the BTE values decrease compared with D100: HVOB5 by 0.1–0.2%, HVOB10 by 0.2–0.3%, and HVOB20 by 0.3–0.4%. The reduction in BTE with HVO and biobutanol fuel blends is small (no 1% BTE difference compared with D100 is achieved).
6. In terms of ecological parameters, biobutanol as an additive up to 20% by volume in HVO fuels does not have a significant effect on CO_2 emissions. Replacing HVO100 with D100 reduced CO_2 emissions by 3.5–6.7%. Using mixtures of HVO and biobutanol fuels (5% to 20% biobutanol concentration), CO_2 concentration does not decrease, although the C/H ratio decreases because the BTE effect was not positive. Due to its oxygen, biobutanol reduces CO emissions at low loads and lower combustion temperatures. However, throughout the load range, HC concentrations increase due to the change in fuel droplets due to biobutanol.
7. Replacing diesel D100 with H100 fuel reduces the smoke at various loads by 22–33%; increasing the biobutanol concentration reduces the smoke by 50–64%. The main influence is the decreasing C/H ratio and the increasing oxygen concentration in the fuel. Compared with D100, H100 reduces NOx emissions in the entire load range by 17–20%, as the higher cetane number reduces the intensity of ROHR and the combustion temperature. The addition of biobutanol to HVO fuel increases NOx emissions by up to 20% (decreases the cetane number of the fuel mixture, increases oxygen concentration, and this increases ROHR intensity and combustion temperature), but nitrogen oxide emissions remain 13–14% lower compared with pure diesel.
8. Replacing pure diesel with a mixture of 100% renewable fuel (hydrotreated vegetable oil and biobutanol up to 20%) can significantly improve the engine's environmental performance without compromising energy efficiency. However, additional studies are needed to assess the effect of fuel on engine reliability and reliability.

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Nomenclature

BMEP	Brake mean effective pressure (bar)
BSFC_m	Brake specific fuel mass consumption (g/kWh)
BSFC_v	Brake specific fuel volume consumption (mL/kWh)
BTE	Brake thermal efficiency
LHV	Lower heating value (MJ/kg)
ROHR	Rate of heat release (J/CAD)
M_B	Brake torque (Nm)
m/m	Mass ratio
n	Rotational speed of the crankshaft (rpm)
v/v	Volumetric ratio

Abbreviations

ATDC	After top dead centre
BTDC	Before top dead centre
BTL	Biomass to liquid fuel
B5	5% biodiesel, 95% diesel
B20	20% biodiesel, 80% diesel
B25	25% biodiesel, 75% diesel
B50	50% biodiesel, 50% diesel
B75	75% biodiesel, 25% diesel
B100	100% biodiesel
CAD	Crank angle degree
C/H	Carbon/hydrogen ratio
CI	Compression ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
D100	100% conventional diesel fuel
ECU	Electronic control unit
EGR	Exhaust gas recirculation
EGT	Exhaust gas temperature
ES	European Union
HC	Hydrocarbons
HVO	Hydrotreated vegetable oil
HVOB5	95% hydrotreated vegetable oil, 5% biobutanol
HVOB10	90% hydrotreated vegetable oil, 10% biobutanol
HVOB20	80% hydrotreated vegetable oil, 20% biobutanol
HVO100	100% hydrotreated vegetable oil
NO_X	Nitrogen oxides
O_2	Oxygen
PM	Particulate matter
RME	Rapeseed methyl ester
SOC	Start of combustion
SOI	Start of injection
TDI	Turbocharged direct injection

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Research of the impact of EGR rate on energy and environmental parameters of compression ignition internal combustion engine fuelled by hydrogenated vegetable oil (HVO) and biobutanol – Castor oil fuel mixtures

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ABSTRACT

The use of the second-generation biodiesel has become an increasing priority in the modern world, and adding a biobutanol additive further improves the engine's environmental characteristics. As biobutanol degrades lubrication characteristics of a fuel blend, HVO and biobutanol blends were supplemented with up to 5% castor oil in the research to form a three-component fuel blend. This blend increases NOx emissions in proportion to the increase of the biobutanol concentration in the fuel blend. The most widely used method of reducing NOx emissions in modern motorisation is the use of EGR. Therefore, this article analyses not only the impact of different EGR rates on both environmental and energy characteristics of the engine. Using various EGR rates with HVO and biobutanol mixtures, the rate of heat release (ROHR) in premixed combustion phase decreased, but in controlled combustion phase it increased in the convergence of its value to that of conventional diesel. A decrease in BTE values was also observed with HVO and biobutanol mixtures, increasing EGR rate. When increasing EGR rate of HVO and biobutanol, BSFC increased both in terms of volume and mass; Smoke, HC and NOx, CO and CO_2 emissions also decrease with HVO and biobutanol mixtures compared with conventional diesel.

1. Introduction

Biofuels are considered a viable alternative to traditional fossil fuels. Recently, biofuel production technologies have improved rapidly, and four generations of biofuels have been developed or offered [1]. First generation biofuels are fuels derived from such sources as starch, sugar, animal fats and vegetable oils. Second generation biofuels are made from cellulose biomass and inedible materials. Third generation biofuels are biofuels produced by algae. With fourth generation biofuels, the aim is to produce and store CO_2 at all stages of production [2].

In order to overcome severe limitation of first-generation biofuels, second generation biofuels have been offered. These biofuels are produced from inedible raw materials such as maize pulp and wheat straw. Currently, the cellulosic bioethanol industry is still in its initial phase, as maize grain dominates bioethanol production in the USA. The country has set a plan to produce up to 16 billion gallons of second-generation biofuels by 2022 [3]. This technology is promising because the cost of biomass in the supply chain can be reduced, as the price of inedible crops, such as maize silage, is much lower than the price of maize grain [4].

The trend towards replacing fossil fuels with renewable materials is a key part of an integrated approach to transport sustainability. The share of biofuels in global energy consumption in the transport sector is currently a mere 4 % [5].

Butanol, which is produced from readily available, renewable and cost-effective sources, is also an alternative to fossil fuels. Butanol is a biofuel that can be used in transport infrastructure to meet sustainability needs. Currently, the most promising source is lignocellulosic materials, the main component of organic waste from agriculture, forestry and industry. Agricultural and industrial wastes and lignocellulosic wood aggregates are reliable and sustainable sources for butanol production [6].

N-butanol is a biomass-based renewable biofuel [7,8]. Butanol is the most developed alternative fuel that can be used in Compression Ignition (CI) engines [9]. As a renewable substitute for diesel, *n*-butanol has properties close to those of diesel [10]. A 40 % *n*-butanol mixture volume share in diesel was found to reduce NOx and soot emissions [11]. The use of *n*-butanol with blends of diesel and biodiesel revealed that an increase in *n*-butanol effectively reduces NOx emissions [12], while the

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Nomenclature

$BSFC_V$	Brake Specific Fuel volume Consumption (ml/kWh)
BTE	Brake Thermal Efficiency
LHV	Lower Heating Value (MJ/kg)
HHV	Higher Heating Value (MJ/kg)
$ROHR$	Rate of Heat Release (J/CAD)
M_B	Brake Torque (Nm)
n	Rotational speed of the crankshaft (rpm)
λ	Air excess ratio

Abbreviations

ATDC	After Top Dead Centre
BTDC	Before Top Dead Centre
BTL	Biomass to Liquid Fuel
B5	5 % biodiesel, 95 % diesel
B20	20 % biodiesel, 80 % diesel
B25	25 % biodiesel, 75 % diesel
B50	50 % biodiesel, 50 % diesel
B75	75 % biodiesel, 25 % diesel
B100	100 % biodiesel
CAD	Crank Angle Degree
CD	Combustion Duration
C/H	Carbon/Hydrogen ratio
CI	Compression Ignition
CO	Carbon monoxide
CO_2	Carbon dioxide
D100	100 % conventional diesel fuel
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EGT	Exhaust gas temperature
ES	European Union
HC	Hydrocarbons
HVO	Hydrotreated vegetable oil
HVOB5	95 % hydrotreated vegetable oil, 5 % biobutanol
HVOB10	90 % hydrotreated vegetable oil, 10 % biobutanol
HVOB20	80 % hydrotreated vegetable oil, 20 % biobutanol
HVO100	100 % hydrotreated vegetable oil
NO_x	Nitrogen oxides
O_2	Oxygen
PODE	Polyoxymethylene dimethyl ethers
PM	Particulate matter
RME	Rapeseed Methyl Ester
SOC	Start Of Combustion
SOI	Start Of Injection
TDI	Turbocharged Direct Injection
TDC	Top Dead Centre

use of 20 % isobutanol with biodiesel lead to a reduction of brake thermal efficiency (BTE) and NOx of 12 % [13]. The use of no more than 40 % *n*-butanol in diesel increases the combustion rate, and the engine power does not decrease [14,15].

The analysis of the impact of butanol isomers on PM emissions allowed determining that at medium and high loads, PM emissions of a butanol and diesel blend were lower than of pure diesel. As the *n*-butanol content of diesel increased, soot and CO emissions decreased, but HC emissions increased [16]. The analysis of PM emissions from diesel and *n*-butanol/diesel blends showed that blended fuels reduced the total PM emissions and the geometric mean diameter [17].

In terms of hydrotreated vegetable oil (HVO) NOx emissions, these fuels do not have the harmful effects of ester-type biodiesel or the tendency to increased NOx emissions and sedimentation. HVO has a higher cetane number than conventional diesel and consists of straight chain paraffinic hydrocarbons free of aromatics, oxygen and sulphur. CO_2 emissions from HVO range from 80 % to 40 % of conventional CO_2 emissions from conventional diesel [18–20].

The energy efficiency of an engine can be improved by using HVO [21]. With pilot injection, the reduction in combustion noise and the impact of the cetane number were less noticeable [22].

The studies conducted with diesel and butanol show that at constant EGR rates, a comparison of D100 and BD20 fuels reveals that for BD20, the average cylinder pressure and heat release rate peaks increase, the ignition delay becomes longer, and the combustion efficiency decreases. The addition of (Polyoxymethylene dimethyl ethers (PODE) 3–4) to BD20 results in a shorter ignition delay, higher peak heat release and mean cylinder pressure values, higher brake thermal efficiency and combustion efficiency, and higher BSFC [23].

When analysing the impact of EGR rates (0–40 %) on the combustion and emission characteristics of *n*-butanol/diesel/PODE 3–4 blends in a low temperature combustion mode in a diesel engine, the results revealed that compared to D100 (conventional diesel), at a constant EGR rate, the average cylinder pressure increased, and the heat release rate of BD20 (20 % butanol and 80 % diesel by volume) and the ignition delay was higher, while BTE increased. For BD20 blended with PODE 3–4, the ignition delay was shorter, while the BTE and combustion efficiency increased [24].

The analysis of the cyclic energy distributions of the fuel mass by different EGR rates and fuels revealed that NB30 has the lowest proportion of soot and CO emission energy and the highest heat release rate [25].

However, the impact of EGR on soot emissions is complex [26]. Initially, when the EGR rate is less than 40 %, EGR levels have a minor impact on soot emissions. However, if the EGR rate exceeds 40 %, soot emissions show a significant increase as the EGR rate increases and reaches the maximum value at approximately 50 % EGR. Soot emissions then begin to decline sharply as the EGR rate continues to increase. This reduction in soot emissions should be associated with a reduction in the overall combustion temperature and a prolonged ignition delay at high EGR flow rates, so the use of high EGR rates can simultaneously inhibit NOx and soot formation. This concept is called EGR High Flow Low Temperature Combustion (LTC) [27].

The impact of air excess ratio (λ) and EGR on the onset of combustion is minor for both HVO and conventional diesel. Despite this insensitivity, small changes in the premixed, test combustion phase and the resulting effect on mixture conditions lead to large differences in emissions [28].

It was found that at high EGR rates (30 % and 40 %), the effect of mixing *n*-butanol with diesel (0…50 %) on the particle emission characteristics of the diesel engine under different EGR conditions resulted in an obvious reduction of the total *n*-butanol/diesel PM concentrations by ~ 74 % compared to conventional diesel. A comparison of *n*-butanol, 2-butanol blended with diesel at the volume of 20 % was made to investigate the impact of fuel properties and oxygenated structures on engine performance in different ways. At EGR rates ranging from 0 % to 62 %, the results showed that butanol-diesel blends produced the lowest soot emissions, especially at high EGR flow rates (greater than40 %) [29].

The use of i-butanol and diesel blends was found to significantly reduce soot emissions at the same EGR rate compared to pure diesel (~90 % reduction at 30 % EGR flow rate) [30].

When using conventional diesel with butanol, increasing the EGR rate leads to the total particulate concentration for all tested fuel blends decreasing at first and increasing later on. The total particle mass concentration remained stable initially and then increased sharply, while the particle geometric diameter changed slowly initially and then increased rapidly. Compared to D100, the peak value of the particle

Table 1
The main parameters of the test engine (1.9 TDI VW-Audi 1Z).

Parameter	Value
Compression ratio	19.5
Number of cylinders	4/OHC
Power	66 kW (4000 rpm)
Displacement	1986 cm^3
Piston diameter	79.5
Piston stroke	95.5
Torque	182 Nm (2000–2500 rpm)
Nozzle and holder assembly	Two spring
Nozzle opening pressure	190 bar
Nozzle type	Hole-type
Fuel injection	Direct (single)
Cooling system and type	Liquid cooling

Table 2
Laboratory equipment.

Equipment	Accuracy of measurement	Purpose of use
VAG-COM diagnostic equipment	–	Fuel injection timing, the start of injection (SOI)
AVL DiCom 4000 gas analyser	CO2, 0.1 % vol.; CO, 0.01 % vol.; HC, 1 ppm; NOx, 1 ppm; smoke, 0.01 m − 1	CO2, CO, HC, NOx, smoke absorption coefficient
Oscilloscope AVL DiSTEST DPM 800	–	In-cylinder pressure and CAD transmit
Encoder A58M- F	0.1758 crank angle degrees (CAD)	Crankshaft position
Piezo pressure sensor AVL GH13P	±0.11 (%FCO)	In-cylinder pressure
Air mass meter BOSCH HFM 5	<2%	Air mass
K type thermo couple	± 0.5 %	Intake air and the exhaust gas temperature
Load bench KI-5543	1.2 Nm	Brake torque
Delta OHM HD 2304.0 sensor TP704-28AI	± 0.0002 MPa	Intake air pressure
Scale SK-500	1.0 g	Fuel consumption

Table 3
Properties of 100% pure diesel, hydrotreated vegetable oil, biobutanol and castor oil.

Parameter	Diesel	Hydrotreated vegetable oil	Biobutanol	Castor oil
Density at 15° C, kg/m^3	830.4	780.0	810.0	964.0
Cetane number	51	70	18	28
Kinematic viscosity @ 40 °C, mm^2/s	3.500	3.200	2.63	246.00
Flash point, °C	60.5	67.0	35.0	220.0
Cold filter plugging point, °C	−34	−20	−39	−11
Sulfur content, mg/kg	7.3	7.1	0	0
Ash content, %	0	0	0	0
Water content, mg/kg	5.0	7.0	10.0	0
Element composition: (% mass): Carbon	86.20	84.55	65.00	73.60
Hydrogen	13.80	15.45	13.50	11.55
Oxygen	0	0	21.50	14.85
Stoichiometric AFR	14.79	15.18	11.30	11.91
Lower heating value, MJ/kg	43.10	44.10	33.00	41.30
Lower heating value, MJ/l	36.09	34.17	26.73	39.81
Higher heating value, MJ/kg	46.40	47.20	35.60	45.15
Higher heating value, MJ/l	38.85	36.57	28.84	43.52
Manufacturer, country	Orlean Lietuva, Lithuania	Neste, Finland	Carl Roth GmbH, Germany	Biochemlit, Lithuania

concentration of BD20 nucleation and the geometric diameter of the particles decrease. Adding PODE 3–4 to BD20 resulted in a decrease in the peak value of the nucleation particle number concentration initially, followed by an increase in the number of particles and a further decrease in the geometric diameter of the particles. At average or low EGR rates, the ratio of the small particle number concentration (up to 25 nm) to the total particle number concentration was significant for each of the four fuels. At high EGR rates, the ratio of concentration of the number of small particles (up to 25 nm) to the total number of particles decreased significantly [23,31].

The use of biodiesel with 10 % and 20 % EGR led to average NO_X emission reductions of 14.4 % and 27.6 %, respectively, compared to those when no EGR was used [32,33]. The use of EGR (0–15 %) and the SOI in a direct injection engine running on a diesel/*n*-butanol blend was found to result in no change in BTE, however it reduced total emissions. Therefore, the use of a proper EGR flow could help to reduce NOx emissions and maintain favourable combustion conditions. However, excessive EGR flow degrades combustion and increases emissions due to excessive gas mixing and a higher specific heat capacity attributable to CO_2 and water vapor in the EGR [34].

At high EGR rates, conventional diesel with different ratios of butanol and pentanol shows advantages in reducing total hydrocarbon content (THC). No significant difference in NOx was observed, with all fuels demonstrating the same emissions at constant EGR rate. B10P20 and B20P10 can not only reduce soot emissions but also carbon monoxide (CO) emissions at different EGR rates compared to conventional diesel. In summary, B20P10 fuels can be concluded to have better combustion and emission characteristics, especially at relatively high EGR rates [35].

When the EGR rate exceeds 30 %, the ignition delay of B20P10 and B30 is shorter than that of D100, because biodiesel contains oxygen and burns better at high EGR flow rates. High EGR flow reduces NOx and soot emissions simultaneously, but increases CO and THC emissions. Depending on the EGR rate and fuel properties, three-component blends with medium EGR flow may be more suitable for diesel engines [35].

The use of second-generation biodiesel such as HVO in internal combustion engines has been increasing. Therefore, adapting the engine itself to this type of fuel, in particular its blends with different alcohols, becomes important, as it allows to improve environmental indicators of the engine. Different EGR intensities are used to reduce nitrogen oxide emissions, but the literature review reveals that such studies have mainly been carried out with blends of first-generation biodiesel with various alcohols. Therefore, this study analysed in detail the impact of EGR rate on the performance of an internal combustion engine using different blends of second generation (HVO) and butanol fuels.

2. Materials and methods

The tests were conducted using a 1.9 TDI (Turbocharged Direct Injection) diesel engine with an Electronic Control Unit (ECU). The test engine was equipped with a BOSCH VP37 rotary fuel pump with two springs hole type nozzle injectors. Table 1 presents the engine characteristics. Exhaust gas recirculation (EGR) control was disconnected from the ECU, controlling the EGR rate using an EGR controller – pulse width modulator. The engine test equipment is described in Table 1, while Table 2 illustrates the test scheme.

Experimental tests were carried out using five different fuels and blends: conventional diesel (labelled as D100), pure hydrotreated

Table 4
Properties of fuel mixtures.

Properties	HVOB5	HVOB10	HVOB20
Density at 15 °C, kg/m³	780.4	782.4	786.4
Cetane number	67	64	59
Kinematic viscosity @ 40 °C, mm²/s	3.75	4.35	5.50
Flash point, °C	65.5	64.5	62.0
Cold filter plugging point, °C	−20	−22	−24
Sulphur content, mg/kg	6.7	6.3	5.6
Ash content, %	0	0	0
Water content, mg/kg	8.0	8.5	8.5
Element composition: (% mass): Carbon	83.55	82.55	80.57
Hydrogen	15.34	15.24	15.03
Oxygen	1.11	2.21	4.40
Stoichiometric AFR	14.98	14.77	14.38
Lower heating value, MJ/kg	43.54	42.98	41.87
Lower heating value, MJ/l	33.98	33.63	32.93
Higher heating value, MJ/kg	46.62	46.04	44.88
Higher heating value, MJ/l	36.38	36.02	35.29

vegetable oil (labelled as HVO100), hydrotreated vegetable oil and biobutanol mixtures: 95/5, 90/10 and 80/20 (% vol/% vol), and blends (labelled as HVOB5, HVOB10 and HVOB20). For better lubricity, castor oil (accounting for 5 % of biobutanol volume) was added as an additive to biobutanol blends. Properties of pure fuels were analysed and are presented in Table 3.

Engines were tested at the loads of 30 Nm, 60 Nm, 90 Nm, and 120 Nm. The selected engine load simulates engine running at speeds of ~ 50 km/h, ~80 km/h, ~100 km/h, and ~ 110 km/h. Experimental tests were conducted by setting a fixed engine shaft speed of n = 2000 rpm. At this shaft speed, the maximum torque of the engine being tested was reached, and the engine operated at the maximum cost efficiency. Tests were carried out at different EGR rates (0 %, 10 %, 20 %, 30 %). The EGR rate is determined by estimating the mass of intake air and is controlled by an EGR controller.

To ensure fuel properties, the fuels used (HVO and biobutanol) were blended on the day of the tests, just before their use. The fuels used were stored at the same temperature before testing to avoid the impact of temperature differences on density. Before and during the tests, the fuels and their blends were continuously stirred to avoid layering of the components due to different densities and to maintain the homogeneity of the mixture. The properties of the fuel mixtures used in the tests are presented in Table 4.

Numerical analysis of the combustion process was performed using AVL BURN software. The start of combustion (SOC), the combustion duration (CD), the rate of heat release (ROHR), the in-cylinder temperature and temperature rise, in-cylinder pressure and pressure rise were determined using the AVL BURN software based on the pressure in the cylinder measured during tests, air and fuel consumption, properties of the fuel used and other engine parameters [36,37]. The above parameters of the combustion process help to explain environmental and energy indicators using the conventional diesel, hydrotreated vegetable oil and biobutanol mixtures.

3. Results and discussion

The graphs of change of environmental and energy indicators are presented based on the experimental research results, using conventional diesel D100, HVO100 and HVOB5, HVOB10, HVOB20 blends in the above – mentioned laboratory compression ignition (CI) engine. The indicators obtained and the change trends were described based on the characteristics of the fuels used, the numerical analysis of the combustion process and the findings of other researchers.

3.1. Combustion indicators

The experimental research was conducted at constant engine crankshaft speed n = 2000 rpm and at four different engine loads (M_B = 30 Nm, M_B = 60 Nm, M_B = 90 Nm and M_B = 120 Nm), which correspond to the brake mean effective pressure BMEP = 0.2 MPa, BMEP = 0.4 MPa, BMEP = 0.6 MPa, BMEP = 0.8 MPa, also setting different EGR rates: 0 %, 10 %, 20 % and 30 %. (See Fig. 1).

Fig. 2 illustrates the start of injection (SOI), start of combustion (SOC) and combustion delay. According to the graph, brake mean effective pressure (0.4 MPa) of fuels and fuel blends was the same at EGR 0 %. SOI in this engine operating mode was different: D100 ~ 2.4 Crank Angle Degree (CAD) Before Top Dead Centre (BTDC), HVO100 ~ 0.8 CAD BTDC, HVOB5 ~ 0.9 CAD BTDC HVOB10 ~ 0.6 CAD BTDC, HVOB20 ~ 0.2 CAD BTDC (which is a 2.2 CAD delay compared to D100). SOI was controlled by the engine's ECU. It is likely that different SOIs were received due to different physico-chemical properties of fuel.

The fuel viscosity impacted the injection rate by affecting both the net hydraulic force and the viscous friction force at the leakage passage [38]. The SOCs were also different: D100 ~ 2.1 CAD After Top Dead Centre (ATDC), HVO100 and HVOB5 ~ 2.7 CAD ATDC, HVOB10 ~ 3.2 CAD ATDC, HVOB20 ~ 3.8 CAD ATDC (which is a 1.7 CAD delay compared to D100). The combustion delay phase duration for the above fuels was different: D100 ~ 4.5 CAD, HVO100 ~ 3.5 CAD, HVOB5 ~ 3.6 CAD, HVOB10 ~ 3.8 CAD and HVOB20 ~ 4.0 CAD. Using HVO100,

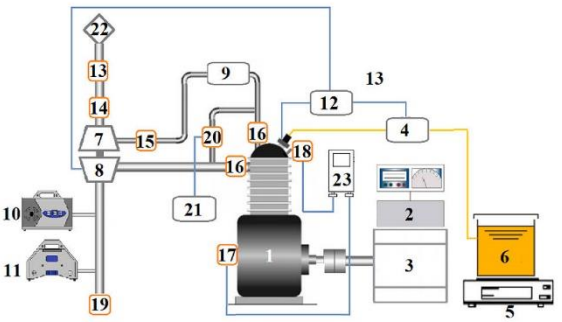


Fig. 1. Engine test equipment. 1 – engine, 2 – measurement output gauges, 3 – engine load unit, 4 – high pressure fuel pump, 5 – scales, 6 – fuel tank, 7 – compressor, 8 – turbocharger, 9 – intercooler, 10 – exhaust gas analyser, 11 – smoke analyser, 12 – ECU, 13 – air mass meter, 14 –intake air temperature sensor, 15 – pressure sensor, 16 – temperature sensor, 17 – crankshaft position sensor, 18 – in-cylinder pressure sensor, 19 – exhaust pipe, 20 – EGR valve, 21 – EGR controller, 22 – air filter, 23 – oscilloscope.

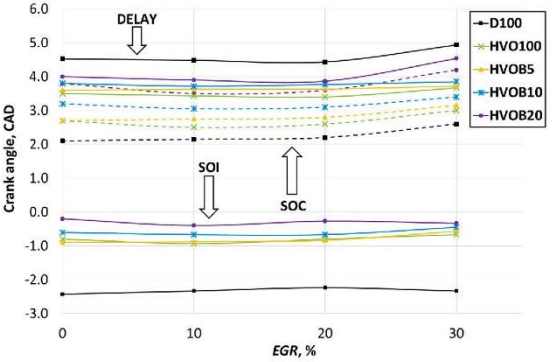


Fig. 2. SOI, SOC and combustion delay depending on EGR rate.

combustion delay was shorter by 1.0 CAD compared to D100 due to a higher cetane number of HVO. Increasing the ratio of biobutanol increases the ignition delay due to a lower cetane content, higher latent heat of vaporization and auto-ignition temperature compared to HVO, but the ignition delay of HVOB20 is 0.5 CAD shorter compared to D100. According to the graph, at EGR 30 %, the start of combustion is as follows: D100 ~ 2.6 CAD ATDC, HVO100 ~ 3.0 CAD ATDC, HVOB5 ~ 3.1 CAD ATDC, HVOB10 ~ 3.4 CAD ATDC, HVOB20 ~ 4.2 CAD ATDC. Increasing the EGR rate from 0 % to 30 % shows a trend of SOC delay. Different start of injection (SOI) was obtained in this engine operating mode: D100 ~ 2.3 CAD BTDC, HVO100 ~ 0.7 CAD BTDC, HVOB5 ~ 0.6 CAD BTDC, HVOB10 ~ 0.5 CAD BTDC, HVOB20 ~ 0.3 CAD BTDC. The SOI values obtained by increasing the EGR rate from 0 % to 30 % remained constant, varying over a small range. The delay times for the above fuels slightly increased due to a decrease in oxygen concentration: D100 ~ 4.9 CAD, HVO100 ~ 3.6 CAD, HVOB5 ~ 3.7 CAD, HVOB10 ~ 3.8 CAD and HVOB20 ~ 4.5 CAD. But with HVO100, compared to D100, the delay time was 1.3 CAD shorter, and with the increase in the ratio of biobutanol, delay values increased. HVOB20 delay was 0.4 CAD shorter compared to D100. Delay values vary within a small range with increasing EGR ratio from 0 % to 30 %, but there was a trend of a slight increase.

