EFFECT OF HVO CNG DUAL-FUEL OPERATION MODE ON EMISSIONS AND PERFORMANCE OF CI ENGINE

Ales Dittrich, Radek Prochazka, Josef Popelka, Dong Nguyen Phu
Technical University at Liberec, Czech Republic
ales.dittrich@tul.cz, radek.prochazka@tul.cz, josef.popelka@tul.cz, dong.nguyen.phu@tul.cz

Abstract. The presented paper aimed to investigate the base effect of the application of HVO (hydrotreated vegetable oil) and CNG (compressed natural gas) and their mixtures as a fuel in the CI (compression ignition) engine. Both fuels were then used in the dual-fuel operating mode (HVO-CNG). Dual-fuel applications are usually made with a liquid fuel (diesel) pilot dose and gaseous fuel (LPG, CNG etc.) main dose. In times of reducing greenhouse emission gases and reducing the dependency on Russian gas and oil, it should be possible and technically possible to reduce both of them in several engine machine applications. As an ecological substitute for diesel oil hydrotreated vegetable oil is used and as an ecological substitute for compressed natural gas biomethane should be used. All experiments were done on a four-stroke direct injection turbocharged CI engine with an installed AC STAG electronic control unit and system for the dual-fuel operating mode. The whole setup was installed on a test bed equipped with ac dyno (which also allows running transient tests) and with other external measurement devices. For the high-pressure indicating parameters, AVL X-ion was used (with an Indicom SW). Horiba mexa-one device was used for gaseous emission measurement. For particulate matter measuring, Horiba SPCS counter was used and Horiba MDLT-One dilution tunnel and TSI EEPS as the particle sizer. As a base level, parameters were set and used for performance and other parameters (emissions, burning, knocking etc.) from the diesel operating mode. All other operating modes were then compared to the base level.

Keywords: CI engine; dual-fuel; hydrotreated vegetable oil; compressed natural gas.

Introduction

The European Parliament, the Council and the Commission have adopted several regulations, directives and proposals in the fields of climate, energy and transport, so that by 2030 greenhouse gas emissions will be reduced by at least 55% compared to 1990. The goal is to achieve climate neutrality by 2050, i.e. an economy with zero net greenhouse gas emissions. The Renewable Energy Directive II on the promotion and use of energy from renewable sources [1] establishes a common framework and a binding target for the share of energy from renewable sources in gross final energy consumption in 2030 of 32%. It also sets criteria for sustainability and savings in greenhouse gas emissions for biofuels, bioliquids and biomass fuels. As motor fuels are produced from renewable sources, the directive considers in particular methyl esters and ethyl esters of fatty acids produced from vegetable oils (FAME), hydrogenated vegetable oils (HVO), dimethyl ether (DME), methanol, ethanol, butanol, biogas, bioLPG, hydrogen and synthetic fuels obtained from renewable energy sources. Dual-fuel engines [2-7] of vehicles with a total weight over 3.5 t intended for road freight transport, are running on alternative motor fuels obtained from renewable sources, such as hydrogenated vegetable oils (HVO) and biomethane (BioCNG). The main advantage of dual-fuel diesel engines is that due to a higher compression ratio (most often in the range of 16-20), they have a higher overall efficiency than gas petrol engines and produce less CO_2 exhaust emissions. In gas diesel engines, diesel is injected into the compressed homogeneous mixture of gas and air in the engine cylinder, heated to a high temperature during compression, serving as a source of ignition of the cylinder filling [8,9]. Most of the energy is supplied to the engine by gaseous fuel [10]. Compared to the course of combustion in diesel engines, gas diesel engines have lower combustion pressures and, at low engine loads, gaseous fuel is not fully utilized. The engine has lower efficiency and a higher CO content in the exhaust gases [11-15]. Gas diesel engines have a longer ignition delay than diesel engines, less efficiency at low and part loads, and higher efficiency at medium to high loads. They produce less NOx and PM emissions than diesel engines but more CO and HC emissions [12, 16-19]. Higher CO and HC emissions come from incomplete combustion. The simultaneous reduction of CO and NOx emissions at a partial load of a dual-fuel engine can be achieved by preheating the intake air and EGR [20]. It is important to determine the optimal gas fuel-diesel ratio. This ratio has a significant influence on the combustion process, stability of operation and exhaust emissions. According to [22], the best conditions for combustion are at the coefficient of excess air lambda (approx. $\lambda = 2$). A negative feature of gas diesel engines is the increased susceptibility to knocking, which can be eliminated by good mapping in the engine ECU [17]. The parameters of individual fuels are listed in Table 1.