Rate of Heat Release is presented in Fig. 3a, with even brake mean effective pressure (0.4 MPa) of fuel and fuel blends at EGR 0 %. The analysis of fuel combustion duration (CD) revealed that pure diesel had the longest combustion duration: D100 ~ 57 CAD, HVO100 was ~ 0.5 CAD less compared to D100). CD decreased slightly with the addition of biobutanol: HVOB5 ~ 1 CAD less, HVOB10 ~ 2 CAD less and HVOB20 ~ 3 CAD less. The maximum ROHR value in the premixed combustion phase was achieved using pure diesel at 6 CAD ATDC – 37.0 J/CAD. When using HVO100, the maximum ROHR value was achieved at 7 CAD ATDC – 22 J/CAD (a decrease of ~ 40 %), HVOB5 value at 6 CAD ATDC – 26.5 J/CAD (a decrease of ~ 29 %). Having added 10 % and 20 % of biobutanol to HVO, the maximum ROHR in the premixed combustion phase was achieved at 7 CAD ATDC, and decreased respectively compared with pure diesel, i.e. ~ 19 % and ~ 5.5 %. A significantly decreasing ROHR in the premixed combustion phase reduced combustion temperature and the intensity of NOx generation [39]. When using pure diesel (D100), the maximum ROHR value in the controlled combustion phase was 31.5 J/CAD at 10 CAD ATDC. When using HVO100, the maximum ROHR value in this phase was 33.5 J/CAD (an increase of ~ 6 %) at 12 CAD ATDC. Having added biobutanol to HVO, the ROHR value in the controlled combustion phase was: HVOB5 – an increase of ~ 8 % at 12 CAD ATDC, HVOB10 – an increase of ~ 4.8 % at 12 CAD ATDC, HVOB20 – an increase of ~ 3.2 % at 13 CAD ATDC, the said ROHR value was compared to pure diesel. The increase of biobutanol concentration in the controlled combustion phase improves soot oxidation, but has a negative impact on engine energy efficiency [40].

The graph presented in Fig. 3d illustrates that fuels and their mixtures have the same brake mean effective pressure (0.4 MPa) at EGR 30 %. The analysis of combustion duration (CD) rendered varying results: D100 ~ 76.5 CAD, HVO100 - ~3.5 CAD higher compared to D100. Respectively, the CD increased slightly by adding biobutanol: HVOB5 was ~ 7.5 CAD higher, HVOB10 - ~7 CAD higher and HVOB20 - ~1 CAD lower. The assessment of combustion duration does not allow determining a clear trend when considering all fuels comprehensively. However, when comparing each fuel or blend separately, there is a clear trend of increasing CD with increasing biobutanol concentration, while when increasing the EGR rate, the CD increases to 30 %. The CO_2 gas and water vapour contained in EGR inhibit combustion and it lasts longer. In the premixed combustion phase, the maximum ROHR value was 31.0 J/CAD using pure diesel at 8 CAD ATDC. Hydrotreated vegetable oil (HVO) had a maximum ROHR value at 8 CAD ATDC – 25 J/CAD (~20 % reduction), HVOB5 at 9 CAD ATDC – 26 J/CAD (~16 % reduction), HVOB10 at 7 CAD ATDC – 24 J/CAD (~24 % reduction), and HVOB20 at 8 CAD ATDC – 26 J/CAD (~16 % reduction). When using pure diesel, the maximum ROHR value for controlled combustion phase was 30 J/CAD at 12 CAD ATDC. When using HVO, the maximum ROHR value in this phase was 29.5 J/CAD at 12 CAD ATDC (a ~ 2 % reduction). Having added biobutanol to HVO, ROHR in the controlled combustion phase was the following: in case of HVOB5 – an increase of ~ 1.5 % at 13 CAD ATDC, in case of HVOB10 – an increase of ~ 1.5 % at 13 CAD ATDC, and in case of HVOB20 – an increase of ~ 3 % at 10 CAD ATDC. The said ROHR value was compared to pure diesel. Having increased EGR rate to 30 %, the following ROHR change trends were observed: in the premixed combustion phase, EGR 30 % compared to EGR 0 % (Fig. 6a, b, c, d): ROHR in D100 decreased by 16 %, in HVO100 – it decreased by 13 %, in HVOB5 – it decreased by 2 %, in HVOB10 – it decreased by 20 %, and in HVOB20 – it decreased by 21 %. The difference in ROHR values in the controlled combustion phase decreased with EGR rate increasing to 30 %: in D100, the value decreased by 4.8 %, and respectively: HVO100 – by 12 %, HVOB5 – by 10 %, HVOB10- by 7 %, and HVOB20 – by 4.6 %.

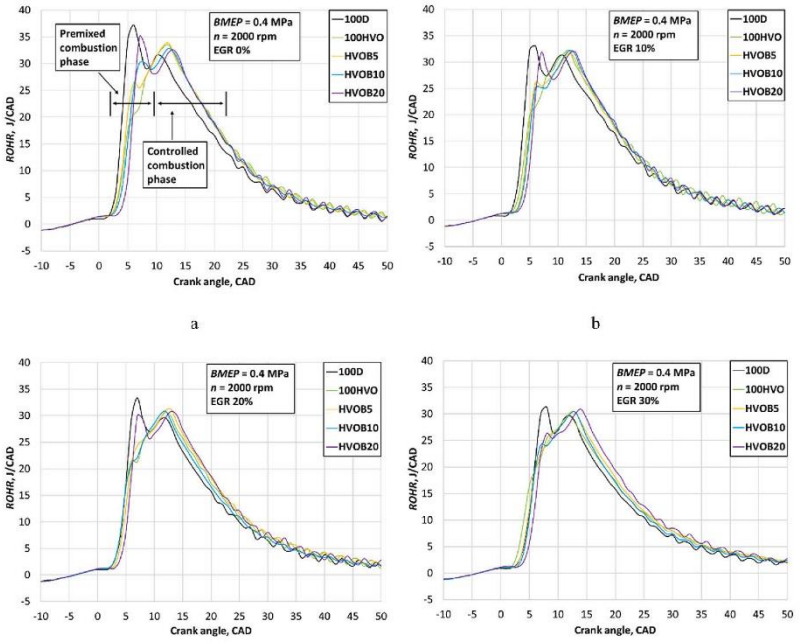


Fig. 3. Rate of in-cylinder heat release depending on fuel composition at different EGR rates.

The peak heat release rate and the in-cylinder temperature decreased with increasing the EGR rate, and the combustion phase was delayed, because with increasing the EGR rate, the volume ratio of CO_2 was increased in the cylinder, which diluted the mixture and reduced the chemical reaction rate. Moreover, CO_2 is s triatomic molecule and has a relatively high specific heat capacity, which means that an increase of the average in-cylinder temperature was limited with increasing the EGR rate [41].

The maximum temperature rise value can be achieved with conventional diesel (BMEP 0.4 MPA, EGR 0 %) ~ 54°K/CAD, at 6 CAD ATDC) (Fig. 4a). When using HVO100, the maximum temperature rise decreased by ~ 40 % at 6 CAD ATDC compared to conventional diesel. Also, HVOB5 dropped by ~ 31 % 6 CAD ATDC, HVOB10 – by ~ 24 % at 7 CAD ATDC and HVOB20 – by ~ 4 % at 7 CAD ATDC. Increasing the biobutanol concentration in HVO, the difference in the temperature rise in the premix combustion phase decreased compared to conventional diesel, and when the biobutanol concentration in HVO reached 20 %, the temperature rise difference was up to 4 % lower than in conventional diesel.

Having increased EGR rate to 30 % (Fig. 4d,) temperature rise values were different. Conventional diesel values in these conditions were ~ 49°K/CAD at 7 CAD ATDC). When using HVO100, the maximum temperature rise decreased by ~ 36 % at 7 CAD ATDC compared to conventional diesel. Meanwhile HVOB5 dropped by ~ 33 % 6 CAD ATDC, HVOB10 – by ~ 22 % at 7 CAD ATDC and HVOB20 – by ~ 14 % at 8 CAD ATDC. Having increased the EGR rate to 30 %, a steady decrease in the maximum temperature rise difference was observed (Fig. 6a, b, c, d) because the EGR gas suppress more intensive combustion more effectively. When increasing biobutanol concentration in HVO at EGR 30 %, the temperature rise difference in the premix combustion phase decreased compared to conventional diesel, as a higher EGR intensity due to high CO_2 content had a greater impact on the significant increase in ROHR due to the biobutanol properties. The comparison of EGR 30 % and EGR 0 % in terms of the temperature rise in the premix combustion phase revealed the following: with D100 – it decreased by 9 %, HVO100 – by 6.5 %, HVOB5 – by 10.5 %, HVOB10 – by 11.5 %, and HVOB20 – by 19 %. However, when biobutanol concentration in HVO100 reached 20 %, the temperature rise difference was 14 % lower than in case of conventional diesel.

The in-cylinder temperature graph (Annex 1) at BMEP 0.4 MPA and EGR 0 % reveals that in-cylinder temperature in the controlled combustion phase and differences in the in-cylinder temperature between different fuels and their mixtures used were minor and almost the same. Lower temperatures were observed in HVOB20 compared to D100.

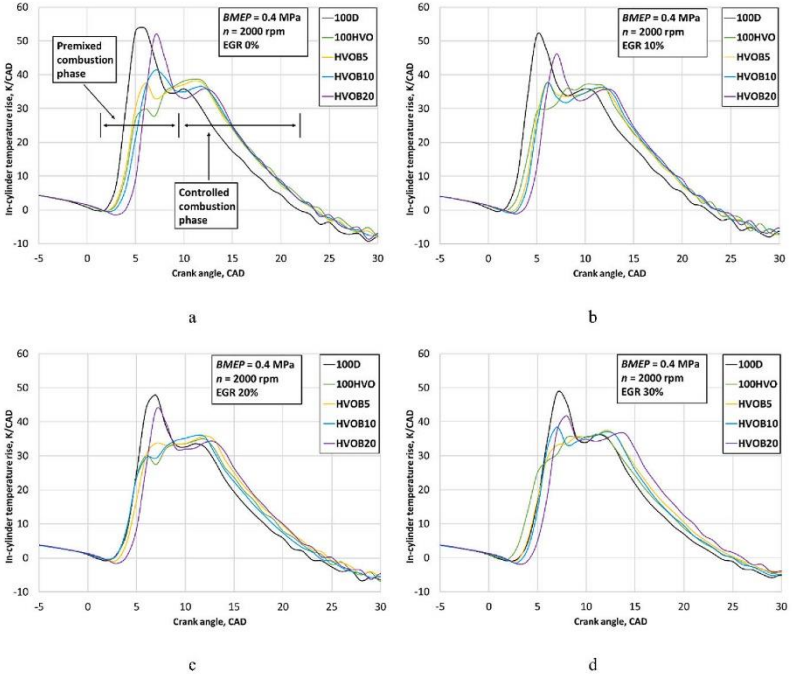


Fig. 4. In-cylinder temperature rise depending on fuel composition at different EGR rates.

When increasing EGR rate to 30 % (Annex 1a, b, c, d), in-cylinder temperature values changed, leading to significant differences. It was observed that increasing the biobutanol concentration in HVO, the in-cylinder temperature increased in the controlled combustion phase. The main reason for the increase in combustion temperature is the oxygen contained in the biobutanol, which improves the combustion process, especially at high EGR conditions [42]. The highest temperature of HVO100 was 1297 K, with D100 it was 1275 K, and in case of HVOB20 – 1316 K. In-cylinder temperature in the controlled combustion phase at EGR 30 %, compared to EGR 0 %, decreased with all fuels and their mixtures: in D100 – by 7.5 %, and, respectively, in HVO100 – by 5.5 %, in HVOB5 – by 6.5 %, in HVOB10 – by 7.5 %, and in HVOB20 – by 4.1 %. An increase of the biobutanol concentration and EGR rate in HVO fuels increases the length of the combustion process, which improves soot combustion. Delayed combustion results in more energy being expelled with exhaust gases, which increases the inflation pressure, leading to increasing pressure (Fig. 5d) and temperature during the compression stroke.

At BMEP = 0.4 MPa and EGR 0 %, the highest in-cylinder pressure rise in the premix combustion phase was achieved using conventional diesel ~ 0.18 MPa/CAD at 6 CAD ATDC (Annex 2a). In HVO100, the pressure rise in the premix combustion phase declined by ~ 77 % at 5 CAD ATDC, in HVOB5 – by ~ 66 % at 6 CAD ATDC, in HVOB10 – by ~ 61 % at 7 CAD ATDC, and in HVOB20 – by ~ 33 % at 7 CAD ATDC. At the same load, when increasing the EGR rate up to 30 %, similar trends in values were observed, but differences in the in-cylinder pressure rise between the fuels used and their blends declined. The highest value was also achieved with conventional diesel – ~0.13 MPa/CAD at 7 CAD ATDC. The HVO100 fuel pressure rise respectively decreased by ~ 62 % at 5 CAD ATDC, in case of HVOB5 – by ~ 61 % at 6 CAD ATDC, in case of HVOB10 – by ~ 46 % at 6 CAD ATDC, and in case of HVOB20 – by ~ 45 % at 7 CAD ATDC. The comparison of the received results at EGR 0 % and EGR 30 % (Annex 2d) revealed a steady remaining trend, with conventional diesel demonstrating the highest pressure rise. When using HVO fuels and increasing biobutanol concentration in them, the pressure rise increased. This can be explained by a lower cetane number, which results in a longer delay phase. Comparing EGR 30 % with EGR 0 %, for all fuels and fuel blends, the in-cylinder pressure rise in the premix combustion phase decreased: D100 – by 28 %, and, respectively, HVO100 – by 20 %, HVOB5 – by 25 %, HVOB10 – by 20 %, and HVOB20 – by 33.5 % (Fig. 5a, b, c, d).

Using conventional diesel, when EGR 0 %, the highest combustion pressure in the cylinder was ~ 7.3 MPa, and in case of HVO100, the maximum combustion pressure decreased to ~ 6.75 MPa (Annex 2a).

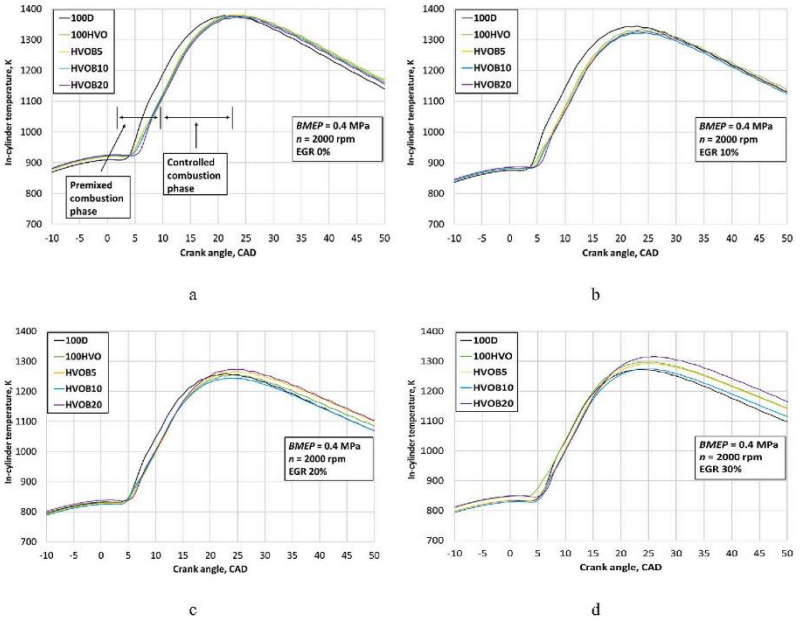


Fig. 5. In-cylinder pressure rise depending on fuel composition at different EGR rates.

When increasing biobutanol concentration in HVO, the maximum combustion pressure of the HVOB20 fuel mixture increased to ~ 6.8 MPa (~7% less compared to conventional diesel). Conventional diesel had the highest and HVO100 – the lowest value. When using the HVOB5 fuel mixture, the pressure value increased compared to HVO100, while further increasing biobutanol concentration, the pressure, though slightly, decreased steadily. This can be explained by different amounts of fuel supplied to maintain a constant torque, and the combustion process itself was different under these conditions when using different fuel mixtures, as different fuels contain different amounts of oxygen. The comparison of results revealed that at 30 % EGR, the highest combustion pressure in the cylinder was obtained with D100 ~ 6.1 MPa. With HVO100, the maximum combustion pressure decreased to ~ 6.0 MPa. Increasing the biobutanol concentration in the HVO fuel resulted in a further decrease in the maximum combustion pressure of the HVOB20 fuel blend, but the decrease was insignificant – ~5.8 MPa (~5% less compared to conventional diesel). At EGR 30 % (Fig. 7d), the trend of change was the same. Conventional diesel once again had the highest value, while using HVO100 and further adding biobutanol, the values decreased compared to HVO100. Adding from 5 % to 20 % of biobutanol, in-cylinder pressure values changed slightly. When comparing EGR 30 % with EGR 0 %, in-cylinder pressure gradually decreased using all fuels and their blends: D100 decreased by 16 %, and, respectively, HVO100 – by 11 %, HVOB5 – by 15 %, HVOB10 – by 15 %, and HVOB20 – by 14 % (Annex 2a, b, c, d).

Fig. 6 presents the dependence of the exhaust temperature (T_{ex}) on the engine load measured during experimental research. With increasing engine load (*BMEP* = 0.2 MPa; 0.4 MPa, 0.6 MPa and 0.8 MPa), temperature of exhausts of the used fuels and their mixtures was observed to increase, and EGR rate increased as well. This is due to the increase in the intake air volume and the temperature of the mixture fed to the EGR, but the combustion of biobutanol is faster than that of the HVO, and it ends faster. The increasing concentration of biobutanol in the mixture with HVO T_{ex} has little effect at low loads. However, at higher loads and higher EGR rate, the oxygen contained in the biobutanol compensates for lower excess air, accelerating combustion and reducing T_{ex}. The comparison in percentage terms at BMEP 0.4 MPa, and comparing EGR 30 % with EGR 0 %, Tex increased steadily: in D100, it increased by 15 %, in HVO100 – by 15 %, in HVOB5 – by 14.5 %, in HVOB10 – by 14 %, and in HVOB20 – by 13.5 %, respectively (Fig. 6a, b, c, d).

With the engine running on D100 and HVO blends with biobutanol (HVOB5, HVOB10 and HVOB20), the turbocharger pressure increased steadily with increasing engine load (Fig. 7). At BMEP 0.4 MPa, in the range from EGR 0 % to EGR 30 %, D100, HVO100, HVOB5, HVOB10 and HVOB20 values were almost the same in the said range. The results are more significant when considering a change in the turbocharger pressure with changing EGR rate. With EGR rate changing from 0 % to 30 %, the turbocharger pressure with D100 decreased by ~ 8 %, in case of HVO100, HVOB5 and HVOB10 it decreased by ~ 9 %, and with HVOB20, it decreased by ~ 8 % (Fig. 7a, b, c, d), because EGR led to decreased engine volumetric efficiency, which in turn reduced the exhaust gas flow. Biobutanol was observed to reduce turbocharger

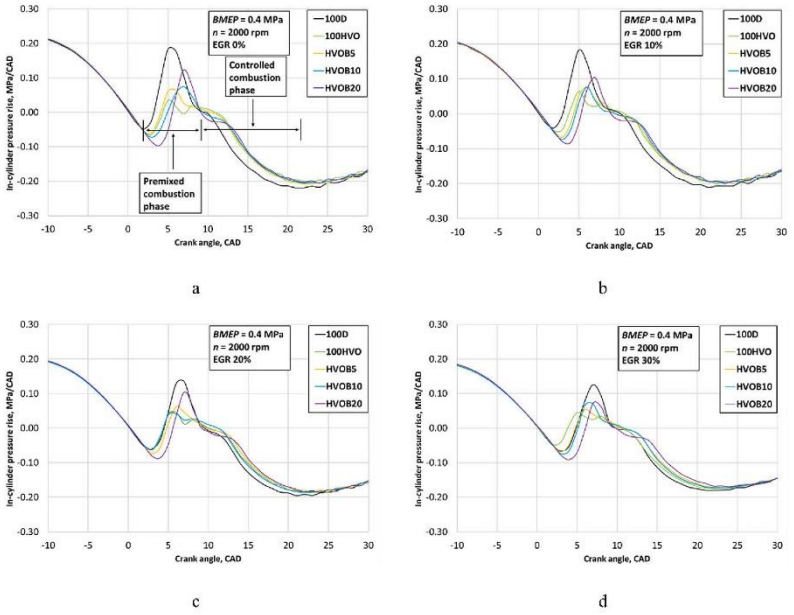


Fig. 6. Dependence of exhaust temperature on fuel composition and engine load at different EGR rates.

pressure at higher loads and higher EGR rate, because the oxygen contained in biobutanol accelerates combustion, which decreases due to the lower air content in the cylinder and in turn reduces exhaust gas energy.

3.2. Energy indicators

The brake specific fuel mass consumption (BSFC by mass) of the compression ignition engine determined during the research shows that at different engine loads and with changing EGR rate, the fuel mass consumption in terms of mass of the HVO100 is always lower compared to D100 (Fig. 8 a, b, c, d). Having added biobutanol to HVO, $BSFC_m$ was higher in HVOB5 compared to HVO100 under all engine loads and all EGR rates. When increasing biobutanol concentration in HVO fuel (from 10 % to 20 %), $BSFC_m$ increased compared to D100. The fuel research results (Table1 and Table 2) revealed that the lower heating value of HVO100 by mass (MJ/kg), (LHV_m) was 2.3 % higher than that of D100. With decreasing LHV_m value, higher $BSFC_m$ values were obtained. LHV_m of HVOB5 fuel blend was by a mere 1 % higher, LHV_m of HVOB10 – 0.3 % lower, HVOB20 LHV_m value – 2.8 % lower compared to D100. When comparing the change in $BSFC_m$ with D100, it was observed that HVO100 fuel mass consumption decreased by ~ 2.5 % at BMEP 0.4 MPa and EGR 0 %, in case of HVOB5 – it decreased by ~ 0.3 %, with HVOB10, it increased by ~ 1.5 %, and with HVOB20 – by ~ 5 %. At EGR 30 %, $BSFC_m$ of HVO100 fuel decreased by ~ 2 %, with HVOB5 it was equal to that of D100, with HVOB10 it increased by ~ 2 %, and with HVOB20 – by ~ 4.5 % compared to diesel. With BMEP 0.4 MPa, $BSFC_m$ values increased when comparing EGR 30 % and EGR 0 % values: D100 increased by 4 %, and, respectively: with HVO100 – by 5 %, with HVOB5 – by 4.8 %, with HVOB10 – by 4 %, and with HVOB20 – by 4 %. A change in $BSFC_m$ was determined not only by LHV_m, but also the engine operating cycle brake thermal efficiency (Fig. 9), which depends on the combustion process.

Results of the dependence of brake specific fuel volume consumption ($BSFC_V$) and the engine load differed compared to $BSFC_m$ (Fig. 8a, b, c, d, Annex 3a, b, c, d). This can be explained by lower HVO and biobutanol LHV values by volume (MJ/l) (Table 3 and Table 4): D100 36.09 MJ/l, and with HVO100 ~ 5 %, HVOB5 ~ 6 %, HVOB10 ~ 7 %, and HVOB20 ~ 9 % less compared to D100. Different trends in the change of LHV_V compared to LHV_m were determined by fuel density, which was ~ 7.5 %, ~7.0 %, ~6.5 %, ~6.0 % lower for HVO100, HVOB5, HVOB10 and HVOB20, respectively, compared to D100. Due to lower LHV_V under different engine loads and with changing EGR rate, $BSFC_V$ values of HVO100, HVO and biobutanol blends were in all cases higher compared to D100. When assessing the $BSFC_V$ change, under a fixed engine load (BMEP 0.4 MPa) and EGR 0 %, HVO100 increased by ~ 5 %, HVOB5 – by ~ 7 %, HVOB10 – by ~ 9 %, and HVOB20 – by ~ 12 % compared to D100. At EGR 30 %, the $BSFC_V$ indicator for HVO100 fuel increased by ~ 6 %, with HVOB5 – by ~ 7.5 %, with HVOB10 – by ~ 9 %, and with HVOB20 – by ~ 11 % compared to D100. We see that at higher biobutanol concentrations (HVOB20), a $BSFC_V$ increase was lower, because oxygen concentration increased in fuel partially compensates for the reduced air content in the engine cylinder due to EGR.

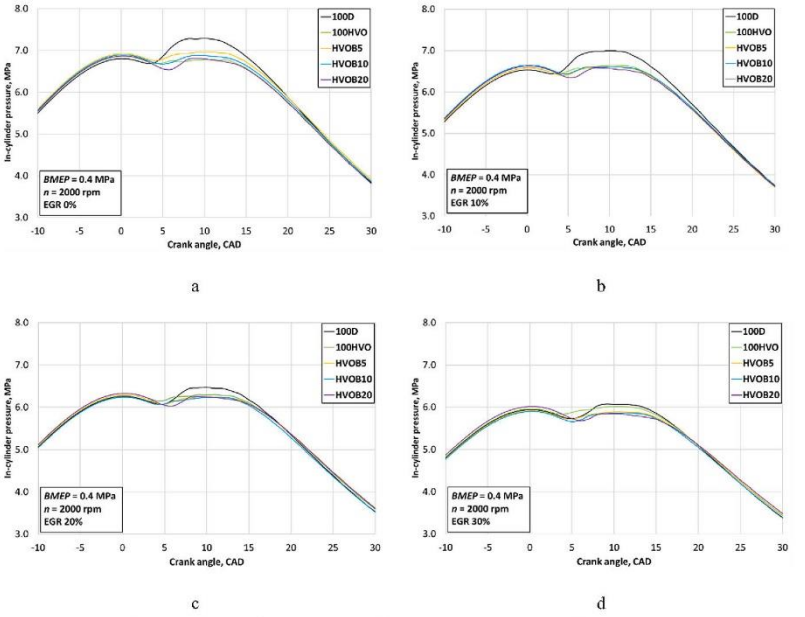


Fig. 7. Dependence of turbocharger pressure on fuel composition and engine load at different EGR rates.

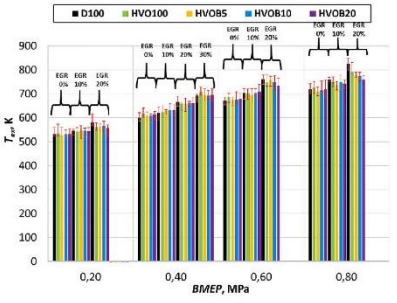


Fig. 8. Dependence of BSFC by mass on fuel composition and the engine load at different EGR rates.

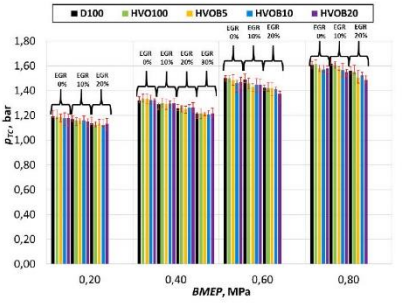


Fig. 9. Dependence of brake thermal efficiency on fuel composition and the engine load at different EGR rates.

At BMEP 0.4 MPa, BSFC $_{V}$ values increased when comparing EGR 30 % and EGR 0 %: in case of D100, they increased by 4 %, and, respectively: with HVO100 – by 5 %, with HVOB5 – by 4.8 %, with HVOB10 – by 4 %, and with HVOB20 – by 4 %.

Fig. 12 illustrates that the engine load changes in the 0.2 MPa – 0.8 MPa interval with EGR rate changing from 0 % to 30 % (Fig. 9). At EGR rate of 0 %, the brake thermal efficiency (BTE) value of HVO100 was 0.2 … 0.4 % higher compared to that of D100. Increasing the concentration

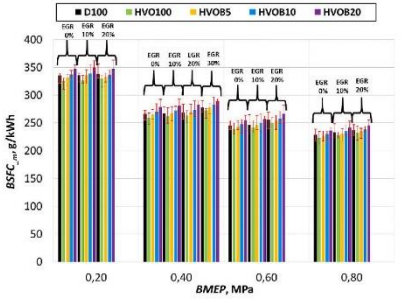


Fig. 10. Dependence of CO_2 emissions on fuel composition and engine load at different EGR rates.

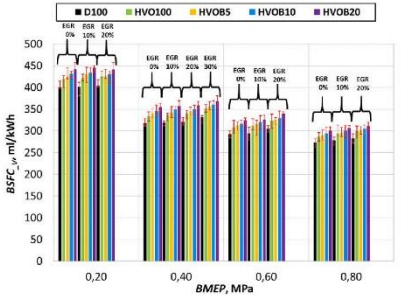


Fig. 11. Dependence of CO emissions on fuel composition and engine load at different EGR rates.

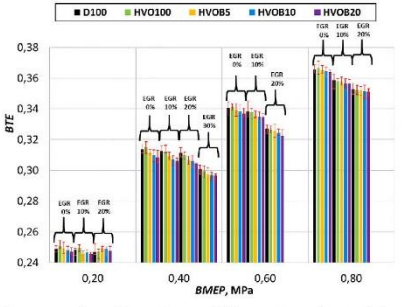


Fig. 12. Dependence of HC emissions on fuel composition and engine load at different EGR rates.

of biobutanol in HVO fuel from 5 % to 20 % shows a downward trend in BTE compared to D100. However, at higher EGR rates, the effect of biobutanol on the thermal efficiency of the engine was reduced or even improved. A percentage change in BTE at constant engine load BMEP = 0.4 MPa, EGR 0 %, BTE value of D100 was 0.315, and with HVO100 it increased by ~ 0.4 %. Having increased the biobutanol concentration in HVO from 5 % to 20 %, the BTE value started to decrease compared to D100: with HVOB5 – by ~ 0.7 %, with HVOB10 – by ~ 1.3 %, and with HVOB20 – by ~ 1.7 %. Compared to EGR 30 %, D100 BTE value was 0.299, with HVO100 it decreased by ~ 0.5 %, and, respectively: with HVOB5 – by ~ 1.1 %, HVOB10 and HVOB20 – by ~ 1.4 % compared to D100. When using HVO and biobutanol fuel blends, BTE reduction was slight, below 1.5 %, compared to D100. The assessment of the impact of EGR on BTE, at BMEP 0.4 MPa revealed that BTE values decreased when comparing EGR 30 % and EGR 0 %: with D100, it decreased by 4 %, and, respectively: with HVO100 – by 5 %, HVOB5 – by 4.6 %, with HVOB10 – by 4 %, and with HVOB20 – by 4 %.

Other studies have shown an increase in the BTE value of blends, which explains that adding *n*-butanol can reduce fuel viscosity, improve injection, and provide more oxygen to the combustion cylinder by converting the chemical energy of the fuel to useful engine performance [43]. However, in our research, the main component of fuel blends, HVO, which had a lower viscosity compared to conventional diesel and biobutanol, could improve injection quality insignificantly, but increased oxygen concentration and improved combustion. Using blends of biodiesel and 2-butanol in the CI engine, Pan. et al. found that BTE decreased at low engine loads, but increased by ~ 7 % at high engine loads [39]. Our study revealed a negative impact of biobutanol on BTE, but it was observed that with the engine running at higher loads, when increasing the EGR rate, an increase of the biobutanol concentration in HVO from 10 % to 20 % does not reduce BTE. When using diesel-butanol blends, under low loads, BTE is lower (about 31 %), while the conventional diesel and *tert*-butanol blend (TB50) has a slightly higher BTE (only 32.5 %). TB50 has a lower calorific value, requires more fuel injection at the same load and increases blend concentration. It reduces incomplete combustion and has slightly higher thermal efficiency than other fuels. An increase in the load from 0.4 MPa to 1.0 MPa increases BTE of test fuels, with diesel showing a larger increase in BTE than butanol blends, and conventional diesel and *sec*-butanol blend (SB50) showing a relatively small increase. This is mainly due to the cylinder temperature rising as the load increases, which creates favourable conditions for fuel and air to mix and burn. As the load continues to increase up to 1.2 MPa, the BTE of butanol blends is higher than (100 % conventional diesel fuel) D100, with a maximum BTE of up to 42 % for TB50 and a 3 % increase compared to D100 [44,45].

3.3. *Environmental indicators*

Carbon dioxide (CO_2) contained in exhaust gases is one of the key environmental indicators identified in research. Carbon dioxide is an important parameter in the environment that causes the greenhouse effect. This compound forms by the combustion of fuel-forming hydrocarbons when there is sufficient oxygen for a complete combustion process. CO_2 emissions depend on the carbon content of the fuel and the amount of fuel used. Having replaced D100 with HVO100, when the engine load varies from 0.2 to 0.8 BMEP (Fig. 10) and when the EGR rate is 0 %, CO_2 emissions decline by 2…3 % (Fig. 10). When increasing biobutanol concentration in HVO from 5 % to 20 %, fuel blend CO_2 emissions were lower, respectively: HVOB5 2.7 … 5.2 %, HVOB10 3.4 … 6.1 %, and HVOB20 2.4 … 6.4 % compared to D100. Bandbafha et. al. explain a reduction in carbon dioxide compared to conventional diesel. They state that biodiesel has a lower elemental carbon to hydrogen ratio (C / H) than conventional diesel, which results in lower CO_2 emissions compared to diesel [46,47]. Studies of the chemical-physical properties of the fuel used (Table1) determined that the Carbon/Hydrogen ratio (C/H) ratio in D100 was 6.25, and in HVO100 – 5.47 (12.5 % lower).

The addition of biobutanol further reduced the C/H ratio.

At a constant engine load BMEP = 0.4 MPa and EGR 30 %, CO_2 emissions in HVO100 decreased by ~ 3.2 %, and, respectively, in HVOB5 – by ~ 7 %, in HVOB10 – by ~ 7.5 %, and in HVOB20 – by ~ 7.8 % compared to D100. The received CO_2 research results allow stating that the use of up to 20 % of HVO in fuel decreases CO_2 emission. Even though when using HVO100 as well as HVO biobutanol blends CO_2 values decrease, when increasing EGR rate from 0 % to 30 %, CO_2 emissions increase because of decreasing engine's BTE and increasing $BSFC_m$.

At different engine loads and changing EGR rate, CO emissions in HVO100 are lower in all cases compared to D100 (Fig. 11). The reduction in CO using pure HVO can be explained by a lower C / H ratio, a simpler molecular structure of HVO and a better combustion. Engine load has been shown to have a significant impact on CO emissions. Higher load values are associated with lower CO emissions [29]. It has also been experimentally shown that the in-cylinder temperature increases from low load to high load, which allows for a better combustion and thus a reduction of CO emissions [48]. Having added biobutanol to HVO at EGR 0 %, CO emissions show a negligible downward trend compared to HVO100 at different engine loads. Bandbafha et. al. concluded that CO emissions from biofuels decrease due to a lower carbon-hydrogen ratio of biodiesel compared to diesel, and CO may also decrease due to z higher oxygen content in the fuel mixture [49].

An increase of EGR rate from 10 % to 30 % shows an increase in CO emissions without reaching values higher than D100 (Fig. 11).

At a constant engine load of 0.4 MPa, with EGR 0 %, CO values of HVO100 decrease by ~ 10.5 %, HVOB5 – by ~ 13 %, HVOB10 – by ~ 14 %, and HVOB20 – by ~ 13 % compared to D100, while with EGR 30 %, CO values are different: HVO100 ~ 9.5 %, HVOB5 ~ 2.2 %, HVOB10 ~ 2 %, and HVOB20 – ~1.4 % lower compared to D100. It was observed that by increasing the EGR rate to 30 %, worse HVO combustion leads to increasing CO emissions, but they remain ~ 10 % lower compared to conventional diesel. The addition of biobutanol at a high EGR rate (30 %) increases CO emissions compared to HVO100 due to increased fuel consumption, but with HVO and 5 … 10 % biobutanol blends, CO emissions are lower than those when the engine is running on D100 fuel.

A compression ignition engine with a turbocharger operates with excess air, resulting in low emissions of unburnt hydrocarbons (HC) [50]. The experimental research results revealed that at different engine loads (BMEP) and changing EGR rate, HC emissions in HVO100 were lower in all cases compared to D100 (Fig. 12) due to a lower C/H ratio and lower fuel mass consumption. The addition of biobutanol to HVO at EGR 0 % increased HC emissions at all engine loads. The use of HVOB20 fuel blend led to higher HC emissions compared to conventional diesel. HC emissions can be associated with lower fuel viscosity. Researchers Farayedhi et al. say that lower viscosity fuels produce smaller droplets in the injection process. These smaller droplets of fuel reach the walls of the cylinder, which causes an extinguishing effect due to a worse mixing of the fuel and air mixture at the walls, thus increasing the emission of unburnt fuel (HC) [51].

With increasing EGR rate from 10 % to 30 %, HC emissions decrease, because the fuel is injected into a higher temperature gas and evaporates better. HC emissions are also lower in all cases when using HVO100 fuel compared to D100. However, when biobutanol is added to HVO and the biobutanol concentration is increased to 20 %, HC emissions increase at all engine loads, but are not higher than emissions from D100. At a fixed engine load of 0.4 MPa with EGR 0 %, HC emissions from HVO100 decrease by ~ 30 % compared to D100, HVOB5 – by ~ 21 %, HVOB10 – by ~ 3.7 %, while with HVOB20 they are ~ 1.6 % higher compared to D100. At EGR 30 %, HC emissions are ~ 21.5 % lower with HVO100, ~7% lower with HVOB5, and ~ 6 % lower with HVOB10 and HVOB20 compared to D100. Considering the effect of EGR on HC emissions at BMEP 0.4 MPa, the comparison of EGR 30 % and EGR 0 % revealed that increasing EGR rate decreases HC emissions: D100 decreased by 13 %, and, respectively, HVO100 – by 0.5 %, HVOB5 – by 3.5 %, HVOB10 – by 14 %, and HVOB20 – by 17 %.

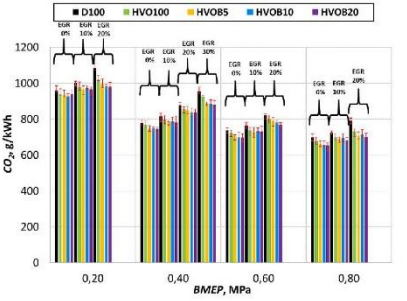


Fig. 13. Dependence of smoke on fuel composition and engine load at different EGR rates.

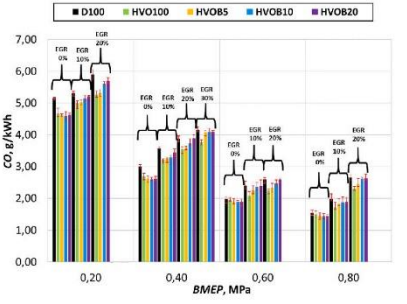


Fig. 14. Dependence of NOx emissions on fuel composition and engine load at different EGR rates.

The analysis of the composition of fuels and fuel blends (Table 3 and Table 4) revealed that the stoichiometric air–fuel ratio (AFR) for D100 fuel was 14.79 kg, HVO100 – 15.18 kg (2.6 % more), HVOB5 – 14.98 kg (1.3 % more), HVOB10 – 14.77 kg (0.1 % less) and HVOB20 – 14.38 kg (2.8 % less). AFR decreased by adding biobutanol and castor oil to HVO fuels due to the oxygen (O_2) contained in the biobutanol and castor oil.

The use of HVO100 and HVO/biobutanol fuel blends resulted in lower smoke emissions compared to D100 (Fig. 13) for a given load and EGR rate. It was observed that an increase of the EGR rate from 0 % to 30 % at constant engine load (BMEP) resulted in an increase in smoke output due to a decrease in O_2 content and an increase in CO_2 and H_2O in the cylinder. At a constant engine load of 0.4 MPa with EGR0%, the smoke values of HVO100 compared to D100 decreased by ~ 29 %, with HVOB5 - by ~ 58 %, with HVOB10 - by ~ 50 %, and with HVOB20 - by ~ 80 %, because the C/H ratio decreases and due to the fact that biobutanol contains oxygen. The researchers Imdadul et al. obtained similar reductions in smoke emissions compared to conventional diesel when using mixtures of *n*-butanol and biodiesel at different ratios [52]. The researchers Imtenan et. al. also confirm that oxygen contained in alcohols such as *n*-butanol reduces smoke emissions when used in combination with biodiesel [53]. In terms of the impact of EGR rate on

the smoke output at BMEP 0.4 MPa, when comparing EGR 30 % with EGR 0 %, increasing the EGR rate resulted in a ~ 6-fold increase with D100, but the smoke output partially decreased when using mixtures of HVO and bio-butanol, with a decrease of ~ 11 % for HVO100, ~23 % for HVOB5, ~47 % for HVOB10, and ~ 57 % for HVOB20 compared to D100. Thus a better smoke reduction performance with HVO/bio-butanol blends is achieved at a lower EGR rate, while a higher EGR rate suppresses the positive impact of biobutanol.

In the experimental research, D100 had the highest NOx emissions and HVO100 – the lowest NOx emissions, for all the presented cases, at different engine loads and EGR rates (Fig. 14). When increasing the biobutanol concentration in HVO fuels, NOx emissions steadily increased at all engine loads and EGR rate conditions, but were not higher compared to D100. The comparison of NOx emissions of pure HVO and its blends with biobutanol and pure D100 at BMEP 0.4 MPa and EGR 0 %, NOx emissions of HVO100 decreased by ~ 7 % (Fig. A3), HVOB5 – by ~ 5.5 %, HVOB10 – by ~ 3 %, and HVOB20 – by ~ 2.3 %. Vojtisek et al. conducted similar research and found that NOx emissions were similar when comparing HVO and butanol blends with pure HVO, but in both cases they were lower than of pure diesel [54]. The addition of oxygen to fuels has also rendered controversial results. Studies conducted by Prabu et al. with biodiesel and *n*-butanol (adding 30 % of *n*-butanol to the biodiesel volume) showed a reduction in NOx emissions compared to alcohol free diesels. This phenomenon is substantiated by a reduction of the combustion temperature [55].

Exhaust gas recirculation is a common and effective technology for reducing NOx emissions [56]. When increasing the EGR rate, NOx emissions decline because of returning CO_2, water vapour and other combustion products to the cylinder, reducing combustion intensity and temperature. This reduces the intensity of thermal NOx formation. At EGR 30 %: HVO100 ~ 22 %, HVOB5 ~ 16 %, HVOB10 ~ 17 %, and HVOB20 ~ 12 % less compared to D100. The impact of EGR on NOx emissions at BMEP 0.4 MPa, the NOx emissions change as follows when comparing EGR 30 % with EGR 0 %: they decrease by 38 % for D100, by 53 % - for HVO100, by 52.5 % - for HVOB5, by 52.5 % - for HVOB10, and by 52 % - for HVOB20, respectively. The results show that in the case of EGR, adding biobutanol to HVO fuel increases NOx emissions because the delay phase increases due to the decrease in the cetane number of the fuel blend, which increases the heat release and the temperature during the premix combustion phase (Figs. 2, 3, 4). The oxygen contained in biobutanol also increases the combustion temperature.

4. Conclusions

1. Having replaced D100 with HVO100 and biobutanol blends, SOI was delayed due to differences in fuel density, viscous friction force and compressibility. CN of HVO100 ~ 37 % is higher and the ignition delay phase shorter if it compared to D100. Biobutanol increases the ignition delay of fuel mixtures due to lower cetane number, higher latent heat of vaporization and auto-ignition temperature, but HVOB20 ignition delay shorter if it compared to D100. This resulted in a lower maximum ROHR for HVO100, HVOB5, HVOB10 and HVOB20 fuels of ~ 40 %, ~29 %, ~19 % and ~ 6 %, respectively, during the premixed combustion phase. During the controlled combustion phase, the maximum ROHR increased by ~ 6 %, ~8%, ~5% and ~ 3 %, because the fuel injection takes longer due to the reduced LHV_V, but the oxygen in the biobutanol intensifies the combustion. For HVOB20, the increase of EGR rate from 0 % to 30 % resulted in an increase in the in-cylinder temperature, however, this did not increase NO_x emissions, because an increase in CO_2 and water vapour caused by EGR reduced combustion intensity in the cylinder.
2. $BSFC_m$ of HVO100 in all cases was lower ~ 2.5 % compared to D100 due 2.3 % higher LHV_m. As the HVOB20 turi 2.9 % lower LHV_m, $BSFC_m$ increased by ~ 5 % compared to D100. $BSFC_V$ increased by ~ 12 % due to 8.8 % lower LHV_V. BTE of HVO100 was 0.2 … 0.4 % higher, but the addition of biobutanol (5 %, 10 % and 20 %) reduced the BTE by ~ 0.7 %, ~1.3 % and ~ 1.7 % respectively compared to D100, because increased $BSFC_V$ fuel injection and combustion takes longer. Increasing EGR rate decreased BTE of all fuels, but increasing the biobutanol concentration from 10 % to 20 % at EGR 30 % stopped the decrease in BTE as the oxygen in the biobutanol compensates for the reduced air content in the cylinder.
3. Having replaced D100 with HVO100, CO_2 emission decreased iki ~ 3 %, and having added 5 %, 10 % and 20 % of biobutanol, CO_2 emissions decreased iki ~ 5 %, ~6%, and iki ~ 6.5 % due to a lower C/H ratio compared to D100. Increasing the EGR ratio for all fuels used resulted in an increase in CO_2 emissions due to increasing $BSFC_m$, but HVO fuel and the 20 % biobutanol additive retained iki ~ 7 % lower GHG emissions compared to D100 due to 8.8 % lower C/H santykio. HVO100 has till 10 % lower CO emissions compared to D100, and when it was used additive of biobutanol CO emissions reduced insignificantly. With EGR on, CO emissions of all fuels increased due to the negative influence of CO_2 on combustion quality, and in this case, the addition of biobutanol even increased CO emissions, but HVOB20 CO emission remained lower compared to D100. HC emissions decreased till 30 % having replaced D100 with HVO100, but increased again to the level of D100 when the biobutanol concentration was increased to 20 % in the blend. The increase in emissions of incomplete combustion products (CO and HC) was due to the addition of butanol, as the decrease in viscosity of the fuel mixture causes fuel droplets to reach the periphery of the combustion chamber, where they are less well mixed with the air and do not burn completely.
4. The replacement of D100 with HVO100 reduced the smoke output by ~ 11 % and the addition of 5 %, 10 % and 20 % biobutanol further reduced smoke output by ~ 23 %, ~47 % and ~ 57 % compared to D100 due to the reduction of the C/H ratio of the fuel and the increase of the oxygen concentration in the fuel. Increasing the EGR rate resulted in an intense increase in smoke, but the biobutanol significantly compensated for the increase in smokiness. NO_x emissions decreased by ~ 7 % having replaced D100 with HVO100 due higher cetane number resulting in a reduction maximum of ROHR during the premixed combustion phase. The use of 5 %, 10 % and 20 % biobutanol additive increased NO_x emissions, but they remained ~ 5.5 %, ~3% and ~ 2.3 % lower compared to D100. At EGR rate of 30 %, NO_x emissions decreased by 40 … 50 % for all fuels therefore at a higher EGR rate an increase in biobutanol concentration in the mixture with HVO does not have a significant impact on increasing NO_x emissions.

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Data Availability Statement

The study did not report any data.

CRediT authorship contribution statement

Gintaras Valeika: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Jonas Matijošius:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Alfredas Rimkus:** Conceptualization, Methodology, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision.

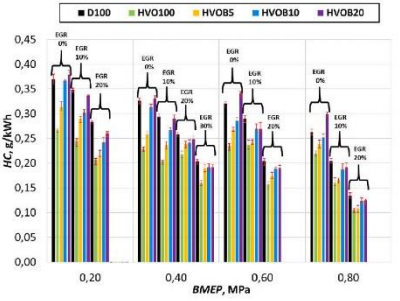


Fig. A1. In-cylinder temperature depending on fuel composition at different EGR rates.

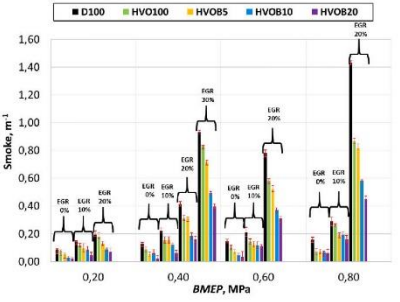


Fig. A2. In-cylinder pressure depending on fuel composition at different EGR rates.

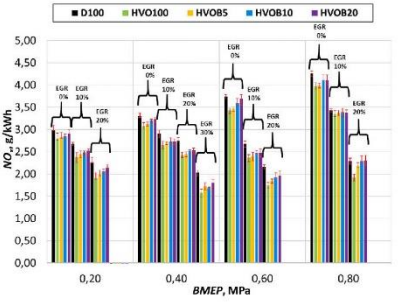


Fig. A3. Dependence of BSFC by volume on fuel composition and the engine load at different EGR rates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

See Figs. A1-A3.

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Smoke Formation during Combustion of Biofuel Blends in the Internal Combustion Compression Ignition Engine

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Abstract: The proposed changes to the legislation on diesel cars require intensification of work on the possibilities of reducing emissions of harmful substances into the atmosphere by these vehicles. The subject of experimental research included in the manuscript was the Skoda Octavia with a 1.9 TDI (turbocharged direct injection) compression ignition engine (type 1Z). Light absorption measurements of smokiness of the exhaust gases emitted after combustion of various biofuels (conventional diesel, pure hydrotreated vegetable oil, hydrotreated vegetable oil, biobutanol) and their blends with fossil diesel fuel were studied. The measured light absorption coefficient is the reciprocal of the thickness of the layer, after passing through which the light has a ten times lower intensity. Its unit is the reciprocal of the meter (1/m or m^{-1}). The results obtained by means of a standard smokiness meter indicate that the use of biofuels or their blends, in general, reduces smoke formation.

Keywords: vehicle; biofuel; diagnostic

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1. Introduction

Emission of harmful exhaust gases is a subject that has accompanied us for years [1–3]. These efforts are particularly highlighted when the next state-of-the-environment reports are published. According to SNAP (Selected Nomenclature for sources of Air Pollution), eleven emission source categories are distinguished: combustion processes in the energy production and transformation sector, combustion processes in the municipal and residential sectors, combustion processes in industry, production processes, extraction and distribution of fossil fuels, use of solvents and other products, road transport, other vehicles and equipment, waste management, agriculture, and other emission and abatement sources [4]. However, to a large extent, policy makers focus primarily on the transport sector [5–7].

The transport sector is responsible for almost a quarter of all global greenhouse gas (GHG) emissions and is a major contributor to air pollution in urban areas [8,9]. Achieving climate neutrality for cars and their factories requires manufacturers to spend billions of dollars, great determination, and the ability to comprehensively analyse issues and impacts on sustainability [10–12]. Consistent action by producer groups brings tangible results in the form of millions of tonnes of carbon dioxide and other pollutants that do not reach the atmosphere. It is not only emissions from car exhaust pipes that have an impact on the environment [13–15]. Compounds released during tyre wear during driving are also harmful.

Moreover, during braking, the brake discs emit solid particles; this can be eliminated by introducing an electrical component into the drive systems, permitting regenerative braking with an electric motor, which largely replaces the conventional braking system [16,17]. The issues of so-called secondary dusting are also important. A moving car blasts into the air what lies on the roadway: nitrogen oxides, carbon, benzene compounds, heavy metals, and aromatic hydrocarbons. Carbon dioxide and monoxide, nitrogen oxides, sulphur dioxide, and dust are also produced in the power plant production process necessary for steelworks and factories. Therefore, the way in which this energy is obtained is also crucial [18–20].

The operation of any internal combustion engine is associated with the emission of a certain amount of harmful substances [21,22]. Their maximum content in exhaust gases is determined by the relevant standards, which are set separately for petrol and diesel units [23,24].

Emission standards are the limits set by the European Union for the emission of harmful substances in the exhaust gases, which are imposed on new cars sold in the EU and the European Economic Area. The first Euro 1 standard was introduced in 1993 and the new Euro 7 emission standard is planned for early 2025. Each of the successive standards introduced lowered the limit value for emissions into the atmosphere. Information about the emission standard of the car is contained in the vehicle documents and visible on the sticker located in the door opening next to the driver's seat. This is important not only from the point of view of environmental awareness, but also from the point of view of clean transport zones in cities [25,26].

Compression ignition engines differ, compared to spark ignition engines, in the way the mixture is prepared, its combustion, and the type of fuel used. The consequence of these differences is different values of the combustion parameters and different composition and concentration of the main components of the exhaust gas [27–29].

Currently, work on second-generation biofuels (e.g., cellulosic ethanol, biohydrogen, biomethanol) and third-generation biofuels (e.g., biofuels produced from algae and other micro-organisms) is continuing in many research centres around the world. One way to reduce the environmental impact of toxic components of exhaust gases is to use fuels of plant origin [30–32].

Studies of exhaust emissions, composition of engine exhaust gases, and level of smoke are the subject of many scientific papers. A review of the analysis of performance and emission characteristics of a diesel engine fuelled by different gaseous fuels and biofuels was carried out in [33]. Modification of diesel with oxide nanoparticles to investigate its effect on engine behaviour was the subject of research in [34]. A multi-objective optimisation test of performance, combustion, and emissions characteristics of a diesel engine fuelled with diesel, kerosene, and ethanol was the subject of research in [35].

Due to its specific physicochemical properties, butanol is listed among the potential successors of ethanol. Butanol is an alcohol that can be produced either by petrochemical processes or by biomass fermentation and, therefore, from renewable sources (biobutanol).

Butanol is found in the form of four isomers: n-butanol, sec-butanol, isobutanol, and tert-butanol, differing from each other in both the location of the hydroxyl group and the structure of the hydrocarbon chain (simple or branched). Isobutanol, due to its fairly high octane number, is a component of gasoline (the normative requirements allow its content in petrol up to 10% (*v*/*v*)). Tert-butanol is used as an additive to gasoline, increasing the octane number. N-butanol is used as an intermediate for organic synthesis, an additive for oils, and a raw material for the production of solvents and co-solvents. This isomer is also most commonly used for testing applications in compression ignition engines. The advantage of butanol is the ability to use blends with petroleum fuels with a higher alcohol content (up to 40%) without engine modification [33–35].

Among the fuels on which laboratory tests are ongoing is HVO (hydrogenated vegetable oil). HVO emits 90% less carbon dioxide, 30% less particulate matter, and 9% less nitric oxide compared to conventional diesel. The basis for its production is waste of vegetable origin, such as leftovers of vegetables and fruits or even expired margarine. HVO

can be sold as pure HVO100 or blended with conventional diesel in various proportions, e.g., HVO30, HVO50, etc. In pure form, it reduces CO_2 emissions by approx. 90% [36,37].

As a result of a technical fault or exploitation, the engine of a car may emit an above-average amount of harmful substances. Detecting deviations from the standards adopted in this area is the task of vehicle inspection stations, which are currently obliged to check exhaust emissions during the periodic technical inspection. Depending on the type of drive unit, not only the measurement methods and measuring equipment but also the measured parameters are different.