DOI: 10.22616/ERDev.2023.22.TF010

Table 1

Basic parameters of diesel fuel, HVO, CNG and BioCNG [23]

Parameter	Diesel	HVO	CNG	BioCNG
C content, % mass	86.2	84.2	74.7	74.7
H content, % mass	13.5	15.1	24.9	24.9
Other elements, % mass	0.3	0.7	0.4	0.4
Density at 20ºC, $kg \cdot m^{-3}$	835	780	0.68	0.68
Calorific value, $kWh \cdot kg^{-1}$	11.94	12.22	13.9	13.9

Compressed Natural Gas (CNG) used in dual-fuel diesel engines is blown under high pressure directly into the cylinders and ignited by injecting a small amount of diesel. This diesel working cycle, HPDI (High-Pressure Direct Injection), achieves higher overall engine efficiency and lower CO_{2eq} production than a gasoline engine. The main advantages of using CNG as a motor fuel compared to petrol and diesel are, from a general point of view, oil savings, less environmental burden from harmful exhaust emissions and lower production of CO_{2eq}.

Biomethane (BioCNG) is produced from biogas, produced by biological decomposition of organic substances in anaerobic conditions (the so-called anaerobic methane fermentation of organic materials). The result of methane fermentation is always a mixture of gases and the fermented residue of organic matter. The properties of the motor fuel BioCNG from renewable sources and CNG of fossil origin are practically identical. See Tab. 1.

Hydrotreated vegetable oils (HVO) are fuels obtained by hydrogenating vegetable oils or animal fats. During the hydrogenation of vegetable oils for the production of fuels, a mixture of hydrocarbons is produced, which in terms of its distillation range, is close to diesel fuel. More than 60% of raw materials of a waste nature (animal and fish fat and waste products from oil refining) are used to produce HVO, so the HVO fuel produced in this way can be described as biofuel. Almost 40% of the raw material base consists of palm oil or smaller amounts of other vegetable oils. The basic parameters of HVO are in Table 1. HVO has a lower tendency to bind atmospheric moisture than biodiesel (FAME), it does not polymerize, is not subject to biological decomposition and has better oxidation properties. However, the most significant advantage of HVO is its high flammability (cetane number 70-95). HVO can be used as a motor fuel for diesel engines, but it is usually added to diesel (dual-fuel engines), which is possible in any ratio.

Experiment

The dual-fuel diesel engine was created by supplementing the original Cummins ISBe4 diesel engine with gas fuel accessories. The parameters of the originally turbocharged diesel engine operated on diesel fuel are listed in Table 2. The engine has multi-stage diesel injection into the engine cylinders. Depending on the engine operating mode, the total fuel dose is divided into pre-injection, injection and post-injection. Pre-injection means injecting a very small dose at a position approx. 30 ºCA before TDC, approx. 10 ºCA before TDC, the main dose (injection) is injected, and pre-injection means injecting a dose of fuel approx. 30-50 ºCA after TDC.

Table 2

Engine parameters specified for laboratory measurements

Type	CI, 4 cylinder inline, turbocharged & aftercooled
Bore X Stroke	107.61 X 123.7 mm
Displacement	4.5 dm^3
Maximum torque	730 Nm
Compression ratio	17.3 : 1
Cooling system	water

The original diesel engine was supplemented with AC S.A. gas fuel accessories. (CNG/air blender, gas pressure regulator, CNG injection valves, electronic control unit for dual-fuel operation and sensors of some engine operating parameters). The individual elements of gas fuel accessories and their arrangement are shown schematically in Fig. 1. The complete setup is also shown here, and all devices used are marked.

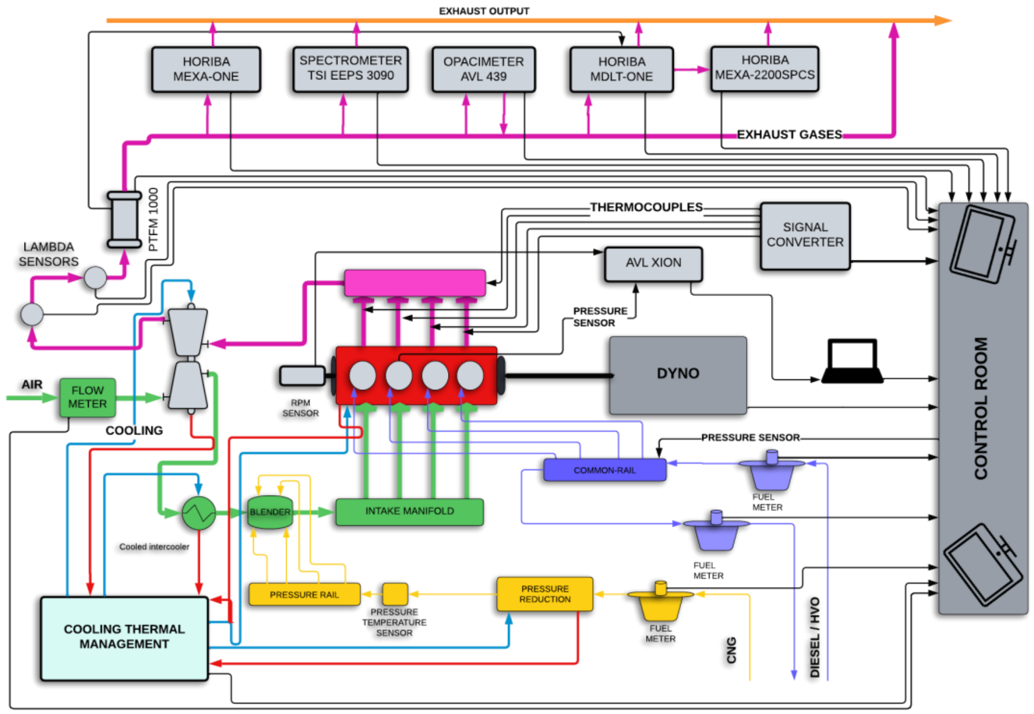
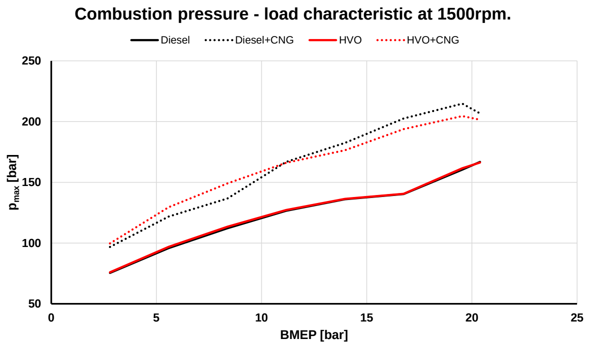