Gasoline cars use a high-precision analyser to measure carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and hydrocarbons (CH), as well as to calculate the lambda coefficient (λ) for the composition of the fuel–air mixture that burns in the cylinders.

In the case of cars equipped with compression ignition engines, a device named an opacimeter is used to measure the so-called light absorption coefficient. During the periodical technical inspection, exhaust smoke control shall be carried out by means of a free acceleration test, which is reduced to measuring the maximum smoke occurring during free acceleration of the engine from idle speed to maximum speed. The smoke that occurs during the free acceleration test is assumed to be comparable to the smoke at the highest engine torque.

Nitrogen oxides (NO_x) and particulate matter (PM) are the main toxic components in the exhaust gas of compression ignition engines. Particulate matter (PM) emissions are specific to compression ignition engines and result from the properties of the fuel used, the combustion process, and the formation of a combustible mixture. The measurement of the correctness of the combustion process in a compression ignition engine is the smoke of the exhaust gases. Exhaust smoke is the result of the presence of particulate matter (mainly black smoke), hydrocarbons (blue smoke), and water vapour (white smoke). The exhaust smoke measurement for diagnostic purposes shall be carried out with the vehicle stationary, with the gear lever in the neutral position, while the engine is running in free gear using the free acceleration method. The parking brake should be engaged. The setting of the fuel dose adjustment screw of the injection pump shall be as recommended by the manufacturer.

One of the fundamental issues in assessing air quality is the concentration of particulate matter. Particulate matter is a term generally used for a type of air pollution consisting of a complex of different mixtures of suspended particles that vary in size, composition, and location of formation. The basic distribution of particulate matter results from their aerodynamic diameter, which allowed the determination of two main groups: PM2.5 and PM10 (particulate matter) for diameters smaller than 2.5 μm and 10 μm, respectively. PN is the particle number (PN).

All exhaust components from complete and incomplete combustion of motor fuels shall be transparent and colourless. Incorrect combustion of the mixture is evidenced by the emission of opaque exhaust gases of a specified colour into the environment by the engine in operation. Exhaust gases become discoloured as a result of incomplete combustion of fuel. The products of such combustion are coal in the form of fine soot particles and unburned hydrocarbons and water vapour condensing in the exhaust pipe. Soot is not present in pure form. It absorbs large quantities of hydrocarbons and is, therefore, a very toxic component of exhaust gases, mainly in compression ignition engines. The colour of the exhaust gases and the degree of their blackening allow to determine with a high probability the type of underwriting and the degree of engine wear [38–40].

The aim of the study, the results of which are presented in the manuscript, was to analyse the exhaust smoke and the concentration of particulate matter (PM) emitted by a diesel vehicle. The subject of the research was the Skoda Octavia with a 1.9 TDI (turbocharged direct injection) compression ignition engine (type 1Z) powered by 5 different fuels and their mixtures: conventional diesel (labelled as D100), pure hydrotreated vegetable oil (labelled as HVO100), hydrotreated vegetable oil and biobutanol mixtures (95/5, 90/10, and 80/20 (% vol/% vol)), and blends (labelled as HVOB5, HVOB10, and HVOB20). For better lubricity, castor oil (accounting for 5% of biobutanol volume) was added as an additive

to biobutanol blends. Experimental tests were carried out using the MAHA LPS 2000 test stand and with the ROSS-TECH VCDS vehicle diagnostic device.

For many years, the authors of this manuscript have been studying the application of very different compositions of fuel mixtures (Petrol 95, ethanol, methanol, DME, CNG, LPG, diesel FAME, rapeseed oil butanol), taking into account both engine type and vehicle type [41–45]. The tests carried out are laboratory tests performed on measuring stations and tests performed using computer simulations (based on hourly fuel consumption characteristics, g/kWh). For studies based on computer simulations, the author's computational tools are based on neural networks, and the results of the studies must always be analysed in the context of laboratory studies. Taking into account the very broad context of the research carried out in the context of the composition of fuel mixtures, the vehicle brand is taken into account. This is relevant in the context of driving tests, where the emissions of pollutants from the vehicle into the atmosphere are analysed in the context of permissible limits (taking into account additional vehicle equipment, e.g., air conditioning, heated seats). In addition, not only exhaust emissions but also water vapour emissions from the vehicle's exhaust system are analysed in the data presented by the authors.

2. Materials and Methods

Tests were conducted using the Skoda Octavia with a 1.9 TDI (turbocharged direct injection) compression ignition engine (type 1Z), with 4 cylinders, 1896 cm^3 displacement TDI (type—1Z) compression ignition engine. Maximum power of engine: 66 kW at 4000 rpm. Maximum torque: 182 Nm at 1900 rpm. Detailed technical data of the 1.9 TDI engine are listed in Table 1 [46].

Table 1. The main parameters of the test engine (1.9 TDI type: 1Z) [46].

Parameter	Value
Engine type—number of cylinders	Inline 4
Engine code	ALH
Fuel type	Diesel
Engine alignment	Transverse
Engine displacement	1896 cm^3
Bore × stroke	79.5 × 95.5 mm
Number of valves	8 valves
Aspiration	Turbo
Maximum power	66 kW (4000 rpm)
Maximum torque	210 Nm (1900 rpm)
Drive wheels	FWD
Piston diameter, mm	79.5 mm
Piston stroke, mm	95.5 mm
Compression ratio	19.5
Displacement	1896 cm^3
Number of cylinders	4/OHC
Fuel injection	Direct (single)
Nozzle type	Hole-type
Nozzle opening pressure	190 bar
Nozzle and holder assembly	Two-spring
Cooling system type	Liquid cooling
Transmission gearbox—number of Speeds	5-speed manual

Using computerized vehicle test bench, MAHA LPS 2000 (Table 2) was established testing vehicle engines' (Skoda Octavia with 1.9 TDI diesel, type 1Z) torque and power (Figure 1).

Vehicle test bench has options to make measurements using any gear, with selected load or calculated driving resistance. The load for vehicle is generated by an electromagnetic brake which converts the mechanical energy of the engine transmitted to the wheels into

thermal energy and radiates it outwards. Vehicle load bench technical parameters are listed in Table 2.

Table 2. The main parameters of vehicle load bench (MAHA LPS 2000) [47].

Parameter	Value
Load equipment	Electromagnetic brake
Rate adjustment limits	260
Maximum measuring load	6 kN (attractive force)
Maximum break power, kW	260
Measurement error	±2

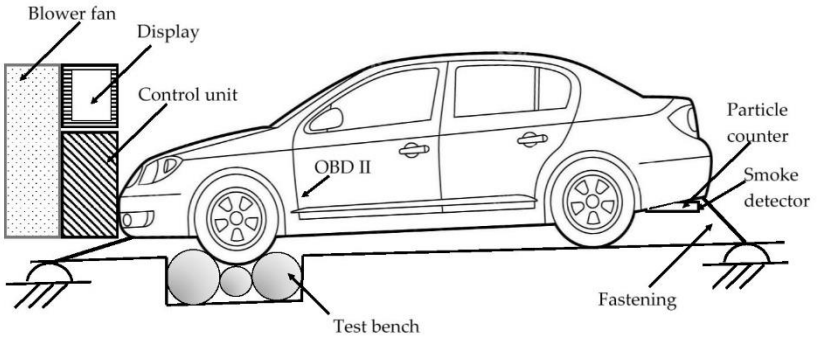


Figure 1. Laboratory test equipment.

During experimental tests, car diagnostic device ROSS-TECH VCDS was used, in addition to device scan data using OBDII connection from electronic control unit (ECU) to measure the following: fuel consumption, turbocharger pressure, fuel injection timing. Data from the car diagnostic device ROSS-TECH VCDS were recorded at ~2.5 s interval [48–50].

Analysing engine ECU (electronic control unit) data, we observed that recorded data points are sent in separate blocks and are not exactly synchronized in time (engine speed (rpm), cyclic fuel quantity (mg/cycl), cyclic air mass (mg/cycl), fuel injection timing (°BTDC), turbocharger pressure (mbar), or fuel injection timing (mg/cycl).

Experimental tests were carried out three times using vehicle test bench MAHA LPS 2000. Engine external speed characteristic was measured using the ECU data recorded by the car diagnostic device ROSS-TECH VCDS.

Emission of diesel cars is estimated using two different methods: measuring exhaust gas smoke and particle matter (PM) concentration. Smoke measured with a smoke detector CET2200C, which determines light absorption coefficient, showing how much light is emitted by the light installed in the meter source, is absorbed by the smoke emitted from the vehicle. Smoke meter measurement limits are 0–99.99 m^{-1} and accuracy is 0.01 m^{-1}.

Particulate matter (PN) emissions from vehicles equipped with particulate filters are very low. Particulate number measurements in the exhaust gas are carried out on diluted (PEMS, portable emissions measurement systems) or solid exhaust gas. Particles with a nominal diameter of 23 nm to 2.5 µm shall be measured. PEMS measures raw exhaust gases with all related challenges (e.g., condensation, instrument wear). The legal basis for the analysis of PNs are: UN/ECE Global Technical Regulation No. 15; UNECE Regulation No. 83; Regulation (EC) No. 715/2007—EC 692/2008 [51–53].

Before each measurement is checked, engine is warmed up to normal operating temperature. The exhaust system is accelerated at least three times from the minimum idle speed to the limiter limited speed. The smoke of the exhaust gas measured when the engine is allowed to accelerate, free from load, from minimum idle speed to the limiter limited speed. Before each free acceleration cycle, the engine and turbocharger must be running at steady minimum idle speeds not less than 15 s. Each free acceleration, the cycle starts quickly and consistently so that the fuel injection operates at maximum efficiency. During the free acceleration cycle, before the accelerator pedal is released, the engine must reach the speed limit frequency.

The concentration of particle matters in the exhaust gas was measured immediately after measuring the smoke, with the engine running at idle speed, using the PM concentration counter P-Trak ultrafine particle counter 8525. The technical parameters of the PM counter are presented in Table 3.

Table 3. PM concentration counter P-Trak parameters.

Parameter	Value
Concentration range	0–500,000 pcs/cm^3
Aerodynamic PM diameter range	0.02–1 µm
Temperature range	−40–70 °C
Intake air flow	approximately 100 cm^3/min
Device memory	470 points
Type of alcohol used	100% isopropanol

The PM counter only detects very fine PM (particles with an aerodynamic diameter of 0.02–1 µm). In the device, we installed a pump, data processing equipment, a cartridge containing isopropanol, and a telescopic probe. In the cassette, the required level of isopropanol must be maintained. This technical fluid ensures the detection of the smallest microscopic particles. PM increases significantly when it flows through isopropanol.

Experimental tests were carried out using 5 different fuels and blends: conventional diesel (labelled as D100), pure hydrotreated vegetable oil (labelled as HVO100), hydrotreated vegetable oil and biobutanol mixtures (95/5, 90/10, and 80/20 (% vol/% vol)), and blends (labelled as HVOB5, HVOB10, and HVOB20). For better lubricity, castor oil (accounting for 5% of biobutanol volume) was added as an additive to biobutanol blends. Properties of pure fuels were analysed and are presented in Tables 4 and 5.

Table 4. Properties of 100% pure diesel, hydrotreated vegetable oil, biobutanol, and castor oil [54–60].

Parameter	Diesel	Hydrotreated Vegetable Oil	Biobutanol	Castor Oil
Density at 15 °C, kg/m^3	835.2	779.1	810.0	964.4
Element composition: (% mass): Carbon	86.50	84.80	65.00	73.80
Hydrogen	13.40	15.30	13.55	11.50
Oxygen	0.0	0.0	21.50	14.85
Stoichiometric AFR	14.79	15.18	11.30	11.91
Cetane number	51	70	18	28
Lower heating value, MJ/kg	43.09	44.9	33.3	43.1
Lower heating value, MJ/l	36.90	34.10	26.71	39.81
Purity,%	N/A	N/A	99.5	100
Manufacturer, country	Orlean Lietuva, Lithuania	Neste, Finland	Carl Roth GmbH, Germany	Biochemlit, Lithuania

Table 5. Properties of fuel mixtures.

Properties	HVOB5	HVOB10	HVOB20
Density at 15° C, kg/m^3	780.5	782.4	786.4
Element composition: (% mass): carbon	83.45	82.55	80.58
Hydrogen	15.32	15.25	15.03
Oxygen	1.11	2.21	4.41
Stoichiometric AFR	14.99	14.77	14.38
Cetane number	67.3	64.7	59.3
Lower heating value, MJ/kg	43.55	42.98	41.88
Lower heating value, MJ/L	33.98	33.64	32.93

Because the use of biobutanol deteriorates the lubrication properties of the fuel mixture, it is necessary to use certain specialized fuel additives or a fuel component that provides lubrication. Because the use of specialized additives is expensive and requires special compatibility studies, castor oil was chosen as a cheap lubricating alternative.

All physicochemical fuel parameters have been verified on the basis of data found in the literature and fuel characteristics provided by their manufacturer [54–60].

3. Results

The results obtained during the study allow us to justify the perspectives of second-generation biofuels, taking into account the amount of smokiness and PN. When examining the smokiness values (Figure 2), its decrease is noticeable compared to standard diesel.

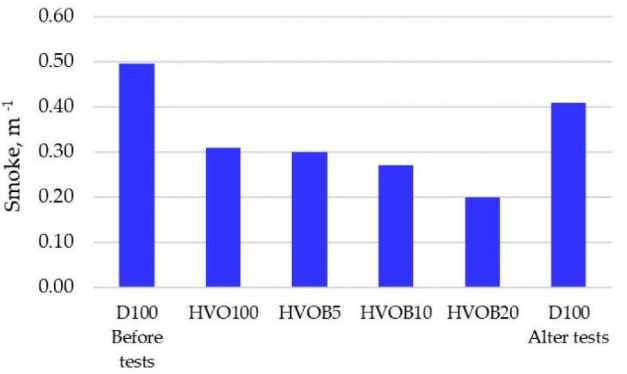


Figure 2. Smoke readings using different biofuel blends.

The information shown in Figures 2–5 is visually complementary. Its purpose is to show the differences in the fuel mixtures analysed.

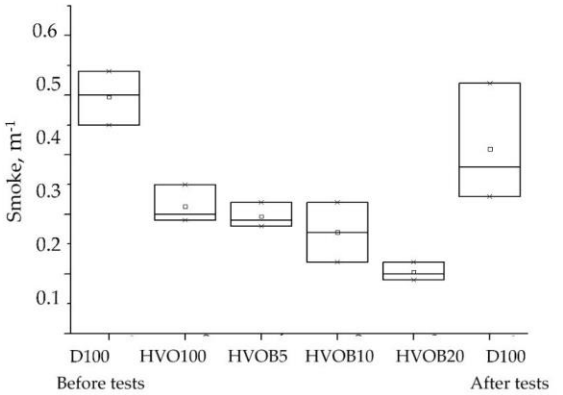


Figure 3. Scattering of smoke readings using different biofuel blends.

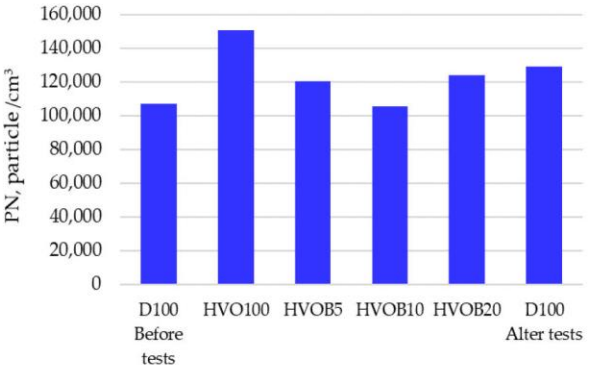


Figure 4. PN readings using various biofuel blends.

The smokiness values tended to be highest when using standard diesel (in this comparison, for the time being we will use the data from D100 Before Tests). Using second-generation biodiesel HVO100 as fuel reduced smokiness by 40%. This was because of the better combustion process of HVO 100 due to the additional oxygen contained in it. With the addition of biobutanol, smokiness reduction trends increased even more. As the concentration of biobutanol in HVO fuel increases, a significant decrease in smokiness trends can be seen (comparing the HVOB20 mixtures with HVO100 (36%) and with D100 (60%)). This was due to the oxygen present in biobutanol, which further initiated the improvement of the combustion process; this was also observed in other works by the authors. A small addition of biobutanol (up to 5%) had no significant effect on the smoke values. Another interesting effect occurred when measuring smokiness using diesel after tests with biofuel blends. The use of biofuel mixtures promotes the cleaning of the exhaust

system with the reduction of smog emissions, and the effect when fueling diesel (D100 After Tests) compared to D100 Before Tests reached 18%.

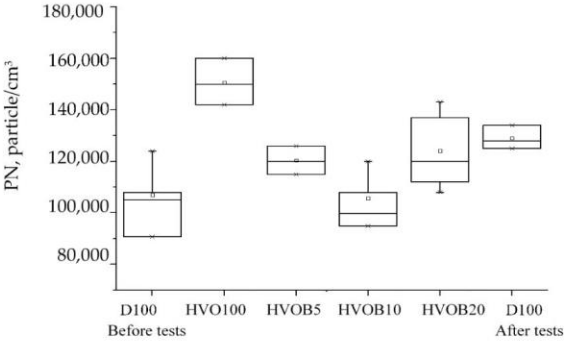


Figure 5. Scattering of PN readings using different biofuel blends.

Such smoke values show a sufficient motivation to use biofuels from an environmental point of view. However, if we examine the smoke dispersion values obtained during the tests (Figure 3), it can be stated that only a higher amount of biobutanol (up to 20% HVOB20 mixture) reduces the smoke dispersion limits (quartile range was 0.3 m^{-1}).

Both the D100 Before Tests and HVO100, HVOB5, and HVOB10 generated a similar quartile field of results, which reached 0.4–0.1 m^{-1}. Such a spread of smokiness is acceptable when evaluating real steady car test conditions. After the biofuel tests using diesel again (D100 After Tests), the dispersion of the results was the highest and reached 0.19 m^{-1}. Such scattering allows us to say that although the exhaust system is cleaned, this effect causes the reduction of smogginess to decrease very quickly, leading us to believe that during further exploitation it will return to the original values of diesel smogginess (D100 Before Tests).

Examining the total concentration of PN (range 0.02 to 1 µm) shows a different result than when examining smokiness. The highest PN value was observed with HVO 100 fuel. This can be explained by the better volatility properties of these fuels, as these fuels have a smaller weight fraction compared to diesel. However, the concentration of PN decreased with the use of biobutanol. Such a decrease can raise two main hypotheses. The first would be that biobutanol changes the physical properties of HVO during chemical reactions, allowing the formation of derivatives of a heavier fraction. Another hypothesis would be that the measuring device cannot register smaller particles and they are eliminated from the scoreboard. Seemingly, cardinal hypotheses allow us to assume the possibility of using biobutanol as a reactive fuel additive. It is volatile and evaporates well, but its density is closer to that of HVO fuel, allowing for the formation of stable mixtures that do not tend to stratify compared to ethanol or other alcohols.

The second hypothesis is supported by the fact that the dispersion of the HVOB20 results is the highest and reaches 35,000 particles/cm^3 (Figure 4). However, when using diesel and biofuel mixtures, such a greater difference was not observed (15,000–30,000 particle/cm^3).

It is likely that increasing the biobutanol concentration would increase the dispersion of PNs and it could be argued that very small particles are generated using alcohols as biofuel additives.

4. Discussion

The results show that using biofuel mixtures (HVO with biobutanol) can reduce smokiness. This is very relevant, according to the currently valid legal acts of the Republic

of Lithuania, which state that a vehicle cannot be driven if the smoke limits are exceeded. These provisions are particularly relevant for older diesel cars (starting with EURO 4 and below). After the entry into force of the new EURO 6B and expected EURO 7 standards, the particle concentration itself (which can also be expressed through PM or smokiness) and the actual PN will both be important. The introduction of this provision should limit the emissions of ultrafine particles that can already occur with leaner fuel mixtures. In our case, it becomes very important to identify correlational dependencies between smokiness and PN indicators. They allow the identification of individual fuel blends that reduce smog but may generate large amounts of PN. The correlations between smoke and PN may differ when using different biofuel blends, so it is important to identify and demonstrate them (Figure 6).

In order to analyse the value of the standard deviation, in the context of the change in the distribution of parameters, to assess the reliability of statistical data, Table 6 presents the results for the Shapiro–Wilk normality test and the compliance of the statistical data curve with the descriptive characteristics of the curve (Kolmogorov–Smirnov normality test). These parameters are interesting for correct data processing and show how exactly the exponential curve fits the statistical curve of the experimental data. The results obtained show that the data were processed correctly (smoke and PN data were significantly drawn from a normally distributed population at the level of 0.05). The authors believe that the purpose of this study is not to show how statistical data processing is performed, but rather to analyse and interpret the results.

Table 6. Comparison results of standard deviation, Shapiro–Wilk normality test, and Kolmogorov–Smirnov normality test using different fuels.

Fuel Blends	D100 before Tests	D100 after Tests	HVO100	HVO5	HVO10	HVO20
Parameter			**Standard Deviation**			
Smoke, m^{-1}	0.04509	0.09849	0.03215	0.02082	0.05	0.01528
PN, particle/cm^3	13,658.54433	4582.57569	9018.49951	5507.57055	10,940.44484	15,378.5565
			Shapiro–Wilk Normality Test			
Smoke, m^{-1}	0.9959	0.93041	0.87097	0.92308	1	0.96429
PN, particle/cm^3	0.97711	0.96429	0.9959	0.99725	0.95783	0.90727
			Kolmogorov–Smirnov Normality Test			
Smoke, m^{-1}	0.19613	0.28633	0.32752	0.29228	0.17468	0.25304
PN, particle/cm^3	0.21863	0.25304	0.19613	0.1908	0.20515	0.20261

In research practice, it is very often the case that due to the high cost of the analysis (the cost of the experiment conducted on the test bench) there is a need to verify the consistency of the data distribution with the normal distribution for a small sample size. In this case, the tests were repeated 3 times (p-value: 0.345).

Among the many tests verifying the compatibility of empirical and theoretical distributions, the focus was on the Shapiro–Wilk compatibility test. This test is considered to be one of the strongest tests for normal distribution, especially when testing "small numbers" samples. The test is used to verify the hypothesis that the distribution of the tested random variable is in accordance with the normal distribution.

In the case of the test used, the zero hypothesis indicates the normal distribution of the tested characteristic. For a p-value below 0.05, we reject this hypothesis in favour of an alternative one. However, taking into account the p-value—which is, nonetheless, different from 0—the median value very close to the mean, and considering the skewness and excess coefficient to be insignificantly different from 0, we can conclude, with some caution, that the distribution of smoke measurements is close to normal [61].

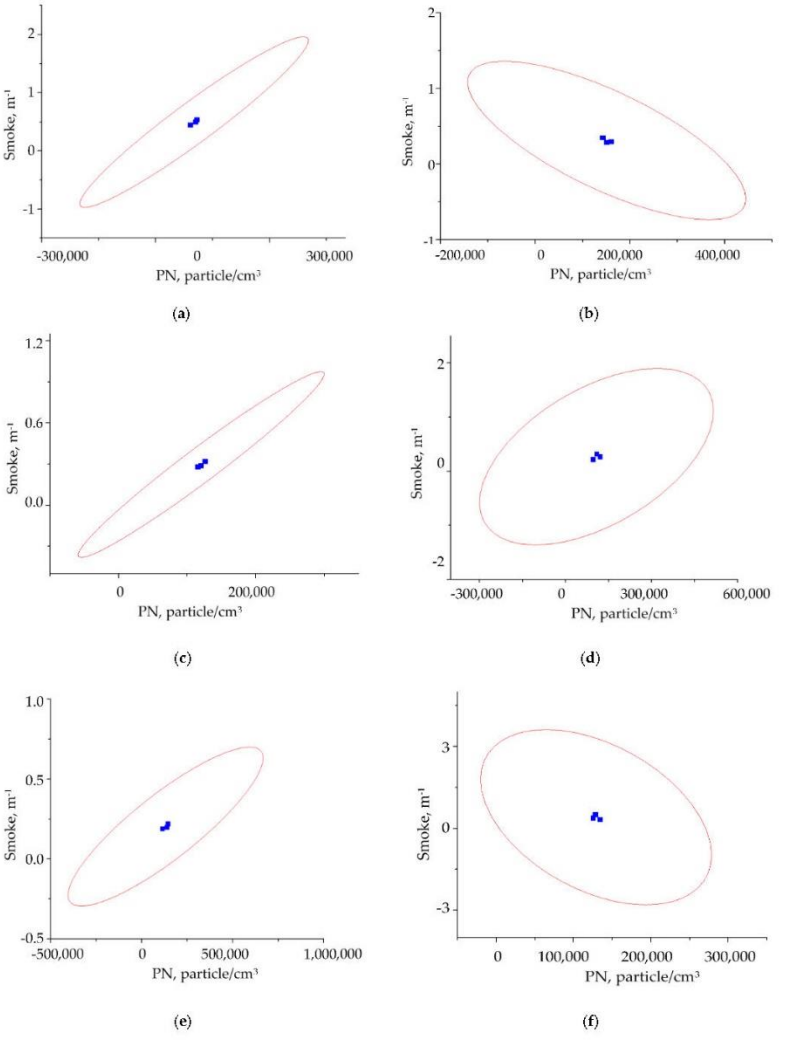


Figure 6. Correlation between smokiness and PN parameters using different fuels: (a) D100 Before Tests; (b) HVO100; (c) HVOB5; (d) HVOB10; (e) HVOB20; (f) D100 After Tests.

The manuscript uses elements of descriptive statistics as a method of summarizing data in a valid and meaningful way. In this way, it was shown that good and appropriate measurement is important not only for the data, but also for the statistical methods used to test hypotheses. For continuous data, normality testing is very important, because based on the state of normality, measures of central tendency, dispersion, and the choice of parametric/nonparametric test are decided. In the literature, there are various methods of testing normality. Most literature sources indicate that for a small sample size ($n < 50$), the Shapiro–Wilk test should be used, as it has greater power to detect non-normality and is the most popular and widely used method.

When our sample size (n) is at least 50, any other methods (Kolmogorov–Smirnov test, skewness, kurtosis, value from skewness and kurtosis, histogram, box plot, P-P plot, Q-Q plot, and SD with respect to the mean) can be used to test the normality of continuous data.

In addition, the two-sample Kolmogorov–Smirnov test was used in the manuscript. This test is used to check whether two basic one-dimensional probability distributions differ. Again, the larger the sample sizes, the more sensitive the minimum limit. It should be noted that the two-sample test evaluates whether the two data samples are from the same distribution. It does not determine what the common distribution is (e.g., whether it is normal or not). The disadvantage of the one-dimensional Kolmogorov–Smirnov test is that it is not very strong, as it was designed to be sensitive to all possible types of differences between the two distribution functions [62].

It is known from statistical theory that there is direct dependence, very strong, strong, medium, weak, very weak, and no correlation. The visualization of these relationships indicates that the strongest correlations are with D100 Before Tests, HVOB5, and HVOB20 (the closest in form to linear dependence), and the least smoke and PN parameters are correlated with HVO100, HVOB10, and D100 After Tests fuels. To identify the strength of the correlation relations, a comparison of the Pearson correlation coefficients by absolute value is applied using different fuel mixtures (Figure 7).