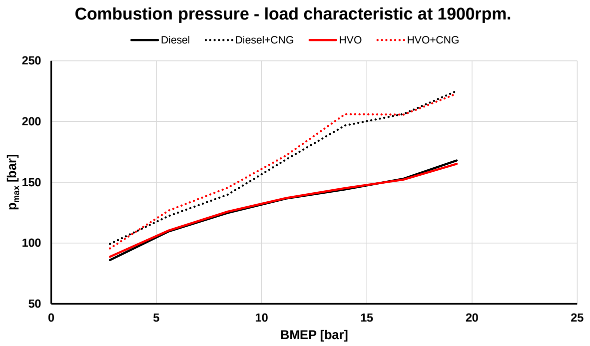
Fig. 1. **Experimental setup**

Results and discussion

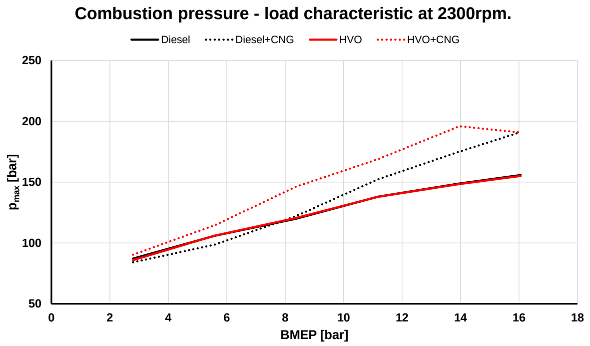
Figure 2 shows combustion pressures in load characteristic modes for diesel/HVO and dual-engine operations, as determined by high-pressure indication (mean values – arithmetic maximum cylinder pressures in 200 consecutive engine operating cycles).



(a)



(b)



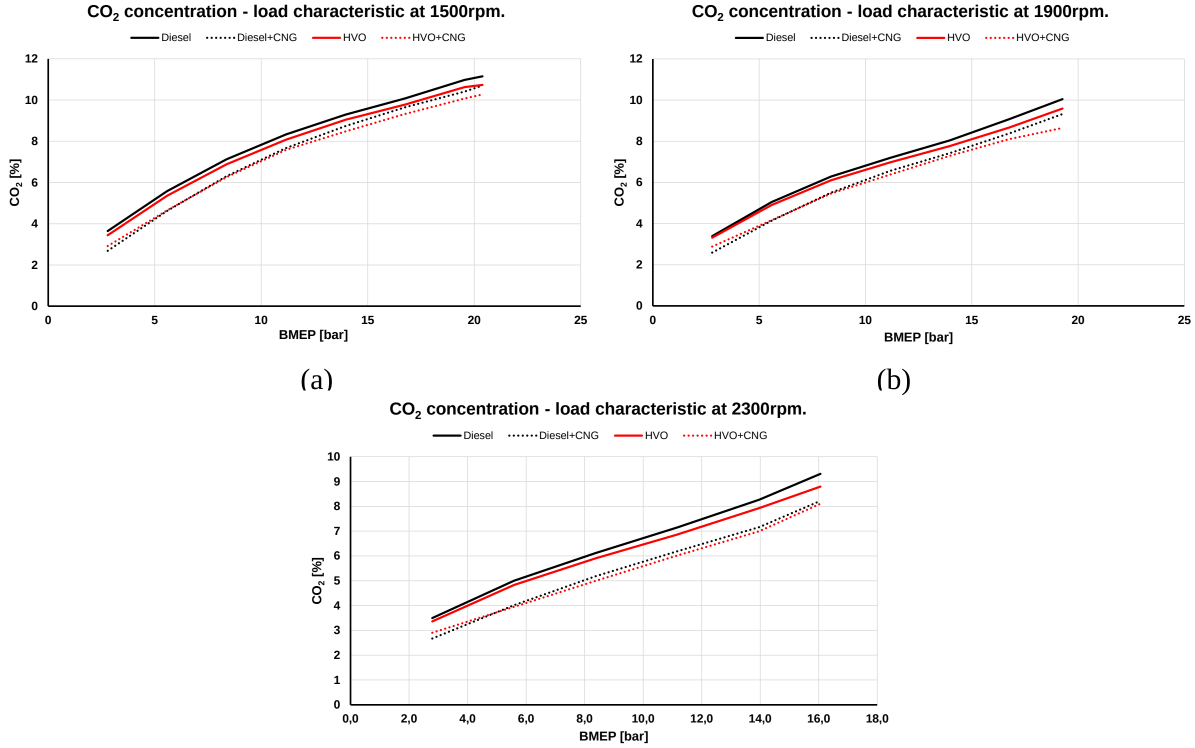
(c)