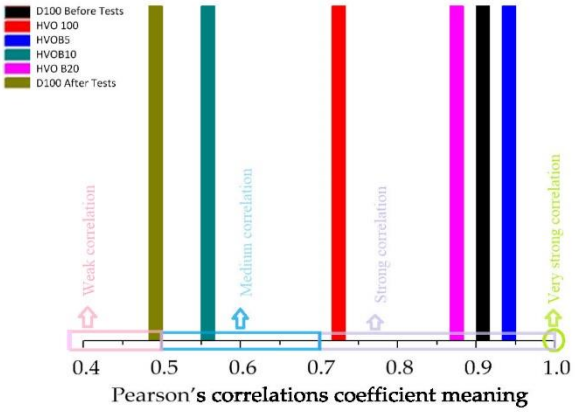


Figure 7. Comparison of Pearson correlation coefficients using different fuels.

When comparing according to Pearson correlation coefficients, a strong correlation dependence was identified. Very close correlation values were observed between D100 Before Tests, HVOB5, and HVOB20, while HVO100 fuel showed a somewhat smaller, but still strong, correlation dependence. Moderate correlation dependence was observed with

HVOB10 fuel and weak correlation dependence with D100 after testing. Based on this, the following generalisations can be made:

- Increasing biobutanol concentration does not affect the strength of the correlation between smokiness and PN indicators;
- After the use of biofuels, when resupplying diesel to the engine, the correlation dependence between smokiness and PN decreased by 45% when evaluating the values of the Pearson correlation coefficient and changed from a very strong dependence to a weak dependence of the smokiness and PN indicators, according to the Pearson correlation coefficient.

Currently designed car engines with compression ignition are modern units equipped with state-of-the-art power and control systems. Despite the use of state-of-the-art technological, design, and electronic control, the challenge for the designers of modern compression ignition engines is to meet stringent exhaust toxicity requirements, e.g., emissions of nitrogen oxides, NO_x, PM. This limits the further development of automotive compression ignition engines and their maximum performance, especially those with low displacement.

An important problem for engines is the emission of particulate matter (PM), which, due to its hygroscopicity and low density relative to air, is a serious environmental hazard. For this reason, PM emissions have been the most severely reduced in recent years, compared to other toxic components of exhaust gases. It is not only the mass emission of PM, but also the total particle number (N), that have been reduced. The main component of particulate matter and its carrier is soot, formed by the thermal cracking of higher diesel hydrocarbons oxidized in rich flame zones, mainly in oxygen-deficient conditions.

One way to reduce PM emissions may be by adding oxygen compounds to diesel, using a light fuel, e.g., diesel/biobutanol blends.

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Compression Ignition Internal Combustion Engine's Energy Parameter Research Using Variable (HVO) Biodiesel and Biobutanol Fuel Blends

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Abstract: This study investigates the impact of different biofuels, such as pure hydrogenated vegetable oil, hydrogenated vegetable oil, and biobutanol, as well as their blends, on the non-energetic operational characteristics of a compression ignition internal combustion engine. The research investigations were conducted using a turbocharged direct injection compression ignition engine that was put within a Skoda Octavia 1.9 TDI automobile. Throughout the investigation, the primary emphasis was placed on analyzing energy characteristics such as power, brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and other related factors. The analysis involved the utilization of multiple combinations of bio-based fuels, namely four mixes of HVO with biobutanol (HVO100, HVOB5, HVOB10, and HVOB20), which were subsequently compared to fossil diesel (D100). The findings of the study indicate that the utilization of HVO100 fuel results in notable reductions in power output and mass fraction when compared to D100 gasoline. HVO100 fuel demonstrates superior performance to D100 gasoline, exhibiting a range of 1.7% to 28% improvement in brake-specific fuel consumption. Additionally, at an engine speed of 4500 rpm, the use of HVO100 fuel leads to a decrease in brake thermal efficiency of 4.4%.

Keywords: vehicle; HVO and biobutanol fuel blends; biofuels; engine's power; BSFC; BTE

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1. Introduction

The heightened consciousness throughout society regarding the detrimental effects of the road transport industry on the environment necessitates the implementation of more aggressive and transformative measures [1,2]. These activities primarily concentrate on the domains of legislation, technology, and fuel. The adverse effects of climate change and the persistent degradation of the environment present a significant risk to Europe and the global community as a whole [3,4].

Based on data provided by the European Environment Agency, it is seen that almost one-fourth of the European Union's aggregate carbon dioxide (CO_2) emissions in the year 2019 originated from the transportation sector. Notably, road transport accounted for 71.7% of these emissions [5]. The European Commission has recently implemented a comprehensive set of legislative propositions aimed at harmonizing the European Union's climate, energy, transport, and tax policies [6,7]. The primary objective of these recommendations is

to achieve a substantial reduction in net greenhouse gas emissions, targeting a minimum decrease of 55 percent by the year 2030 in comparison to the emission levels recorded in 1990. In accordance with the European Green Deal, there is a pressing need to curtail CO_2 emissions and attain climate neutrality by 2050 [8]. To this end, it is imperative to achieve a 90% reduction in greenhouse gas emissions by 2050, relative to the levels seen in 1990 [9,10].

The European Union has been implementing measures over an extended period of time in order to mitigate the adverse effects of human activities on the environment [11,12]. One example of such endeavors involves the implementation of a series of laws that establish acceptable thresholds for exhaust emissions produced by automobiles sold within the European market. These regulations, known as the Euro exhaust emission standards (EURO), serve as a framework for governing the permitted levels of emissions [13–15]. The primary objective is to mitigate the adverse effects of road transportation on the environment and public health through the regulation of air pollutants, including nitrogen oxides (NOx), particulate matter (PM), hydrocarbons (HC), and carbon dioxide (CO_2) [16–18]. The Euro 6d-ISC-FCM standard has been implemented since 2021. From a technology standpoint, these standards mandate the installation of fuel consumption monitoring devices in passenger vehicles [19–21]. Drawing on the literature, a comparative analysis can be conducted to assess the disparity between the quantities of pollutants discharged into the atmosphere by a vehicle during real-world driving conditions and the emission values officially reported by the manufacturer. Presently, in order to avoid financial penalties, automotive corporations are required to uphold an average carbon dioxide emission level of 95 g/km across all vehicles manufactured. In 2019, the mean carbon dioxide (CO_2) emissions produced by automobiles registered within the European Union (EU) amounted to 122.4 g per kilometer. This figure exceeded the relevant regulatory threshold by an additional 27.4 g [22].

Standardized measuring testing is conducted on all newly manufactured automobiles [23,24]. The WLTP (Worldwide Harmonized Light Vehicles Test Procedure) driving cycle was implemented in September 2018, replacing the previously used New European Driving Cycle (NEDC) [25,26]. Furthermore, the Real Driving Emissions (RDE) emission test is employed to directly assess pollutant emissions while vehicles are in operation on public roads [27,28].

The European Union (EU) places significant emphasis on the promotion of issues pertaining to alternative fuels [29,30]. Biofuels derived from biomass for transportation purposes are regarded as a very promising category of alternative fuels with the potential to mitigate dependence on petroleum-based fuels and contribute to environmental sustainability [31,32].

The term "biofuel" encompasses a broad range of interpretations and encompasses a diverse array of substrates. Liquid or gaseous biofuels serve as a viable substitute for diesel oil due to their composition, which includes plant biocomponents such as rapeseed, soybean, sunflower, palm oil, and other oil plants. This composition contributes to a reduction in the use of petroleum-based fuels [33,34].

Biofuels can be categorized based on their physical state, the generation of production technique employed (first, second, or third generation), the type of engine they are used to power (compression ignition or spark ignition), or their specific application [35,36]. Biodiesel, classified as a first-generation biofuel, is widely recognized as the prevailing kind of biofuel. It mostly consists of methyl or ethyl esters of fatty acids, commonly referred to as Fatty Acid Methyl Esters (FAME) or Fatty Acid Ethylesters (FAEE) [37–40]. The primary methods employed in their manufacturing include esterification, transesterification, and cold pressing. Second-generation biofuels are derived only from waste biomass or substances that are not acceptable for use as food. Biohydrocarbons are a specific category of biocomponents that are added to biofuels as an admixture. The production of these substances involves the use of catalytic oil hydrogenation technology, a process that entails the elimination of oxygen and unsaturated bonds from triglyceride structures (known as hydrotreated vegetable oils—HVO) [41–43]. The resulting composition predominantly

consists of liquid paraffinic hydrocarbons. The primary source of third-generation biofuels is predominantly derived from algae [44,45].

The European Union has been actively advocating for the advancement of electromobility in recent years. Battery electric vehicles (BEVs) are characterized by their emission-free nature during operation. The ecological impact of these entities is contingent upon the energy source used for their operation. The use of renewable energy sources (RES) for charging purposes ensures that the indirect emissions associated with an electric vehicle are primarily confined to its production phase. The factors that contribute to a lack of faith in this particular technical solution encompass deficiencies in the technical infrastructure, concerns over fire safety, and potential electromagnetic interference [46,47].

Many experts hold the view that investments in technology pertaining to electromobility are of a transitory nature. The focal solution pertains to hydrogen technologies [48]. The expeditious establishment of a competitive hydrogen production sector is of utmost importance, as it serves as a safeguard against political instability and has the potential to enhance the competitiveness and trade balance of numerous nations. The use of hydrogen will hold significant significance for economic sectors that face challenges in achieving decarbonization through direct electrification. This encompasses various sectors, including but not limited to transportation (road, sea, and rail) and industrial operations that necessitate elevated temperatures, such as the production of steel. Support is necessary for the development of both electric vehicle charging and hydrogen refueling infrastructures [49,50].

Primary biofuels and processed biofuels are the two categories that can be used to classify biofuels [51,52]. Primary biofuels are fuels that are produced from natural, unprocessed biomass and that may be used directly to generate heat and energy [53,54]. An example of a primary biofuel is firewood. Fuels that have been processed are referred to as processed biofuels. These fuels can be generated by processing biomass using a variety of different processes. Biofuels that have been processed can be classified as either first-, second-, or third-generation biofuels. First-generation biofuels are largely oxygen compounds, such as ethyl alcohol, fatty acid methyl esters (FAME), and ethers. These first-generation biofuels are created using biomethanol and bioethanol as their starting materials. Higher fuel stability during fuel storage and distribution is one advantage that hydrocarbon biofuels and second-generation biocomponents have over first-generation biofuels. This advantage is gained by comparing first-generation biofuels to second-generation biocomponents [55]. The production of bioethanol from lignocellulosic raw materials is one example. Other examples include the production of synthetic fuels from syngas produced by the gasification of biomass and the production of hydrocarbon fuels through the hydroconversion process (for example, HVO) [56]. It is possible to manufacture second-generation biofuels based on waste biomass, such as that which contains organic components of municipal garbage, waste vegetable oils and animal fats, or pure vegetable oils acquired from crops grown in degraded areas that are unfit for use in the food business. Microalgae are the primary component of biofuels of the third generation.

First-generation biofuel conversion procedures involve cold pressing, extraction, and transesterification in order to produce biodiesel [57]. This biodiesel is comprised of rapeseed oil methyl esters (RME) or methyl esters (FAME) and ethyl esters (FAEE) of higher fatty acids derived from other oil plants. The majority of FAME comes from the transesterification of various vegetable oils. HVO is a type of fuel that can be produced using a process known as catalytic hydrogenation. During this process, oxygen and unsaturated bonds are eliminated from triglyceride structures. In contrast to fatty acid methyl esters, HVO does not precipitate paraffin even at temperatures 20 degrees below zero, which results in a reduction of 10%. Mineral fuels have a cetane number that ranges from 70 to 90, do not include sulfur or aromatic hydrocarbons, and have zero nitrogen oxide emissions; however, diesel fuel made from minerals only has a cetane value of 51. The standards for fuels do not specify a maximum level of HVO concentration; rather, they demand simply that the finished product, in the form of diesel oil, meets the quality requirements that are specified

in the standard. In actuality, diesel fuel can have between 20 and 30 percent HVO and an additional 7 percent FAME added to it.

Biofuels and alternative fuels for spark-ignition engines include ethanol, methanol, ethers, hydrocarbon synthetic fuels, liquefied petroleum gas, and hydrogen [58–60]. These fuels are also regarded as alternatives. In the field of powering compression-ignition engines, work is currently being carried out to obtain and use the following alternative fuels derived primarily from biomass: fatty acid esters (FAME and FAEE, from transesterification processes of rapeseed, sunflower, and soybean oils), dimethyl ether, fuel emulsions (water, pure vegetable oils, and hydrocarbon synthetic fuels), and fatty acid esters (FAME and FAEE). Fermentation and distillation are the two basic processes involved in the manufacturing of ethanol [61]. Using this method to produce fuel results in high overall production costs. Utilizing alternative substrates, such as waste cellulosic or lignocellulosic material, can help bring down the overall cost of production.

Diesel and natural gas are the two fuels that are used the most frequently to power generators; however, there are additional possibilities available. The performance of generator engines that are powered by renewable liquid fuels is comparable to the performance of generator engines that are driven by conventional diesel; however, there is a slight decrease in power as well as in fuel economy. The low-temperature characteristics of HVO and biodiesel must be suitable for the surroundings of the generator in order for them to be used.

When compared to the expenses of getting mineral fuels, the costs of manufacturing biofuels are significantly higher. The price of the raw material accounts for between 55 and 70 percent of the total production expenses; therefore, it has a significant impact on the overall cost of manufacturing biofuels. Due to this, many nations around the world encourage this industry by implementing administrative and fiscal restrictions on the biofuel market. This is carried out in the hopes of increasing the use of biofuels and, as a result, achieving the societal goals that have been presupposed. The availability and steadily increasing cost of the essential raw materials for production is the primary obstacle that all manufacturers of biocomponents are currently confronted with.

2. Materials and Methods

The vehicle used for the experiments was the Skoda Octavia, equipped with a 1.9-L TDI (Turbocharged Direct Injection) compression ignition engine, namely the type 1Z. This particular engine configuration consists of four cylinders and possesses a displacement of 1896 cm^3. The engine exhibits a maximum power output of 66 kilowatts (kW) at an engine speed of 4000 revolutions per minute (rpm), while its maximum torque is recorded at 182 Newton meters (Nm) at an engine speed of 1900 rpm. Table 1 presents detailed information regarding the 1.9 TDI engine [62].

Table 1. The main parameters of the test engine (1.9 TDI type: 1Z) [62].

Parameter	Value
Engine type—number of cylinders	Inline 4
Engine code	ALH
Fuel type	Diesel
Engine alignment	Transverse
Engine displacement	1896 cm^3
Bore x Stroke	79.5 × 95.5 mm
Number of valves	8 Valves
Aspiration	Turbo
Maximum power	66 kW (4000 rpm)
Maximum torque	210 Nm (1900 rpm)
Drive wheels	FWD
Piston diameter, mm	79.5 mm
Piston stroke, mm	95.5 mm

Table 1. *Cont.*

Parameter	Value
Compression ratio	19.5
Displacement	1896 cm^3
Number of cylinders	4/OHC
Fuel injection	Direct (single)
Nozzle type	Hole-type
Nozzle opening pressure	190 bar
Nozzle and holder assembly	Two spring
Cooling system type	Liquid cooling
Transmission gearbox—number of speeds	5 speed Manual

The torque and power of the engine in a Skoda Octavia equipped with a 1.9-L TDI diesel engine, namely the type 1Z, were assessed using a computerized vehicle test bench known as the MAHA LPS 2000 (as depicted in Figure 1 and detailed in Table 2).

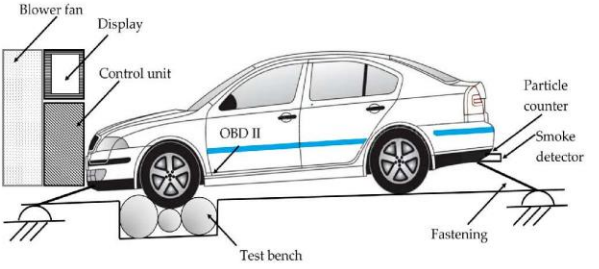


Figure 1. Laboratory testing apparatus.

Table 2. The main parameters of the vehicle load bench (MAHA LPS 2000) [63].

Parameter	Value
Load eqiupment	Electromagnetic brake
Rate adjustment limits	260
Maximum measuring load	6 kN (attractive force)
Maximum break power, kW	260
Measurement error	±2%

During the experimental tests, the ROSS-TECH VCDS diagnostic tool was employed to retrieve data from the Electronic Control Unit (ECU) of the vehicle through an OBDII connection. The car diagnostic system known as ROSS-TECH VCDS collected data at regular intervals of 2.50 s [64–66].

The examination of engine ECU (electronic control unit) data revealed that the recorded data points, including engine speed (rpm), cyclic fuel quantity (mg/cycle), cyclic air mass (mg/cycle), fuel injection timing (°BTDC), turbocharger pressure (mbar), and fuel injection timing (mg/cycle), are transmitted in distinct blocks and lack precise synchronization in time.

Three sets of experiments were performed using the MAHA LPS 2000 vehicle test bench. During these studies, ECU data was recorded, and engine external speed parameters were measured.

The trials involved using an aggregate total of five distinct fuels and blends. The tested fuel samples encompassed several compositions, namely D100 (normal diesel), HVO100

(pure hydrotreated vegetable oil), 95/5, 90/10, and 80/20 (vol/vol) combinations of hydrotreated vegetable oil and biobutanol, as well as blends branded as HVOB5, HVOB10, and HVOB20. In order to enhance the lubricity of biobutanol blends, the inclusion of castor oil at a concentration of 5% by volume was implemented. The findings pertaining to the characteristics of pristine fuels are shown in Tables 3 and 4.

The effective use of biobutanol requires the incorporation of specialized fuel additives or a fuel component that provides lubrication, as biobutanol diminishes the lubricating properties of the fuel blend. The selection of castor oil as a lubricant is attributed to its cost-effectiveness and the avoidance of expensive compatibility tests associated with the use of specialized additives.

The physicochemical parameters of the fuel were verified by using literature data and fuel characteristics provided by the manufacturer [67,68].

Table 3. Properties of 100% pure diesel, hydrotreated vegetable oil, biobutanol, and castor oil [69–72].

Parameter	Diesel	HVO	Biobutanol	Castor Oil
Density at 15 °C, kg/m^3	835.2	779.1	810.0	964.4
Element composition: (% mass): Carbon	86.50	84.80	65.00	73.80
Hydrogen	13.40	15.30	13.55	11.50
Oxygen	0.0	0.0	21.50	14.85
Stoichiometric AFR	14.79	15.18	11.30	11.91
Cetane number	51	70	18	28
Lower heating value, MJ/kg	43.09	44.9	33.3	43.1
Lower heating value, MJ/L	36.90	34.10	26.71	39.81
Purity, %	N/A	N/A	99.5	100
Manufacturer, City, Country	Orlean Lietuva, Juodeikiai, Lithuania	Neste, Espoo, Finland	Carl Roth GmbH, Karlsruhe, Germany	Biochemlit, Kaunas, Lithuania

Table 4. Properties of fuel mixtures.

Properties	HVOB5	HVOB10	HVOB20
Density at 15 °C, kg/m^3	780.5	782.4	786.4
Element composition: (% mass): Carbon	83.45	82.55	80.58
Hydrogen	15.32	15.25	15.03
Oxygen	1.11	2.21	4.41
Stoichiometric AFR	14.99	14.77	14.38
Cetane number	67.3	64.7	59.3
Lower heating value, MJ/kg	43.55	42.98	41.88
Lower heating value, MJ/L	33.98	33.64	32.93

3. Results

Figure 2 depicts the relationship between engine load and fuel composition across various engine speeds. The conventional diesel engine is capable of achieving a maximum torque of 190 Nm. The use of HVO100 fuel resulted in a reduction of 10% in this metric when compared to the use of D100 gasoline. The gradual addition of biobutanol to HVO fuel, increasing from 5% to 20%, resulted in a consistent drop in torque, with reductions of 11%, 15%, and 18% seen at each respective increment. Figure 3 displays engine power characteristics, exhibiting a similar pattern. The use of D100 gasoline results in a maximum

power output of 64.5 kW, whereas HVO100 fuel exhibits a decrease in power output of 8%. Similarly, HVOB5 fuel demonstrates a reduction in power output of 11%, HVOB10 by 17%, and HVOB20 by 22% when compared to D100 fuel. The observed outcomes can be attributed to the reduced lower heating value (LHV) values, as indicated in Tables 4 and 5. While the lower heating value of hydrotreated vegetable oil (HVO100) is higher than that of conventional diesel in terms of MJ/kg, it is important to note that the density of HVO100 is significantly lower than that of conventional diesel. Consequently, the lower heating value of HVO100, expressed in MJ/L, is lower when compared to D100, HVOB5, HVOB10, and HVOB20. This decrease in value is observed consistently across these fuel types.

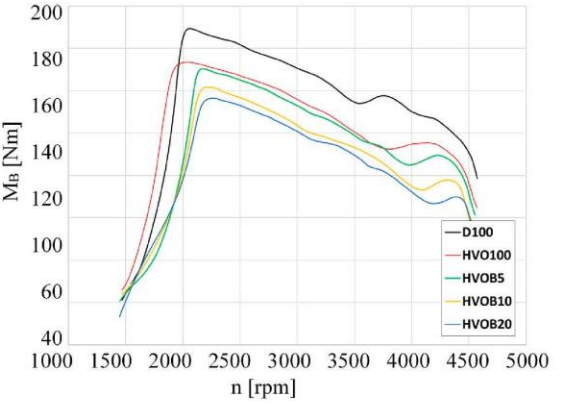


Figure 2. Engine load depending on fuel composition at different engine speeds.

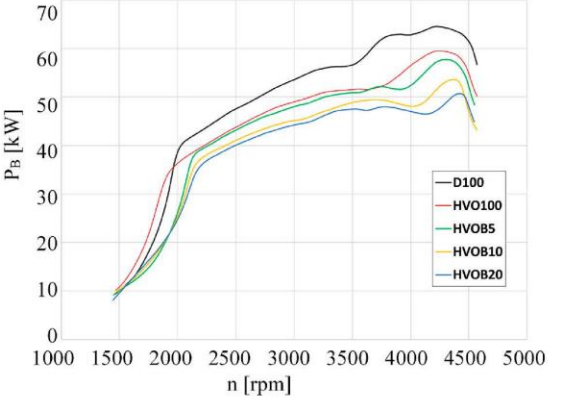


Figure 3. Engine power depending on fuel composition at different engine speeds.

Table 5. The Pearson correlation coefficient values pertaining to various types of fuels.

Engine's Parameter	n [rpm]	P-Norm [kW]	M-Norm [Nm]	b_e [g/kWh]	η_e	Lambda	SOI [CAD BTDC]	m_{air} [mg/cycle]	m_f [mg/cycle]
D100									
n [rpm]	1.000	0.898	0.249	−0.684	0.712	0.126	0.974	−0.519	−0.632
P-norm [kW]	0.898	1.000	0.638	−0.894	0.903	0.313	0.959	−0.112	−0.254
M-norm [Nm]	0.249	0.638	1.000	−0.848	0.819	0.646	0.411	0.677	0.491
b_e [g/kWh]	−0.684	−0.894	−0.848	1.000	−0.984	−0.665	−0.774	−0.243	0.002
η_e	0.712	0.903	0.819	−0.984	1.000	0.669	0.778	0.167	−0.094
lambda	0.126	0.313	0.646	−0.665	0.669	1.000	0.145	0.471	0.109
SOI [CAD BTDC]	0.974	0.959	0.411	−0.774	0.778	0.145	1.000	−0.347	−0.445
m_{air} [mg/cycle]	−0.519	−0.112	0.677	−0.243	0.167	0.471	−0.347	1.000	0.928
m_f [mg/cycle]	−0.632	−0.254	0.491	0.002	−0.094	0.109	−0.445	0.928	1.000
HVO100									
n [rpm]	1.000	0.885	0.121	−0.667	0.668	0.355	0.969	−0.234	−0.334
P-norm [kW]	0.885	1.000	0.555	−0.840	0.809	0.399	0.969	0.212	0.114
M-norm [Nm]	0.121	0.555	1.000	−0.711	0.646	0.436	0.344	0.903	0.802
b_e [g/kWh]	−0.667	−0.840	−0.711	1.000	−0.987	−0.773	−0.757	−0.397	−0.174
η_e	0.668	0.809	0.646	−0.987	1.000	0.786	0.733	0.303	0.068
lambda	0.355	0.399	0.436	−0.773	0.786	1.000	0.358	0.286	−0.023
SOI [CAD BTDC]	0.969	0.969	0.344	−0.757	0.733	0.358	1.000	−0.004	−0.094
m_{air} [mg/cycle]	−0.234	0.212	0.903	−0.397	0.303	0.286	−0.004	1.000	0.951
m_f [mg/cycle]	−0.334	0.114	0.802	−0.174	0.068	−0.023	−0.094	0.951	1.000
HVOB5									
n [rpm]	1.000	0.840	−0.188	−0.448	0.413	−0.405	0.988	−0.709	−0.588
P-norm [kW]	0.840	1.000	0.357	−0.771	0.718	−0.454	0.897	−0.231	−0.084
M-norm [Nm]	−0.188	0.357	1.000	−0.729	0.705	0.076	−0.071	0.808	0.803
b_e [g/kWh]	−0.448	−0.771	−0.729	1.000	−0.990	−0.113	−0.513	−0.220	−0.194
η_e	0.413	0.718	0.705	−0.990	1.000	0.210	0.462	0.204	0.146
lambda	−0.405	−0.454	0.076	−0.113	0.210	1.000	−0.469	0.221	−0.091
SOI [CAD BTDC]	0.988	0.897	−0.071	−0.513	0.462	−0.469	1.000	−0.607	−0.462
m_{air} [mg/cycle]	−0.709	−0.231	0.808	−0.220	0.204	0.221	−0.607	1.000	0.951
m_f [mg/cycle]	−0.588	−0.084	0.803	−0.194	0.146	−0.091	−0.462	0.951	1.000
HVOB10									
n [rpm]	1.000	0.814	−0.161	−0.423	0.367	0.176	0.979	−0.340	−0.373
P-norm [kW]	0.814	1.000	0.421	−0.751	0.683	0.241	0.889	0.235	0.218
M-norm [Nm]	−0.161	0.421	1.000	−0.737	0.722	0.382	−0.031	0.966	0.917
b_e [g/kWh]	−0.423	−0.751	−0.737	1.000	−0.992	−0.729	−0.459	−0.584	−0.425
η_e	0.367	0.683	0.722	−0.992	1.000	0.765	0.388	0.565	0.391
lambda	0.176	0.241	0.382	−0.729	0.765	1.000	0.103	0.333	0.064
SOI [CAD BTDC]	0.979	0.889	−0.031	−0.459	0.388	0.103	1.000	−0.204	−0.204
m_{air} [mg/cycle]	−0.340	0.235	0.966	−0.584	0.565	0.333	−0.204	1.000	0.961
m_f [mg/cycle]	−0.373	0.218	0.917	−0.425	0.391	0.064	−0.204	0.961	1.000
HVOB20									
n [rpm]	1.000	0.850	0.125	−0.560	0.494	0.246	0.985	−0.186	−0.241
P-norm [kW]	0.850	1.000	0.616	−0.861	0.823	0.335	0.917	0.321	0.276
M-norm [Nm]	0.125	0.616	1.000	−0.860	0.884	0.452	0.267	0.915	0.849
b_e [g/kWh]	−0.560	−0.861	−0.860	1.000	−0.982	−0.656	−0.661	−0.667	−0.527
η_e	0.494	0.823	0.884	−0.982	1.000	0.643	0.590	0.666	0.524
lambda	0.246	0.335	0.452	−0.656	0.643	1.000	0.260	0.389	0.091
SOI [CAD BTDC]	0.985	0.917	0.267	−0.661	0.590	0.260	1.000	−0.031	−0.076
m_{air} [mg/cycle]	−0.186	0.321	0.915	−0.667	0.666	0.389	−0.031	1.000	0.951
m_f [mg/cycle]	−0.241	0.276	0.849	−0.527	0.524	0.091	−0.076	0.951	1.000

Figure 4 depicts the fuel mass consumption per cycle (mf) as a function of fuel composition across various engine speeds. Based on the findings of the conducted research, it is evident that the greatest levels of fuel consumption are observed when employing ordinary diesel fuel, specifically at an engine speed of 1500 rpm. Following the substitution of the fuel with HVO100 and the subsequent introduction of biobutanol in several concentrations ranging from 5% to 20%, a consistent decline in the aforementioned value was observed. Specifically, the reduction percentages were as follows: HVO100—17%, HVOB5—18%, HVOB10—19%, and HVOB20—20%. When the engine speed reaches 4500 rpm when using HVO fuel and its blends with biobutanol, a little alteration in the trend is observed: the mass fraction (mf) value of HVO100 fuel is approximately 17% lower in comparison to D100. The use of HVOB5, HVOB10, and HVOB20 resulted in a decrease of approximately 2.4% as compared to the use of D100.

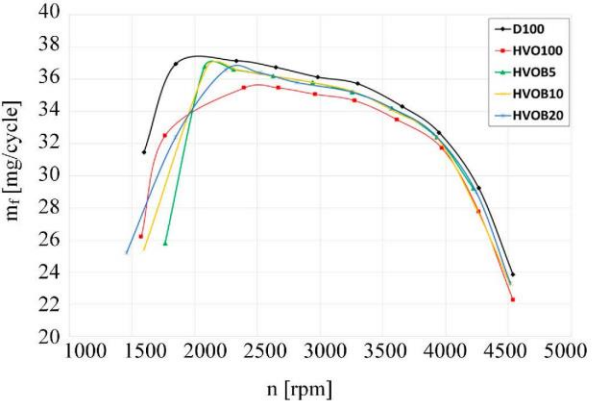


Figure 4. Fuel mass consumption per cycle depending on fuel composition at different engine speeds.

The air mass consumptions for each cycle, denoted as mair, are depicted in Figure 5. The use of D100 fuel resulted in the maximum air mass at a low engine speed of 1500 rpm. After transitioning the fuels to HVO100, there was an observed reduction of around 17% in this value. Additionally, as the concentration of biobutanol in HVO fuel was further raised from 5% to 20%, there was a consistent decrease in this value throughout the different fuel blends. Specifically, the reductions were as follows: HVOB5—18%, HVOB10—19%, and HVOB20—24% when compared to D100. In this particular scenario, the introduction of biobutanol into HVO fuel results in the presence of oxygen alongside biobutanol. Consequently, the resulting mair values exhibit a decrease in comparison to those observed in conventional diesel. When the engine speed reaches 4500 rpm when using HVO fuel and its blends with biobutanol, the observed trend remains consistent, albeit with slightly smaller variations in the drop compared to D100, ranging from 1% to 3.5%.

The air intake system of a compression ignition engine functions with an abundance of air, as depicted in Figure 6. Based on the obtained results, it can be observed that at an engine speed of 1500 rpm, the excess air ratio of HVO100 is decreased by 3% compared to conventional diesel, depending on the engine speed. Nevertheless, the introduction of biobutanol to HVO resulted in an increase in the excess air ratio. The addition of biobutanol at a concentration of 5% (referred to as HVOB5) resulted in a 12% increase, while the

addition of biobutanol at a concentration of 10% (referred to as HVOB10) yielded a value equivalent to that of D100. Nevertheless, when the concentration of biobutanol in HVO fuel was increased to 20%, it was observed that the excess air ratio value was lower compared to that of conventional diesel, namely at 2.2%. The engine speed reached a maximum of 4500 rpm when using HVO100, HVOB10, and HVOB20 fuels. The air surplus values for these fuels were slightly higher, ranging from 0.6% to 1.8%, compared to ordinary diesel. The value of HVOB5 fuel was 1.2% lower compared to D100. The air-to-fuel ratio parameter determines the concentration of unburned hydrocarbons.

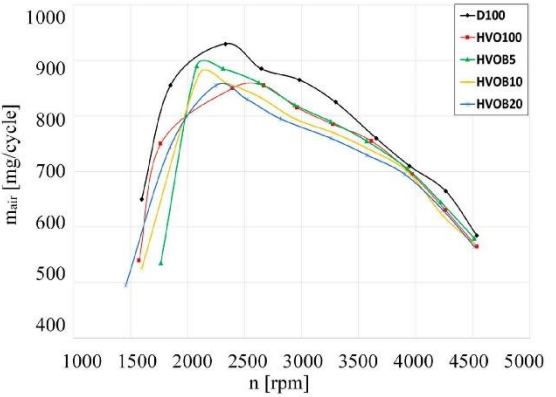


Figure 5. The dependence of air mass consumption per cycle on fuel composition at different engine speeds.

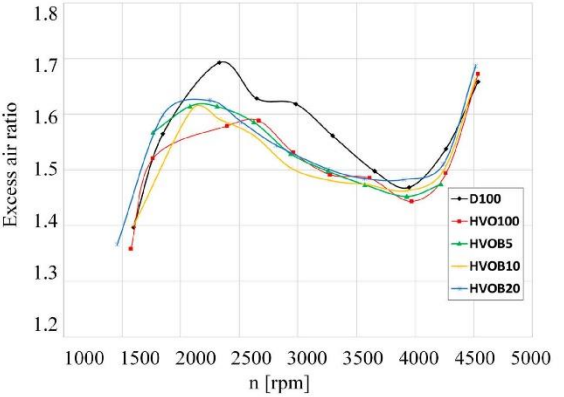


Figure 6. The dependence of excess air ratio on fuel composition at different engine speeds.

The brake-specific fuel mass consumption (BSFC) of the compression ignition engine is depicted in Figure 7. At an engine speed of 1500 rpm, the fuel mass consumption of HVO100, HVOB5, and HVOB10 is observed to be approximately 23% to 24% lower than that of D100. When biobutanol was incorporated into HVO at a concentration of up to 20%, the brake-specific fuel consumption (BSFC) exhibited a 7% increase in comparison to the use of pure diesel fuel (D100). When the engine speed is raised to 4500 rpm, the brake-specific fuel consumption (BSFC) of HVO fuel and blends of HVO and biobutanol (ranging from 5% to 20%) consistently exhibited higher values compared to D100. Specifically, the BSFC values for HVO100, HVOB5, HVOB10, and HVOB20 were found to be 1.7%, 10%, 19%, and 28% higher, respectively, than those of D100. Based on the findings of the fuel analysis (Tables 1 and 2), it can be shown that the lower heating value of HVO100 by mass (MJ/kg), denoted as LHV_m, exhibited a 2.3% increase compared to D100. As the LHV_m value decreases, higher values of BSFC are obtained. The lower heating value (LHV_m) of the HVOB5 fuel mix was observed to be 1% greater compared to D100. Conversely, the LHV_m of HVOB10 was found to be 0.3% lower, while the LHV_m of HVOB20 was 2.8% lower, both in comparison to D100. The significance of brake-specific fuel consumption (BSFC) varies not only due to changes in LHV_m but also due to the engine brake thermal efficiency (Figure 8), which is influenced by the combustion process.

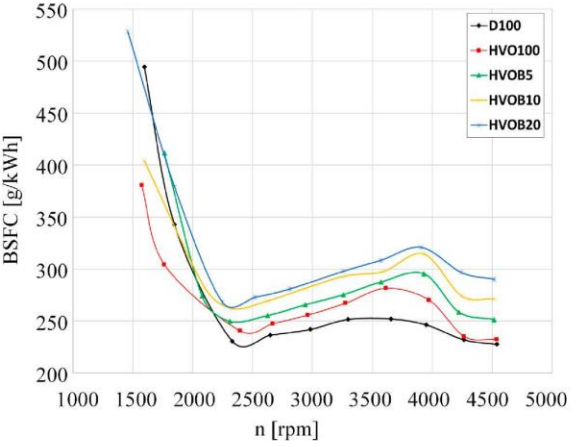


Figure 7. The dependence of BSFC by mass on fuel composition at different engine speeds.

Figure 8 depicts the variation in brake thermal efficiency as a function of engine speed, ranging from 1500 rpm to 4500 rpm. The brake thermal efficiency (BTE) value of HVO100 was approximately 26% higher than that of D100 when operating at 1500 rpm. By elevating the biobutanol concentration in HVO fuel from 5% to 10%, a notable increase in the brake thermal efficiency (BTE) value of around 19% to 22% was observed in comparison to D100. However, when the biobutanol concentration reached 20% in HVO fuel, a decline of approximately 3.5% in BTE value was observed in comparison to D100. Nevertheless, the impact of biobutanol on thermal efficiency diminished as the engine speed increased. The brake thermal efficiency (BTE) of the D100 experienced a drop of around 4.4% at a constant engine speed of 4500 rpm. After increasing the concentration of biobutanol in HVO from 5% to 20%, it was observed that the brake thermal efficiency (BTE) value fell in comparison

to D100. Specifically, the BTE value declined by approximately 10% with HVOB5, 16% with HVOB10, and 20% with HVOB20. The introduction of hydrogenated vegetable oil (HVO) and various combinations of HVO and biobutanol, coupled with an elevation in engine speed, reveals a discernible adverse impact of biobutanol on brake thermal efficiency (BTE).

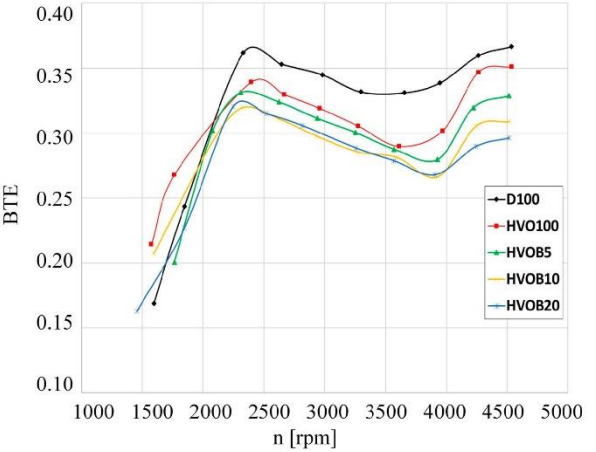


Figure 8. The dependence of brake thermal efficiency on fuel composition at different engine speeds.

The commencement of fuel injection, as shown by the start of injection (SOI) values, exhibited a consistent upward trend in direct correlation with the progressive escalation of engine speed, ranging from 1500 rpm to 4500 rpm. Based on the graphical representation, it is evident that the Start of Injection (SOI) values for various fuels and fuel mixes exhibit disparity when the engine operates at around 1500 revolutions per minute (rpm). In this specific engine mode, the SOI values were observed to vary. The D100 value corresponds to a crank angle degree (CAD) of around 2.6. The parameter known as Before Top Dead Center (BTDC) is denoted by HVO100 and has a value of around 1.3 CAD. Based on the data provided, it can be observed that the BTDC (Before Top Dead Center) timings for HVOB5, HVOB10, and HVOB20 are around 3.5 CAD, 3.6 CAD, and 1.3 CAD, respectively. It is worth noting that the HVOB20 timing exhibits a delay of 1.3 CAD compared to the D100 reference. The State of Interest (SOI) was regulated by the Electronic Control Unit (ECU). Various SOI values were acquired as a result of the distinct physicochemical characteristics of the fuel. At the maximum engine speed of around 4500 revolutions per minute (rpm), the disparities in Start of Injection (SOI) between various fuels and their combinations exhibited reduced magnitudes (Figure 9). The ignition timing for D100 is seen to be 15.0 CAD before top dead center (BTDC), while HVO100 exhibits an ignition timing of 15.6 CAD BTDC. Similarly, HVOB5 demonstrates an ignition timing of 15.8 CAD BTDC, HVOB10 exhibits an ignition timing of 15.4 CAD BTDC, and HVOB20 also displays an ignition timing of 15.4 CAD BTDC, which is 0.4 CAD sooner compared to D100. In summary, the delay values exhibited a modest decrease within a limited range as the engine speed increased up to 4500 rpm when employing HVO and HVO fuel combinations.

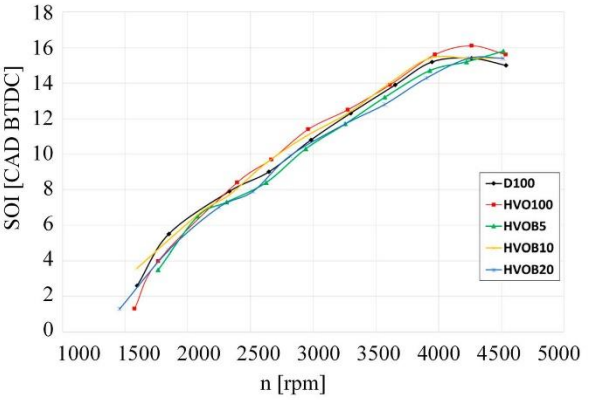


Figure 9. The start of injection depending on the fuel composition at different engine speeds.

4. Discussion

When using various fuel sources, it is crucial to ascertain the parameters of interdependence alterations, which are evident in the correlation between distinct variables. Correlation enables the description of the patterns of co-variation between variables as well as the deliberate justification of the magnitude of relationships between variables. Various types of biofuels and their respective blends were used in the present investigation, alongside regular diesel fuel, which served as a reference for comparative analysis. To expedite the assessment of the impact of fuel type modifications on dependency strength, correlation dependencies were employed. These dependencies are visually depicted in Figures 10–14 and quantitatively summarized in Table 5.

Upon closer inspection of Figure 10, it becomes clear that different fuel types result in the emergence of distinct inter-parameter connection patterns that are analogous to those previously observed. It is essential to recognize the interrelationships between revolutions and power, revolutions and SOI, power and engine speed, power and SOI, efficiency ratio, and fuel consumption, as well as the reciprocal influences of fuel and air masses. While emphasizing a robust connection ranging from 0.999 to 0.800, it is imperative to acknowledge the interrelationships between revolutions and power, revolutions, and SOI. When biofuels are used, whether in their unadulterated form or when combined with other substances, a strong connection may be seen developing between the load, the fuel mass, and the air mass.

While analyzing the correlations across individual biofuels and conducting comparisons between them, it is noted that the variations are less than 10%. This finding suggests that the parameters exhibit independent correlations regardless of the biofuel category. However, it is important to note that the parameters are not similar and exhibit variations based on the specific biofuel being considered.

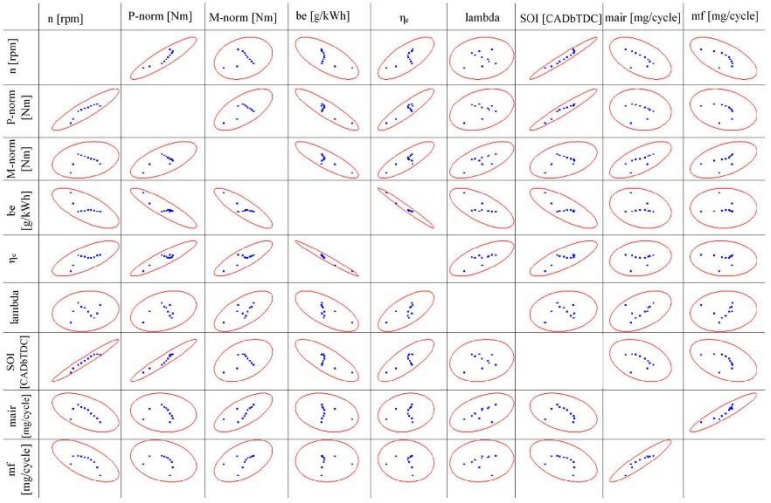


Figure 10. Correlation parameters of engine parameters using different fuels: D100.

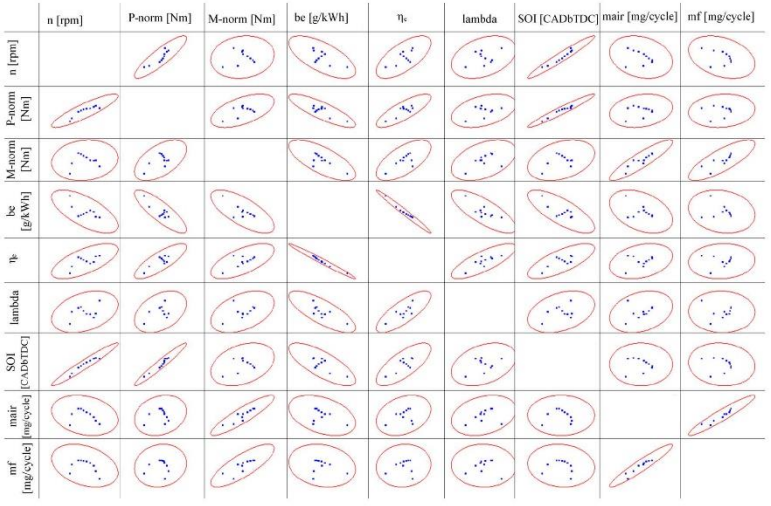


Figure 11. Correlation parameters of engine parameters using different fuels: HVO100.

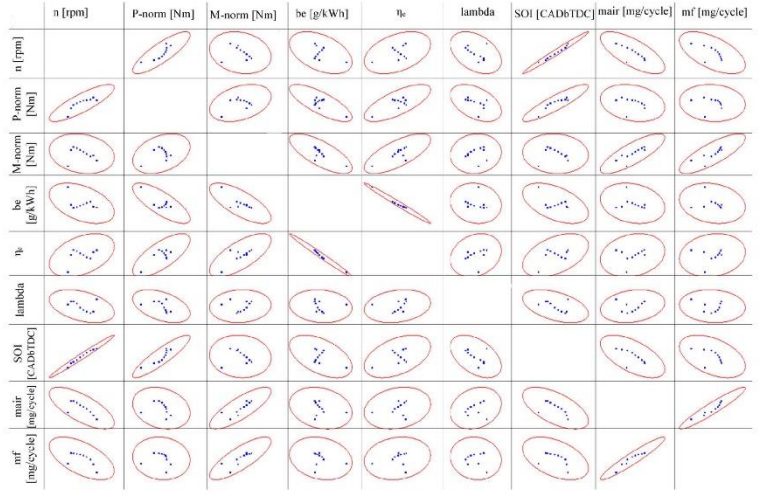


Figure 12. Correlation parameters of engine parameters using different fuels: HVOB5.

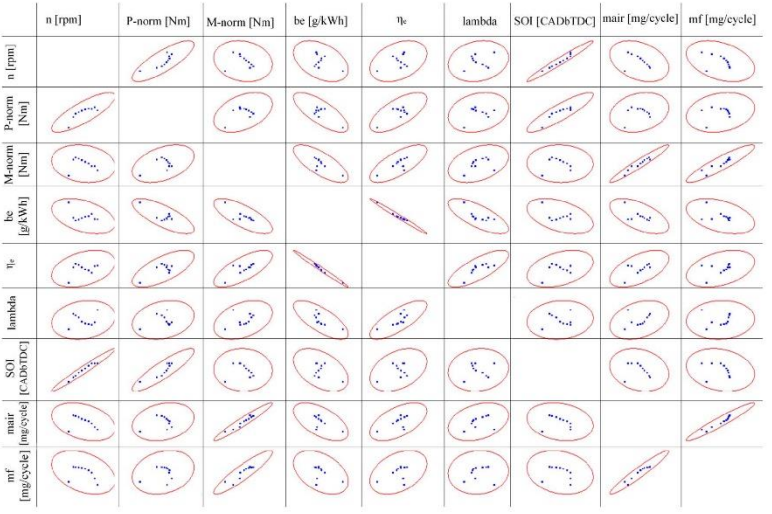


Figure 13. Correlation parameters of engine parameters using different fuels: HVOB10.

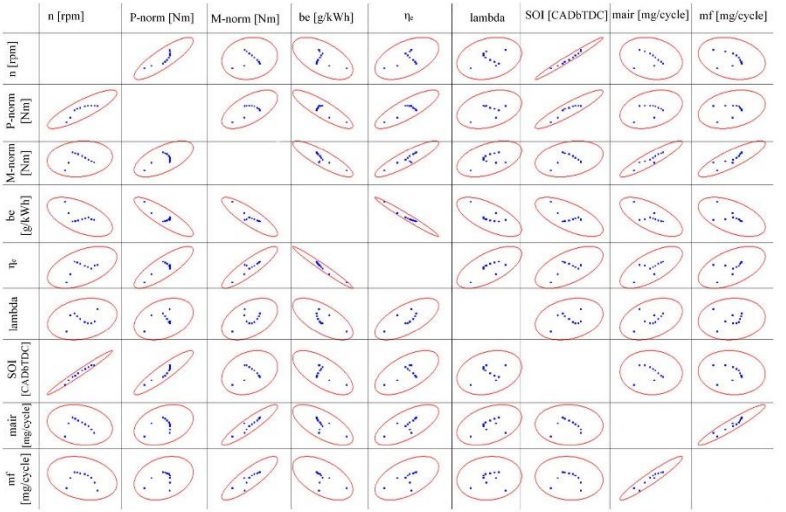


Figure 14. Correlation parameters of engine parameters using different fuels: HVOB20.

5. Conclusions

The analysis carried out allowed for the following conclusions:

- The maximum power output of D100 gasoline is 64.5 kW. However, when using HVO100 fuel, there is an 8% loss in power output. Similarly, HVOB5 fuel results in an 11% decrease, HVOB10 fuel leads to a 17% decrease, and HVOB20 fuel causes a 22% decrease in power output.
- The research conducted revealed that the mass fraction (mf) of HVO100 fuel experiences a reduction of 17% when blended with biobutanol as the engine speed hits 4500 rpm. Additionally, a little alteration in the observed trend is observed at this specific engine speed.
- The use of D100 fuel resulted in the attainment of the highest air mass at an engine speed of 1500 revolutions per minute (rpm). However, the subsequent switch to HVO100 fuel led to a reduction of approximately 17% in the aforementioned air mass. The values of HVOB5, HVOB10, and HVOB20 dropped as the concentration of biobutanol grew from 5% to 20%.
- The brake-specific fuel consumption (BSFC) of HVO fuel and various blends of HVO and biobutanol consistently demonstrates superior performance compared to D100, exhibiting a range of values that consistently surpass D100 by 1.7% to 28%.
- The brake thermal efficiency of the D100 had a decline of 4.4% at an engine speed of 4500 rpm. Furthermore, augmenting the concentration of biobutanol in HVO led to a reduction in the brake thermal efficiency value.
- The Start of Injection (SOI) values exhibit variations across different fuels and mixtures during engine operation at 1500 rpm. The timings for Before Top Dead Center (BTDC) for HVOB5, HVOB10, and HVOB20 exhibit variations of 3.5 CAD, 3.6 CAD, and 1.3 CAD, respectively. Notably, the timing for HVOB20 demonstrates a delay of 1.3 CAD.

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Summary in Lithuanian

Įvadas

Problemos formulavimas

Vadovaujantis Europos klimato kaitos įstatymu (European, 2023), kuriuo siekiama kovoti su klimato kaita ir aplinkos tarša, svarbu įgyvendinti priemones, apimančias teisėkūros veiksmus, technologinę pažangą ir degalų politikos pokyčius. „Klimatui neutrali Europa“, kaip nurodyta Europos žaliojo kurso strategijoje (European, 2024), atlieka svarbų vaidmenį skatinant ekonomikos pažangą, didinant konkurencingumą ir efektyviai naudojant išteklius, ypatingą dėmesį skiriant atsinaujinantiems alternatyviesiems biodegalams.

HVO ir biobutanolio degalų mišiniai, palyginti su iškastiniu dyzelinu, išskiria mažiau šiltnamio efektą sukeliančių dujų. Šių degalų naudojimas prisideda prie pasaulinių tikslų mažinti CO_2 ir kitų šiltnamio efektą sukeliančių dujų išmetimą, taip kovojant su klimato kaita. Europos aplinkos agentūra teigia (Environment, 2021), kad 2019 m. 25 % CO_2 emisijų ES buvo priskirta transporto sektoriui, o kelionės automobiliu sudarė 71,7 %. Europos Komisija pateikė teisinius pasiūlymus, kuriais siekiama klimato, energetikos, transporto ir biudžeto politikos integracijos. Europos žaliojo kurso programos tikslas – pasiekti anglies dioksido neutralumą, sutelkiant dėmesį į tai, kad iki 2030 m. išmetamo anglies dioksido kiekis būtų sumažintas 55 %, o iki 2040 m. – 90 %, palyginti su 1990 m. lygiu.

Apibendrinant galima teigti, kad HVO ir biobutanolio degalų mišinių naudojimas vidaus degimo varikliuose yra svarbus žingsnis siekiant energetinio saugumo, aplinkos tvarumo ir ekonominės plėtros. Transporto sektoriui siekiant mažinti poveikį aplinkai, šie atsinaujinančių išteklių degalų mišiniai yra perspektyvus ir veiksmingas sprendimas.

Darbo aktualumas

Perėjimas prie tvarių ir aplinką tausojančių transporto būdų yra esminis tikslas mažinant neigiamą klimato kaitos poveikį ir aplinkos taršą. Atsižvelgiant į tai, degalų mišinių, ypač tų, kuriuose yra HVO ir biobutanolio, naudojimas vidaus degimo varikliuose yra aktuali strategija ieškant tvarių alternatyvų įprastiniams iškastiniams degalams.

Europos klimato teisės akte (European, 2023) nustatytas tikslas iki 2050 m. pasiekti nulinę šiltnamio efektą sukeliančių dujų emisiją, ir nurodyti keli pagrindiniai aplinkos taršos šaltiniai, tarp kurių svarbiausi yra energijos gamyba ir transformavimas, iškastinių degalų naudojimas, kelių transporto ir įrangos, kurioje taikomi vidaus degimo procesai, sukeliamos emisijos. Atsižvelgiant į tai, perėjimas prie biodegalų, tokių kaip HVO ir biobutanolio mišiniai, yra ne tik alternatyva, bet ir būtinybė siekiant tvarios ir mažiau taršios ateities.

Biobutanolio panaudojimas HVO degalų mišiniuose yra perspektyvus būdas visiškai pakeisti iškastinį dyzeliną. Šis degalų mišinys yra biologinis sprendimas, atitinkantis kieliamus Europos Sąjungos aplinkos politikos tikslus (European, 2024).

HVO ir biobutanolio degalų mišinius verta naudoti vidaus degimo varikliuose, nes tai leidžia sumažinti kenksmingų išmetamųjų teršalų kiekį ir pasiekti pasaulinės aplinkos politikos tikslus. Pažangūs šios srities moksliniai tyrimai yra labai svarbūs norint išnaudoti visą šių biodegalų potencialą ir taip prisidėti prie tvaraus ir ekologiško transporto ateities.

Tyrimų objektas

Disertacijos tyrimo objektas – slėginio uždegimo vidaus degimo variklio, veikiančio naudojant HVO-biobutanolio mišinius, energinės ir ekologinės charakteristikos.

Darbo tikslas

Darbo tikslas – ištirti iš HVO ir biobutanolio susidedančius biologinės kilmės degalų mišinius, naudojamus slėginio uždegimo vidaus degimo varikliuose, siekiant nustatyti energinius ir ekologinius rodiklius.

Darbo uždaviniai

Tikslui pasiekti tyrime daug dėmesio skiriama tikslių ir sudėtingų elementų nagrinėjimui. Sprendžiami šie uždaviniai:

1. Ištirti HVO ir biobutanolio įtaką degalų mišinių savybėms ir degimo procesui variklyje.
2. Ištirti HVO ir biobutanolio degalų mišiniais varomo slėginio uždegimo variklio energinį efektyvumą ir sukeliamas emisijas.
3. Išnagrinėti išmetamųjų dujų recirkuliacijos ir įpurškimo pradžios įtaką energiniams ir ekologiniams rodikliams, slėginio uždegimo vidaus degimo variklyje naudojant tiriamus degalų mišinius.
4. Įvertinti gautų eksperimentinių duomenų tikslumą, slėginio uždegimo varikliyje naudojant HVO ir biobutanolio degalų mišinius.

Tyrimų metodika

Objektui tirti pasirinkti šie tyrimo metodai:

- *Klasifikacija:* apibendrinti ankstesni biodegalų vidaus degimo varikliuose tyrimai, išanalizuoti jų privalumai ir trūkumai.
- *Patirtis*: atlikta paklaidų analizė, siekiant nustatyti pagrindinius rezultatų pokyčius, atsirandančius keičiant eksperimente naudojamus degalų mišinius, ir tų pokyčių priežastis.
- *Eksperimentinis metodas:* ištirta HVO ir biobutanolio degalų mišinių naudojimo, didinant slėginio uždegimo variklio degimo, energinį efektyvumą ir ekologinį tvarumą, pridėtinė vertė.
- *Statistiniai metodai*: eksperimento metu surinkti duomenys naudojami analizuojant ir vertinant konkrečias sąsajas, susijusias su biodegalų naudojimu slėginio uždegimo vidaus degimo varikliuose.

Darbo mokslinis naujumas

Mokslinio naujumo aspektai, susiję su skirtingos sudėties antros kartos biodegalų (HVO ir biobutanolio), kai biobutanolio koncentracija iki 20 %, t. y. HVOB20, panaudojimo slėginio degimo vidaus degimo variklyje energiniais ir ekologiniais rodikliais, yra tokie:

1. Tiriamųjų degalų mišinių savybėms nustatyti taikyta originali HVO ir biobutanolio mišinių ruošimo metodika.
2. Nustatytas HVO ir biobutanolio struktūrizuotų mišinių *SOI* poveikis degimo proceso efektyvumui ir emisijoms.
3. Nustatyta, kad biobutanolio koncentracija HVO degaluose ir EGR sąveika (esant iki 30 % EGR režimui) nedidina NO_X emisijos.
4. Pearsono koreliacijos metodika taikoma tiriant dūmingumo ir PN rodiklių ryšį slėginio uždegimo varikliuose.

Darbo rezultatų praktinė reikšmė

Antrosios kartos biodegalų, tokių kaip HVO ir biobutanolio degalų mišinių, privalumas yra jų stabilumas ir ekonomiškumas, siekiant tvarių ir ekonomiškų energijos alternatyvų. Šie biodegalai pasižymi stabilumu dėl patobulintų gamybos procesų, tai leidžia sumažinti priemaišas ir užtikrinti pastovią degalų kokybę.

Didinant EGR intensyvumą iki 30 %, padidėja išmetamųjų teršalų kiekis ir kartu sumažėja neigiamas poveikis *BTE* ir dūmingumui. Maišant biobutanolį su HVO iki 10 %, pasiekiamas balansas tarp mažesnio išmetamųjų teršalų kiekio ir degimo proceso efektyvumo. Tačiau naudojant biobutanolio iki 20 % mažėja *BTE*.

Siekiant užtikrinti optimalų variklio veikimą ir efektyvumą, ypač esant kintančioms variklio apkrovoms ir EGR intensyvumui, būtina koreguoti ciklinį įpurškiamų degalų kiekį, kad būtų kompensuotas mažesnis HVO ir biobutanolio mišinių *LHV*, palyginti su D100. HVO veiksmingiau sumažina NO_X, CO_2 ir kietųjų dalelių emisijas, pagerėjus degimo proceso savybėms, palyginti su įprastiniais iškastiniais degalais. Biobutanolis leidžia pagerinti išmetamųjų dujų emisijų poveikį degimo proceso efektyvumui ir išmetamiesiems teršalams, tokiems kaip HC.

Apibendrinant galima teigti, kad antrosios kartos biodegalų naudojimas yra tvarus būdas suderinti aplinkosaugą ir ekonominę naudą. Šių degalų mišinių stabilumas leidžia užtikrinti patikimą variklio veikimą, o konkurencingų kainų modeliai, paremti gamybos technologijų pažanga ir palankia politika, daro juos perspektyvia tradicinių energijos šaltinių alternatyva.

Ginamieji teiginiai

1. Biodegalų mišiniai, atitinkantys degalų kokybės standartus, yra tinkami naudoti vietoje iškastinių degalų.
2. Dėl mažesnio biobutanolio *LHV* ilgėja įpurškimo trukmė, tai lemia ilgesnį degimą ir mažesnį *BTE*.
3. Dididnant EGR intensyvumą, didėjantį dūmingūmą efektyviai mažina biobutanolio priedas HVO degaluose.
4. Analizuoti Pearsono koreliacijos koeficientai ir ryšiai apibrėžia PN reikšmes pagal dūmingumą slėginio uždegimo variklyje.

Darbo rezultatų aprobavimas

Šio tyrimo tema paskelbti 6 straipsniai, 4 iš jų – mokslo žurnaluose, indeksuotuose *Clarivate Analytics Web of Science* duomenų bazėse ir turinčiuose cituojamumo rodiklį. Autorius skaitė 2 pranešimus 2 tarptautinėse mokslinėse konferencijose:

- 12-ojoje tarptautinėje konferencijoje „Transbaltica XII: Transportation science and technology“, 2021 m.Vilniuje, Lietuvoje.
- 12-ojoje tarptautinėje mokslinėje konferencijoje „Transport Problems 2020“, 2020 m. Katovicoje, Lenkijoje.

Disertacijos struktūra

Disertaciją sudaro trys skyriai. Pirmajame skyriuje pateikiamos biobutanolio ir HVO mišinių, kaip alternatyvos įprastiniam dyzelinui, panaudojimo galimybės. Šis skyrius baigiamas nustatant pagrindinį atlikto tyrimo tikslą ir uždavinius.

Antrajame skyriuje aprašoma tyrimo metodika, naudojami variklio ir traukos stendai. Aprašomos naudojamų degalų mišinių fizinės ir cheminės savybės.

Trečiajame skyriuje pristatomas ekologinių ir energinių rodiklių tyrimas, skirtas įvertinti biobutanolio ir HVO degalų mišinių naudojimo įtakai slėginio uždegimo vidaus degimo variklio darbui. Pateikiami tyrimų rezultatai ir išvados: energinių rodikliai *BTE, BSFC* ir degimo proceso rezultatai, tokie kaip *SOI, SOC, ROHR*, taip pat ekologiniai rodikliai, tokie kaip dūmingumas, NO_X, CO_2 ir PN, priklausomai nuo konkretaus naudojamo degalų mišinio.

Pateikiamas literatūros sąrašas ir 4 autoriaus mokslinių publikacijų disertacijos tema kopijos. Disertaciją sudaro 136 puslapių, 21 paveikslų, 3 lenteles ir darbe cituojami 32 literatūros šaltiniai.

Padėka

Šio darbo autorius išreiškia padėką savo moksliniam vadovui doc. dr. Jonui Matijošiui už pagalbą rengiant disertaciją. Taip pat yra dėkingas doc. dr. Alfredui Rimkui už vertingus

patarimus ir rekomendacijas organizuojant eksperimentinius tyrimus ir rengiant straipsnius. Autorius dėkoja ir prof. Krzysztof Górski bei dr. inž. Tomasz Skrzek iš Kazimiero Pulaskio universiteto Radome (Lenkija). VILNIUS TECH kolegoms autorius yra dėkingas už jų pagalbą, pastabas, patarimus, taip pat norėtų atskirai padėkoti Sauliui Pociūnui už vertingą pagalbą doktorantūros studiju metu. Savo šeimai išreiškia nuoširdžią padėką už nuolatinį palaikymą ir supratimą.

Autorius dėkoja AVL kompanijai už suteiktą galimybę panaudoti variklio modeliavimo programą AVL BOOST, kuri taikyta ištirti degimo procesui. Bendradarbiavimo sutartis pasirašyta tarp VILNIUS TECH Transporto inžinerijos fakulteto ir *AVL Advanced Simulation Technologies*.

1. Mokslinių publikacijų dyzelino ir biodyzelino panaudojimo tema analitinė apžvalga

Šiame skyriuje analizuojami autorių tyrimai, kuriuose apžvelgiami biobutanolio ir HVO degalų mišiniai kaip iškastinio dyzelino alternatyva. Analizuojant atliktus tyrimus nustatyta, kad trūksta degimo procesų rezultatų. EGR sistemų naudojimas efektyviai sumažina azoto oksido emisiją *n*-butanolio turinčiuose mišiniuose. Šiame skyriuje apibrėžiamas pagrindinis šio tyrimo tikslas ir uždaviniai.

N-butanolis – biodegalai, gaunami iš biomasės – yra atsinaujinantis energijos šaltinis. Remiantis atliktais tyrimais, butanolis yra pažangūs alternatyvieji biodegalai, kurie gali būti naudojami slėginio uždegimo varikliuose. *N*-butanolio maišymas su dyzelinu ir biodyzelino mišiniais turi pastebimą įtaką degimo greičiui, tačiau nustatomas ir nedidelis degimo temperatūros pokytis. *N*-butanolio įmaišius į degalus sumažėjo kietųjų dalelių dydis. Pridėjus *n*-butanolio, pailgėjo uždegimo gaištis ir sulėtėjo kinetinio degimo fazė, ypač tai pastebima esant mažoms variklio apkrovoms. *N*-butanolio ir dyzelino mišiniai nedidina NO_X emisijos, sumažina kietųjų dalelių ir dūmingumo emisijas. Vertinant emisijas, atlikti eksperimentai su HVO ir *i*-butanolio mišiniais. NO_X ir kietųjų dalelių emisija sumažėjo, palyginti su iškastinio dyzelino sukeliama emisija. Tyrimas parodė, kad mišiniai su i-butanoliu, kuris sudaro 30 % įprastinio dyzelino tūrio, sukelia didesnę NO_X emisiją, palyginti su įprastais dyzeliniais degalais, bet mažesnę NO_X emisiją nei mišiniai su HVO-i-butanoliu (su *i*-butanoliu, kuris sudaro 30 % HVO degalų) (Xia et.al., 2019). N-butanolio ir *i*-butanolio savybės yra tokios pačios kaip ir biobutanolio.

Atlikti tyrimai rodo, kad dyzelino ir alkoholio mišiniai mažina kietųjų dalelių emisiją (Rimkus et. al., 2019). Palyginti su įprastiniu dyzelinu, naudojant *n*-butanolio ir dyzelino mišinius vėluoja užsidegimas. Naudojant HVO ir *n*-butanolio mišinius (iki 30 %) sumažėja kietųjų dalelių emisija, palyginti su įprastiniu dyzelinu ir HVO keliama emisija (Zöldy, 2019).

Tiriant kietųjų dalelių dydį ir kiekius nustatyta, kad naudojant įprastinį dyzeliną ir HVO susidarė mažesnės kietosios dalelės (mažiau nei 50 nm) ir sumažėjo HVO PM emisija. Kiti eksperimentai parodė, kad kietųjų dalelių emisija sumažėja ankstinant *SOI*; vis dėlto taikant išankstinį įpurškimą susidaro didesni PM kiekiai, palyginti su vieno įpurškimo strategija (Huang et al., 2019).

Atlikti eksperimentiniai tyrimai, siekiant ištirti skirtingo EGR nustatymo poveikį dyzelino ir *n*-butanolio mišinių degimo charakteristikoms ir emisijoms. EGR veikia

kietųjų dalelių susidarymą. Esant mažiau nei 10 % EGR, nėra matomų reikšmingų pokyčių. Didėjant EGR intensyvumui, PM emisija mažėja dėl sumažėjusios degimo temperatūros ir ilgesnės užsidegimo gaišties. Šis reiškinys, žinomas kaip EGR didelio srauto ir žemos temperatūros degimas (LTC), veiksmingai slopina azoto oksidų ir PM susidarymą (Han et al., 2010).

Kai įprastinis dyzelinas maišomas su butanoliu, didinant EGR intensyvumą, sumažėja bendra visų vertinamų degalų mišinių kietųjų dalelių koncentracija. Toliau didėjant EGR intensyvumui kietųjų dalelių koncentracija pradeda didėti. Bendra kietųjų dalelių masės koncentracija pradeda didėti, o dalelių geometrinis skersmuo laipsniškai pasikeičia ir padidėja. Palyginti su D100, BD20 kietųjų dalelių susidarymo koncentracija ir geometrinis skersmuo sumažėjo.

Naudojant biodyzeliną kartu su 10 % ir 20 % EGR, NO_X emisija sumažėjo atitinkamai 14,4 % ir 27,6 %, palyginti su režimais, kai EGR nebuvo naudojamas. Esant dideliam EGR intensyvumui, įprastinis dyzelinas, sumaišytas skirtingomis proporcijomis su butanoliu ir pentanoliu, leido sumažinti bendrą išmetamo angliavandenilio kiekį. Nebuvo pastebimų NO_X emisijos skirtumų, visų degalų emisija buvo lygiavertė esant pastoviam EGR intensyvumui. Nustatyta, kad B10P20 ir B20P10 degalų mišinių naudojimas veiksmingai sumažina tiek suodžių, tiek CO emisiją esant skirtingam EGR intensyvumui, priešingai nei įprastinio dyzelino naudojimas (Liang et al., 2021).

Apibendrinant galima teigti, kad HVO ir biobutanolio degalų mišiniai turi didelį potencialą plečiant biodegalų panaudojimą ir gali būti tinkamas iškastinio dyzelino pakaitalas. Svarbu pažymėti, kad minėtas degalų mišinys susideda iš biologinės kilmės komponentų ir atitinka Europos klimato teisės akte nustatytus tikslus. Ribota šios srities tyrimų apimtis palieka klausimų dėl šių degalų degimo procesų. Atliktuose tyrimuose daugiausia dėmesio skirta degalų suvartojimo modelių ir įtakos aplinkai apibendrinimui. Išsamus energinių ir ekologinių rodiklių ir degimo proceso analizės įvertinimas suteiktų tvirtesnių įrodymų, kad šių degalų mišinių naudojimas slėginio uždegimo varikliuose nereikalauja papildomų variklio modifikacijų.

Perėjimas prie iškastinių degalų pakeitimo atsinaujinančiais energijos šaltiniais yra svarbiausias visapusės strategijos, kuria siekiama tvaraus transporto, aspektas. Šiuo metu biodegalai sudaro tik 4 % pasaulio energijos suvartojimo transporto sektoriuje. HVO ir biobutanolio degalų mišiniai, gaunami iš atsinaujinančių, tvarių ir ekonomiškų šaltinių, yra perspektyvus iškastinių degalų pakaitalas. Minėti degalų mišiniai gali būti naudojami transporto sektoriuje ir atitinka tvarumo reikalavimus.

Remiantis atlikta literatūros apžvalga iškeliami šie uždaviniai:

1. Ištirti HVO ir biobutanolio įtaką degalų mišinių savybėms ir degimo procesui variklyje.
2. Ištirti HVO ir biobutanolio degalų mišiniais varomo slėginio uždegimo variklio energinį efektyvumą ir emisijas.
3. Išnagrinėti išmetamųjų dujų recirkuliacijos ir įpurškimo pradžios įtaką energiniams ir ekologiniams rodikliams, slėginio uždegimo vidaus degimo variklyje naudojant tiriamus degalų mišinius.
4. Įvertinti gautų eksperimentinių duomenų tikslumą, slėginio uždegimo variklyje naudojant HVO ir biobutanolio degalų mišinius.

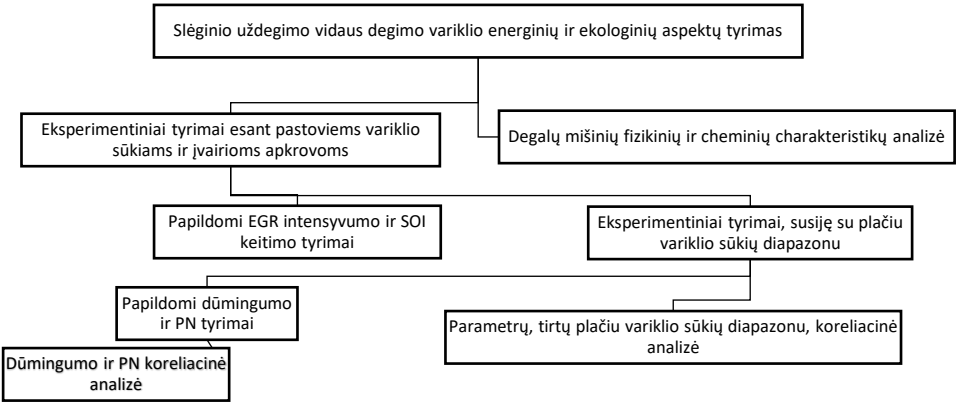
2. Hidrinto augalinio aliejaus ir biobutanolio mišinių tinkamumo slėginio uždegimo varikliams tyrimo metodologija

Šiame skyriuje pristatoma tyrimo metodologija naudojant variklio tyrimų stendą ir automobilio traukos stendą. Taip pat pateikiamos fizinės ir chemines degalų ir jų mišinių, susidedančių iš dyzelino, HVO ir biobutanolio, charakteristikas. Aprašoma mokslinių tyrimų metodika, skirta apibrėžti tyrimų veiklos sekai. Tekste pateikiamas išsamus variklio ir traukos stendo aprašymas, parametrai, jų matavimo ribos ir tikslumas. Aprašomos degimo proceso analizės ir Pirsono koreliacijos koeficiento skaičiavimo metodikos.

Atliekant eksperimentinius tyrimus analizuojama anksčiau išvardytų biodegalų mišinių įtaka slėginio uždegimo vidaus degimo variklio energiniams ir ekologiniams rodikliams. S2.1 paveiksle parodyta tyrimo schema.

Eksperimentiniai tyrimo etapai:

1. Ištirtos HVO ir biobutanolio degalų mišinių fizinės ir cheminės savybes.
2. Naudojant numatytus degalų mišinius, stendiniai slėginio uždegimo vidaus degimo variklio energiniai ir ekologiniai rodikliai tirti esant pastoviam 2000 aps/min greičiui ir įvairioms apkrovoms.
3. EGR intensyvumo ir įpurškimo pradžios (SOI) parametrai koreguoti nurodytomis sąlygomis.
4. Variklio energiniai ir ekologiniai rodikliai, esant įvairiems variklio sūkiams, išanalizuoti naudojant traukos stendą.
5. Dūmingumo nustatymo testas atliktas pagal Reglamento EB 595/2009 metodiką, PN ir dūmingumo matavimai atlikti naudojant anksčiau minėtus degalų mišinius.



S2.1 pav. HVO ir biobutanolio degalų mišinių tyrimo metodikos schema (sudaryta autoriaus)

Eksperimentiniai tyrimai atlikti naudojant gryną įprastinį dyzeliną (D100), gryną hidrintą augalinį aliejų (HVO100), hidrinto augalinio aliejaus ir biobutanolio mišinius (S2.1 lentelę) skirtingomis proporcijomis: 95 % hidrinto augalinio aliejaus ir 5 %

biobutanolio, 90 % hidrinto augalinio aliejaus ir 10 % biobutanolio, 80 % hidrinto augalinio aliejaus ir 20 % biobutanolio tūrio (atitinkamai vadinama HVOB5, HVOB10 ir HVOB20). Siekiant pagerinti tepumo savybes, į HVO ir biobutanolio mišinius buvo maišomas ricinos aliejaus kaip tepumą gerinantis priedas, o ricinos aliejus sudarė 5 % viso biobutanolio tūrio.

Atlikta naudojamų degalų ir jų mišinių fizinių ir cheminių savybių analizė. Siekiant degalams suteikti degalų savybes, eksperimentuose degalai, būtent HVO ir biobutanolis, sumaišyti prieš pat panaudojimą. Siekiant sumažinti galimą temperatūros svyravimų įtaką tankiui, eksperimente naudojami degalai prieš tyrimą buvo laikomi vienodoje temperatūroje.

Prieš eksperimentą ir jo metu degalai ir jų mišiniai buvo atitinkamai nuosekliai maišomi, kad būtų išvengta sluoksniavimosi dėl skirtingo komponentų tankio ir išlaikytas mišinio vientisumas. Pagal degalų kokybės standartą EN ISO 3104 : 1996 viršutinė ir apatinė kinematinės klampos ribos esant 40°C yra atitinkamai nustatytos 3 ir 5mm^2/s. HVOB20 degalų mišinio klampumas yra būtent 3,08 mm^2/s. Padidinus biobutanolio koncentraciją daugiau nei 20 % HVO degaluose, tai viršytų minimalius standarto EN ISO 3104 : 1996 apribojimus.

S2.1 lentelėje pateikiama informacija apie slėginio uždegimo vidaus degimo variklius, jų modelius ir konkrečias sąlygas, kuriomis atliekami eksperimentai.

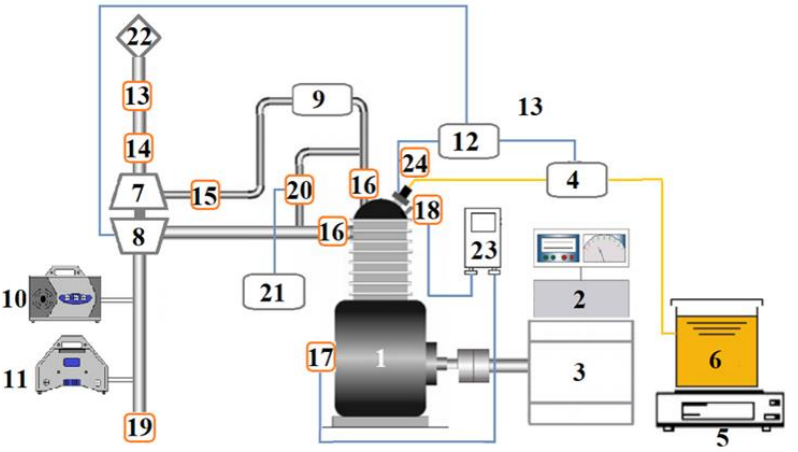
Tyrimai atlikti Vilniaus Gedimino technikos universiteto Transporto inžinerijos ir logistikos laboratorijoje – VILNIUS TECH. Laboratorijoje naudotas variklio tyrimų stendas, kurio schema pavaizduota S2.2 pav.

Variklio alkūninis velenas jungtimi sujungtas su apkrovos stendu KI-5543. Degalų sąnaudos matuotos degalų svarstyklėmis, o išmetamųjų teršalų emisijos matuotos AVL DiCom 4000 dujų analizatoriumi ir dūmingumo matuokliu. Dūmingumo matavimas atliktas įvertinant šviesos intensyvumo sumažėjimą, kurį sukelia sklaidos ir absorbcijos procesai.

Skaitinė degimo proceso analizė atlikta taikant AVL BOOST programinę įrangą. Šilumos išsiskyrimo degimo metu greitis (*ROHR*) apskaičiuotas naudojant tyrimų metu išmatuotus slėgius cilindre, oro ir degalų sąnaudas, naudojamų degalų savybes, variklio parametrus. Nustatyti šie degimo proceso rodikliai: degimo pradžia, temperatūra cilindre, temperatūros padidėjimas cilindre ir slėgio padidėjimas cilindre. Minėti degimo proceso parametrai padėjo analizuoti ekologinius ir energinius rodiklius naudojant įprastą dyzeliną, hidrintą augalinį aliejų bei hidrinto augalinio aliejaus ir biobutanolio mišinius.

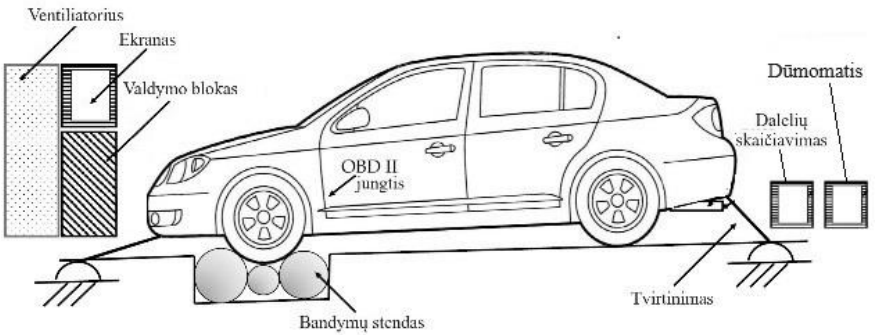
S2.1 lentelė Vidaus degimo variklių eksperimentinių tyrimų seka ir sąlygos

Testo Nr.	Variklio modelis	Testo režimas	Naudoti degalai ir jų mišiniai
1	1,9 TDI VW-Audi 1Z 66 kW (4000 aps/min) 182 Nm (2000 aps/min)	Pastovūs alkūninio veleno sūkiai, *n* = 2000 aps/min, variklio apkrova 30 Nm, 60 Nm, 90 Nm and 120 Nm	D100 HVO100 HVOB5 HVOB10 HVOB20
2		Pastovūs alkūninio veleno sūkiai, n = 2000, variklio apkrova 30 Nm, 60 Nm, 90 Nm and 120 Nm, taikant skirtingą EGR intensyvumą: 0 %, 10 %, 20 %, 30 %	
3	1,9 TDI ALH (Skoda Octavia) 66 kW (4000 aps/min) 210 Nm (1900 aps/min)	Dūmingumo matavimas, kietųjų dalelių koncentracijos matavimas	
4		Išorinės greičio charakteristikos matavimas: sukimo momentas / galia – variklio sūkiai (*n* =1400 – 4600 aps/min)	



S2.2 pav. Eksperimento variklio tyrimo schema: 1 – variklis, 2 – matavimo įranga, 3 – variklio apkrovos blokas, 4 – aukšto slėgio degalų siurblys, 5 – svarstyklės, 6 – degalų bakas, 7 – kompresorius, 8 – turbina, 9 – tarpinis oro aušintuvas, 10 – išmetamųjų dujų analizatorius, 11 – dūmomatis, 12 – ECU, 13 – oro masės matuoklė, 14 – įsiurbiamo oro temperatūros jutiklis, 15 – slėgio jutiklis, 16 – temperatūros jutiklis, 17 – alkūninio veleno padėties jutiklis, 18 – slėgio jutiklis cilindre, 19 – išmetimo vamzdis , 20 – EGR vožtuvas, 21 – EGR valdiklis, 22 – oro filtras, 23 – osciloskopas, 24 – purkštuvas.

VILNIUS TECH automobilių traukos stendas MAHA LPS 2000 buvo naudojamas išplėsti tyrimams ir įvertinti variklio energinėms bei ekologinėms charakteristikoms plačiame variklio sūkių diapazone. Tyrimo schema pavaizduota S2.3 pav., automobilio traukos stendas sukomplektuotas su elektromagnetiniu stabdžiu, galinčiu išmatuoti maksimalų 6 kN sukimo momentą ir 260 kW maksimalią galią. Matavimo paklaida ± 2 %.



S2.3 pav. Automobilio traukos stendas su kietųjų dalelių koncentracijos ir dūmingumo matavimo įranga (sudaryta autoriaus)

Eksperimentinių tyrimų metu buvo naudojama automobilių diagnostikos įranga ROSS-TECH VCDS, atliktas duomenų nuskaitymas prisijungus prie elektroninio valdymo bloko OBDII jungties, siekiant įvertinti šiuos parametrus: degalų sąnaudas,

turbokompresoriaus slėgį ir degalų įpurškimo laiką. Ši diagnostinė įranga buvo naudojama duomenims fiksuoti maždaug 2,5 sekundės intervalais.

Analizuojant duomenis iš variklio ECU pastebėta, kad įrašyti duomenų taškai perduodami atskirais blokais ir trūksta tikslaus sinchronizavimo laiko atžvilgiu. Šie duomenų taškai apima variklio sūkių skaičių (aps/min), ciklinį degalų kiekį (mg /per ciklą), ciklinę oro masę (mg/per ciklą) ir degalų įpurškimo laiką (BTDC), turbokompresoriaus slėgį (m_{bar}) ir degalų įpurškimo laiką (mg / per ciklą).

Atliekant tyrimą automobilio traukos stende papildomai buvo naudotas kietųjų dalelių (KD) koncentracijos matuoklis *P-Trak ultrafine particle counter 8525*, kuriuo matuojama 0,02–1 μm aerodinaminio skersmens dalelių koncentracija 0–500 000 vnt/cm^3 diapazone (aprašymas pateiktas (Rimkus et al., 2019)). Kietųjų dalelių koncentracijos matavimas buvo atliktas varikliui veikiant tuščiąja eiga, prieš tai išmatavus dūmingumą.

Dyzelinių automobilių emisijos įvertinimas atliekamas taikant dvi skirtingas metodikas – išmetamųjų dujų dūmingumo matavimą ir kietųjų dalelių koncentracijos vertinimą. Dūmingumo detektorius CET2200C naudojamas dūmingumui matuoti nustatant šviesos absorbcijos koeficientą. Šis koeficientas parodo, kiek skaitiklio šaltinio skleidžiamos šviesos sugeria transporto priemonės skleidžiamas dūmingumas. Dūmingumo įrangos matavimo ribos svyruoja nuo 0 iki 99,99 m^{-1} 0,01 m^{-1} tikslumu.

Degimo analizei atlikti taikoma AVL BURN programa. Šilumos išsiskyrimo greitis gautas išmatavus cilindro slėgio kreives. Taikant AVL BOOST degimo modelį, slėgis cilindre ir temperatūra apskaičiuoti pagal analizės metu nustatytą šilumos išsiskyrimo greitį. BOOST įrankis pagrįstas algoritmais, naudojamais BOOST cilindre šiai užduočiai išspęsti.

Pirsono koreliacijos koeficientas leidžia išmatuoti tiesinius ryšius tarp dviejų kintamųjų, σ_X ir σ_Y yra atitinkamai dviejų atsitiktinių dydžių X ir Y standartiniai nuokrypiai. Skaičiuojamas kintamųjų Pirsono koreliacijos koeficientas (Bowerman & O'Connell, 1997).

Pateikiamos antrojo skyriaus išvados:

1. Konkrečios HVO ir biobutanolio degalų mišinių proporcijos buvo parinktos atsižvelgiant į jų fizikines ir chemines savybes. Šio metodo parinkimas yra tyrimo tikslo – padidinti variklio efektyvumą ir sumažinti neigiamas pasekmes ekologijai. Tai rodo šių biodegalų mišinių potencialą kaip pakaitalų tvariems energetikos sprendimams. Tai parodo šių biodegalų mišinių potencialą kaip realių pakaitalų tvariems energetikos sprendimams.
2. HVO ir biobutanolio degalų mišinių eksperimentiniai tyrimai susieti su slėginio užsidegimo variklio energinių, degimo proceso ir ekologinių rodiklių metodų parinkimu, klasifikavimu ir patvirtinimu.
3. Remiantis gautais eksperimentų rezultatais buvo patvirtintas teorinio tyrimo duomenų patikimumumas ir jų pagrįstumas.
4. Tyrimų rezultatų parametrams įvertinti ir tarpusavio priklausomybei nustatyti taikytas Pearsono koreliacijos metodas, leidžiantis aproksimuoti variklio veikimo tolydžius duomenis, kiekybiškai įvertinant tiesinės koreliacijas.

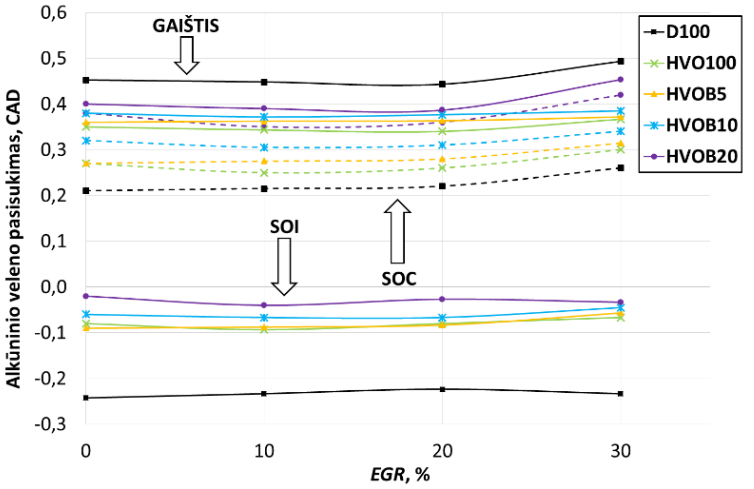
3. Hidrinto augalinio aliejaus ir biobutanolio mišiniais varomo slėginio uždegimo variklio eksperimentinių tyrimų rezultatai

Šiame skyriuje pateikiama ekologinių ir energinių rodiklių analizė, siekiant ištirti HVO ir biobutanolio degalų mišinių panaudojimo poveikį slėgio uždegimo vidaus degimo varikliui. Įpurškimo pradžia buvo reguliuojama ECU pagal pateiktą variklio gamintojo algoritmą. Pateikiami energiniai rodikliai *BTE*, *BSFC* ir degimo proceso charakteristikos, įskaitant *SOI, SOC, ROHR*, bei ekologiniai rodiklai, įskaitant dūmingumą, NO_X, CO_2 ir PN, priklausomai nuo konkretaus naudojamo degalų mišinio. Aprašyti variklio parametrų koreliacijos parametrai, gauti naudojant įvairius degalų mišinius. Remiantis tyrimų rezultatais paskelbtos keturios mokslinės publikacijos.

Eksperimentiniai tyrimai atlikti VILNIUS TECH Transporto inžinerijos ir logistikos laboratorijoje 2020–2022 m. Tyrimo metodika pateikta antrajame skyriuje.

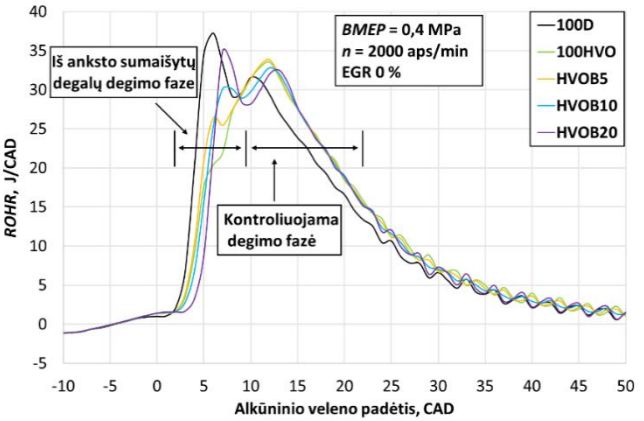
Tyrimo metu variklio sūkiai ir apkrova buvo pastovi, pastebėti energinių rodiklių svyravimai, eksperimenttuota su CI varikliu, naudojant degalų mišinius: D100, HVO100 ir HVOB5, HVOB10, HVOB20. Eksperimentiniai tyrimai atlikti esant pastoviems variklio sūkiams, kai n = 2000 aps/min. Parinktos 30 Nm, 60 Nm, 90 Nm ir 120 Nm variklio apkrovos, atitinkančios 50 km/h, 80 km/h, 100 km/h ir 110 km/h važiavimo greitį. Taip pat buvo nustatomas skirtingas EGR intensyvumas, atitinkamai 0 %, 10 %, 20 % ir 30 %.

Tyrime lyginamas D100 ir HVOB20 degalų ir tiriamų HVO ir biobutanolio mišinių degimo pradžios laikas ir užsidegimo gaištis, daugiausia dėmesio skiriant variklio apkrovos (*BMEP*) ir EGR intensyvumo skirtumui (S3.1 pav.). Remiantis experimentiniais duomenimis ir taikant AVL BOOST programą nustatyti degimo proceso rodikliai. D100 degalų uždegimo laikas buvo 2,4 CAD BTDC, o HVOB20 – 0,2 CAD BTDC, todėl atsirado 2,2 CAD gaištis. Įpurškimo pradžia buvo reguliuojama ECU pagal variklio gamintojo algoritmą.



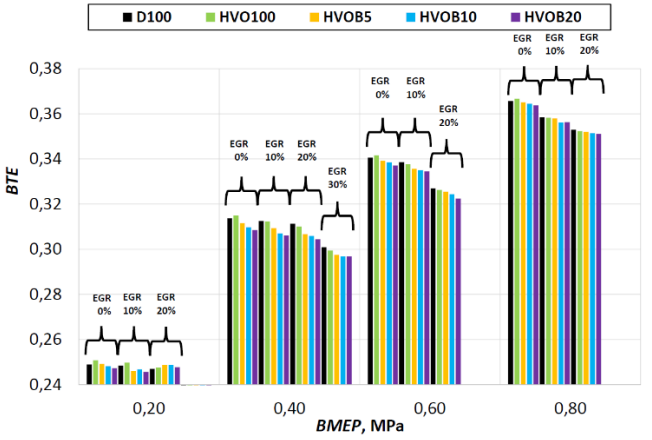
S3.1 pav. *SOI, SOC* uždegimo gaišties priklausomybė nuo naudojamų degalų ir EGR intensyvumo

Maksimalios *ROHR* reikšmės buvo palygintos su įprasto dyzelino reikšmėmis (S3.2 pav.). Kai EGR intensyvumas buvo padidintas iki 30 %, pastebėtas intensyvesnis *ROHR* kitimas: iš anksto sumaišytų degalų degimo fazės metu nustačius 30 % EGR intensyvumą, D100 *ROHR* sumažėjo 16 %, o HVO100 – 13 %, palyginti su EGR režim 0 %.



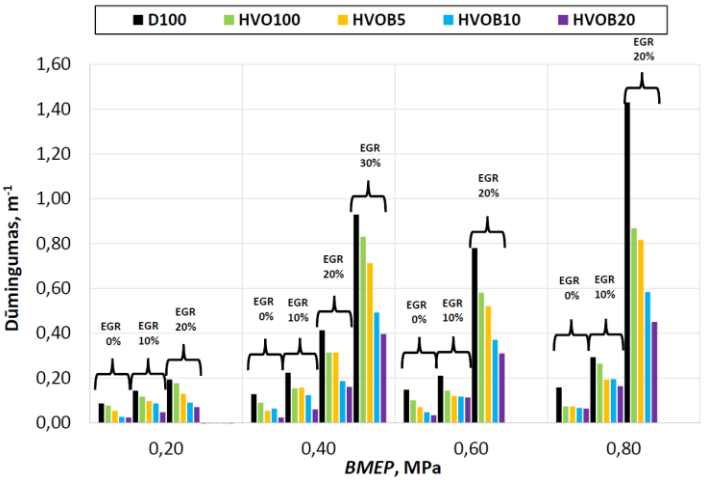
S3.2 pav. Šilumos išsiskyrimo greičio cilindre priklausomybė nuo degalų mišinio

Esant variklio apkrovai esant 0.4 MPa, EGR 0 % (S3.3 pav.), *BTE* reikšmė, naudojant HVOB20, palyginti su D100, sumažėjo maždaug 1,4 %, (*BTE* sumažėjo nuo ~0,301 iki ~0,297). Nustačius EGR režimą nuo 0 % iki 30 %, naudojant HVO degalus, įtakos *BTE* turi kintanti variklio apkrova. Nustačius EGR 0 %, HVO100 *BTE* yra 0,2–0,4 % didesnis nei D100. Tačiau *BTE* mažėja, kai nuo 5 % biobutanolio koncentracijos pereinama prie 20 % koncentracijos. Lyginant EGR 30 % ir EGR 0 %, BTE vertės naudojant HVOB20 sumažėjo 4 %, palyginti su vertėmis naudojant D100.



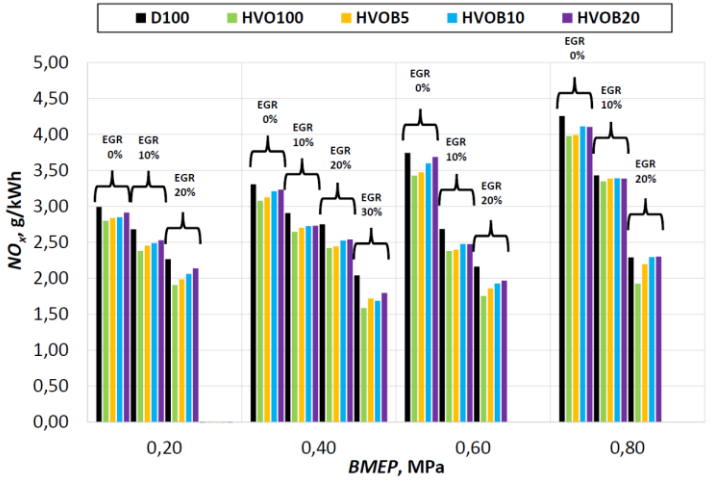
S3.3 pav. *BTE* priklausomybė nuo naudojamų degalų ir variklio apkrovos, esant skirtingam EGR intensyvumui

Analizuojant EGR įtaką dūmingumui pastebėta, kad naudojant HVO100 bei HVO ir biobutanolio degalų mišinius dūmingumo emisija buvo mažesnė, palyginti su D100 (kaip parodyta S3.5 pav.), esant panašioms apkrovoms ir EGR intensyvumui. Iš tyrimo rezultatų matoma, kad EGR padidinus nuo 0 % iki 30 %, esant pastoviai variklio apkrovai (*BMEP)*, pastebimai padidėjo dūmingumas. Taip yra dėl sumažėjusio O_2 lygio ir padidėjusio CO_2 ir H_2O cilindre. Esant pastoviai 0,4 MPa variklio apkrovai, išjungus EGR HVO100 dūmingumo emisija sumažėjo maždaug 29 % (nuo ~0,13 m^{-1} iki ~0,02 m^{-1}), palyginti su D100, o HVOB20 sumažėjo beveik 80 %. EGR intensyvumas daro reikšmingą įtaką dūmingumui, esant 0,4 MPa variklio apkrovai. Padidėjus EGR intensyvumui, naudojant įprastą dyzeliną dūmingumas padidėjo šešis kartus. Tačiau naudojant HVO ir biobutanolio mišinius dūmingumas sumažėjo maždaug 57 % (nuo ~0,93 m^{-1} iki ~0,4 m^{-1}, kai *BMEP* 0,4 MPa, EGR 30 %). Tai rodo, kad HVO ir biobutanolio mišiniai padidina dūmingumo mažinimo efektą, EGR veikiant mažesniu intensyvumu, o didesnis EGR intensyvumas susilpnina teigiamą biobutanolio poveikį mažinant dūmingumą.



S3.5 pav. Dūmingumo priklausomybė nuo naudojamų degalų ir variklio apkrovos, esant skirtingam EGR intensyvumui

Eksperimentinio tyrimo metu nustatyta, kad D100 NO_X emisija gauta didžiausia, o HVO100 – mažiausia (S3.6 pav.). Padidinus biobutanolio koncentraciją HVO degaluose, padidėjo NO_X emisija dėl intensyvesnio degimo esant visoms variklio apkrovoms ir EGR režimams, bet nebuvo emisijos didesnės nei D100. Palyginus HVO100 ir mišinių su biobutanoliu ir D100 sukeliamas NO_X emisijas, kai *BMEP* yra 0,4 MPa ir EGR intensyvumas 0 %, naudojant HVO100 NO_X emisija sumažėjo 7 % (nuo ~237 g/kWh iki ~220 g/kWh). Didėjant EGR intensyvumui, mažėja azoto oksidų emisija (S3.7 pav.), dėl į cilindrą recirkuliuojamo anglies dioksido, vandens garų ir kitų šalutinių degimo produktų. Šis procesas sumažina degimo intensyvumą ir temperatūrą, todėl sumažėja azoto oksidų susidarymas. Esant 30 % EGR intensyvumui, HVO100 ir HVOB20 degalų azoto oksidų emisiją sumažėjo atitinkamai 22 % ir 12 %.



S3.6 pav. NO_X priklausomybė nuo naudojamų degalų ir variklio apkrovos, esant skirtingam EGR intensyvumui

Teorinė paklaidų analizė parodo ryšį tarp biobutanolio koncentracijos HVO mišiniuose ir energinių bei ekologinių parametrų paklaidų. Didėjant biobutanolio koncentracijai, atitinkamai PN paklaidos padidėjo 14 %, HC paklaidos padidėjo apie 5 %, 7 % ir 14 %. Panašiai, didėjant šio parametro absoliutinei vertei, išaugo išmetamųjų dujų temperatūros netikslumai. NO_X paklaidų įvertinimas rodo ryšį tarp didėjančio biobutanolio kiekio ir kylančios temperatūros tendencijos. Pagerėjęs biobutanolio degimo procesas siejamas su esančiu papildomu deguonimi. Šis papildomas deguonis padidina *BTE* ir p_{TC} paklaidas atitinkamai apie 11 % ir 5 %. Tačiau tai kartu sumažina CO_2 paklaidas atitinkamai 2 %, 7 % ir 12 % ir CO paklaidas atitinkamai 7 %, 9 % ir 13 %. Didėjant absoliučioms parametro vertėms, sumažėjęs biobutanolio kaloringumas padidina $BSFC_m$ paklaidas apie 6 %. Panaši tendencija matoma vertinant *BMEP* rodiklio paklaidos. Vertinant automobilio variklio sukimo momento ir galios ir duomenis, didėjant biobutanolio kiekiui pastebima mažėjimo tendencija. Vertinant dūmingumą variklio stende ši tendencija nepastebėta. Kitų rodiklių (*P*, *SOI*, λ) pastebimų paklaidų pokyčių, padidėjus biobutanolio koncentracijai, nepastebėta.

Eksperimentiniai tyrimai rodo, kad HVO ir biobutanolio degalų mišiniai turi poveikį variklio veikimui ir išmetamųjų teršalų kiekiui, tarp kelių veiksnių nustatyti ryšiai. Šie rezultatai pabrėžia šių biodegalų galimybę būti naudojami, kaip tvarūs pakaitalai, mažinant poveikį aplinkai ir laikytis išmetamųjų teršalų reikalavimų.

Tyrimų rezultatų koreliacijos suskirstytos į dvi dalis:

1. Koreliacija tarp ekologinių ir energinių variklio rodiklių, kai taikytas platus variklio sūkių diapazonas.
2. Koreliacija tarp dūmingumo ir PN verčių.

Eksperimente analizuojamos skirtingų degalų šaltinių tarpusavio priklausomybės charakteristikos, naudojant biodegalus ir jų mišinius, taip pat įprastą dyzeliną kaip palyginamąjį etaloną.

Įvertinant biobutanolio koncentracijos poveikį priklausomybės stiprumui, buvo naudojami koreliacinės priklausomybės duomenys, tiksliau įvertinti kintamųjų kitimo ir koreliacijos tendencijas.

Nustatyta stipri koreliacija tarp variklio sūkių, variklio galingumo ir SOI. Biodegalai, be priedų arba sumaišyti, rodo stiprią koreliacija tarp variklio apkrovos, degalų kiekio ir oro kiekio. Skirtumai tarp skirtingų biodegalų yra mažesni nei 10 %, tai rodo autonominę koreliaciją, nepriklausomą nuo biodegalų klasifikacijos. HVO ir biobutanolio degalų mišiniai mažina dūmingumą.

Pateikiamos trečiojo skyriaus išvados:

1. Didžiausias dūmingumas nustatytas naudojant D100. Naudojant HVO100 dėl sumažėjusio C/H santykio dūmingumas sumažėja apie 40 %. Pridėjus biobutanolio dūmingumas dar labiau sumažėja.
2. Kai EGR intensyvumas 30 %, reikšmingai sumažėja NO_X emisija ir biobutanolio koncentracijos padidėjimas mišinyje neturi didelės įtakos didėjančiai NO_X emisijai, nes didelis recirkuliuojamų CO_2 dujų kiekis gerokai sumažina degimo temperatūrą ir slopina degimą gerinantį deguonies, esančio biobutanolyje, poveikį.
3. HC emisijos, kai EGR 0 % naudojant HVO100 sumažėja ~30 %, palyginti su D100, HVOB5 ~21 %, HVOB10 ~3,7 %, HVOB20 jos yra ~1,6 % didesnės nei D100. HC emisijų padidėjimą lemia butanolio pridėjimas, dėl kurio sumažėja degalų mišinio klampumas. Dėl to degalų lašeliai patenka į degimo kameros pakraščius, kur jie netinkamai susimaišo su oru ir ne iki galo sudega.
4. Biobutanolio pridėjimas į HVO degalų mišinius padidina PN ir HC paklaidas ~14 % dėl padidėjusio degalų mišinio garavimo. Dėl šios priežasties padidėja NO_X, *BTE* ir p_{TC} paklaidos atitinkamai ~11 % ir ~5 %. Tačiau CO_2 ir CO paklaidos mažėja. Didėjant biobutanolio kiekiui HVO degalų mišiniuose mažėja degalų šilumingumas, dėl to BSFC m paklaidos padidėja maždaug 6 %.
5. Biobutanolio koncentracijos didinimas neturi įtakos ryšio stiprumui tarp dūmingumo ir PN rodiklių. Dyzeliną pakeitus biodegalais, įvertinus Pearsono koreliacijos koeficientą, ryšys tarp dūmingumo ir PN rodiklių, sumažėja 45 %.

Bendrosios išvados

1. D100 pakeitus HVO ir biobutanolio mišiniais dėl degalų tankio, klampos ir spūdumo skirtumų vėliau įpurškiami degalai. Biobutanolio užsidegimo gaištis yra ilgesnė dėl mažesnio cetano skaičiaus, didesnės latentinės garavimo šilumos ir savaiminio užsidegimo temperatūros, todėl gautas didesnis maksimalus *ROHR* iš anksto sumaišytų degalų degimo fazėje. Dėl ~20 % trumpesnės HVO100 užsidegimo gaišties iš anksto sumaišytų degalų degimo fazėje mišinių su biobutanoliu HVOB5, HVOB10 ir HVOB20 *ROHR* yra atitinkamai ~29 %, ~19 % ir ~5,5 % mažesnis, palyginti su D100 (~37 J/CAD). Kontroliuojamo degimo fazės metu didžiausias *ROHR* padidėja atitinkamai 6 %, 8 %, 5 % ir 3 % dėl sumažėjusios LHV_V reikšmės ir ilgesnės įpurškimo trukmės, palyginti su D100 (~32 J/CAD).

2. $BSFC_m$ sąnaudos naudojant HVO100 buvo mažesnės ~2,5 % (dėl 2,3 % didesnio LHV_m, palyginti su D100). Pridėjus biobutanolio į HVO, degalų mišinio LHV_m sumažėja, todėl HVOB20 $BSFC_m$ ~5 % (nuo ~266 iki ~279 g/kWh) didesnės, palyginti su D100. Vertinant $BSFC_V$ pokytį, HVO100 jis padidėja ~5 % (nuo ~318 iki ~335 ml/kWh), HVOB20 ~12 %, palyginti su D100, nes HVO100 LHV_V yra ~5 % mažesnis, palyginti su D100. HVO100 *BTE* yra 0,2 – 0,4 % didesnis. Dėl padidėjusios biobutanolio koncentracijos HVO degaluose (nuo 5 % iki 20 %) atitinkamai *BTE* reikšmės mažėja, palyginti su D100, nuo 0,1 iki 0,4%. Padidinus EGR intensyvumą, sumažėja visų degalų *BTE*, tačiau padidinus biobutanolio koncentraciją nuo 10 % iki 20 %, esant EGR 30 %, *BTE* nustoja mažėti.
3. D100 pakeitus HVO100 dūmingumas sumažėja ~11 %. Be to, į HVO įmaišius nuo 5 % iki 20 % biobutanolio, dūmingumas sumažinamas atitinkamai nuo 23 % iki 57 % (nuo ~0.93 m^{-1} iki ~0.4 m^{-1}), palyginti su D100. Sumažėjimas siejamas su sumažėjusiu HVO ir biobutanolio C/H santykiu bei padidėjusia deguonies koncentracija degalų mišinyje. Variklio apkrovos didinimas parodė teigiamą biobutanolio poveikį mažinant dūmingumą. Padidinus EGR intensyvumą iki 30 % dėl žemesnės degimo temperatūros ir mažesnio stechiometrinio oro ir degalų santykio (AFR) dūmingumas padidėja apie 40 %.
4. Didesnis HVO cetaninis skaičius sumažina *ROHR* intensyvumą ir degimo temperatūrą, todėl NO_X emisija sumažėja 17–20 % visame variklio apkrovos diapazone, lygnant HVO100 su D100. Į HVO pridėjus iki 20 % biobutanolio, sumažėja degalų mišinio cetaninis skaičius, padidėja deguonies koncentracija, didėja *ROHR* intensyvumas ir degimo temperatūra. Kai EGR 30%, pridėjus biobutanolio į HVO atitinkamai padidėja 5 %, 10 % ir 20 % NO_X emisija arba atitinkamai 6 %, 4% ir 12 %, palyginti su HVO100 (~1,62 g/kWh), bet reikšmės išlieka mažesnės nei D100 (~2,05 g/kWh).
5. Pakeitus D100 į HVO100 CO_2 emisija sumažėja iki 3 %, HC ~30 %. HVOB20 CO_2 emisija buvo iki 6,4% mažesnė, HC ~1,6 % didesnė, palyginti su D100. CO_2 emisijai įtakos turėjo mažėjantis C/H santykis, D100 buvo 6,25, o HVO100 – 5,47 (12,5 % mažesnis, palyginti su D100). HC emisijų padidėjimą lėmė butanolio įvedimas, dėl kurio sumažėja degalų mišinio klampumas. Dėl to degalų lašeliai patenka į degimo kameros pakraščius, kur jie netinkamai susimaišo su oru ir ne iki galo sudega. Padidinus EGR intensyvumą iki 30 % dėl didėjančių *BSFC* reikšmių didėja CO_2 emisija, o HC emisija mažėja: D100 sumažėja 13 %, HVOB20 – 17 % (iki 0,19 g/kWh), nors EGR sumažina degimo temperatūrą ir bloginą degimą, tačiau biobutanolyje esantis deguonis palaiko degimo gerinimo efektą (padidina degimo temperatūrą), taip sumažindamas HC emisijas.
6. Pearsono koreliacijos koeficientai rodo stiprią koreliaciją (0,87…0,99, naudojant biodegalų mišinius) tarp dūmingumo ir PN rodiklių tirtuose slėginio uždegimo varikliuose. Panaudojus biodegalus, koreliacinė priklausomybė tarp dūmingumo ir PN sumažėja 45 %, palyginti su įprastinio dyzelino.

Gintaras VALEIKA

RESEARCH ON ENERGY AND EMISSION PERFORMANCE OF A DIESEL ENGINE FUELLED WITH HYDROTREATED VEGETABLE OIL AND BIOBUTANOL MIXTURES

Doctoral Dissertation

Technological Sciences,
Transport Engineering (T 003)

HIDRINTO AUGALINIO ALIEJAUS IR BIOBUTANOLIO MIŠINIAIS VEIKIANČIO DYZELINIO VARIKLIO ENERGINIŲ IR EMISIJOS RODIKLIŲ TYRIMAI

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