Fig. 2. **Combustion pressure in load characteristics:** a – 1500 rpm; b – 1900 rpm; c – 2300 rpm

The combustion pressures during dual engine operation are higher than those when operating purely on both liquified fuels (diesel or HVO). Higher combustion pressures in the dual operation of the diesel-CNG/HVO-CNG engine result from the mixture's faster combustion with CNG and the burnout position of 50% of the cylinder filling (MBF50) closer to TDC compared to diesel/HVO operation. Air-fuel ratio values were between 4.0 up to 1.5 depending on BMEP.

In dual engine operation modes (both with diesel and HVO as a liquid fuel), the CO2 concentration in the exhaust gas is lower than that of the diesel/HVO engine only. Comparing both dual-engine operation modes shows that the lowest CO_2 emission level is produced when operating in HVO-CNG mode.

The results show that the operation mode only with HVO is slightly better than operating originally with diesel fuel. It results from both a slightly lower carbon content in 1 kg of CNG (than a carbon content in 1 kg of diesel) and a higher efficiency of heat energy conversion to mechanical work. In a dual engine, due to the significantly more intense kinetic phase of combustion of a locally homogeneous mixture and the subsequent diffusion phase (occurring faster and closer to TDC) compared to diesel/HVO-only combustion. It is shown in Figure 3.

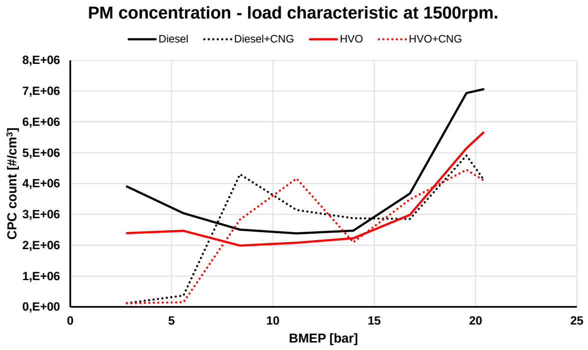


(a) (b)

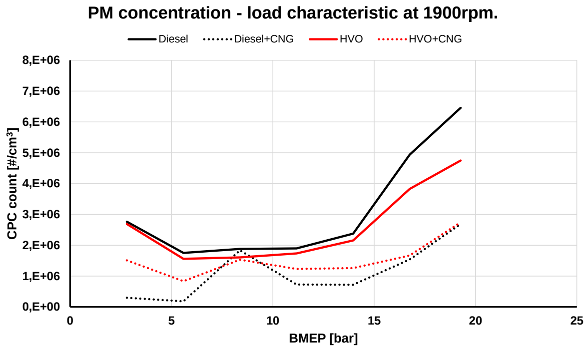
(c)

Fig. 3. **CO_2 concentration in the exhaust gas:** a – 1500rpm; b – 1900 rpm; c – 2300 rpm

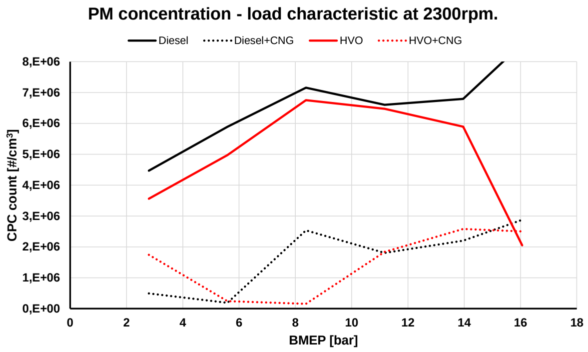
Figure 4 shows the total sum of particle emission in the observed particle size spectrum (with a diameter bigger than 23nm). It shows lower total concentration when operating in dual – mode compared to diesel or HVO engine operation. This is due to the more complete oxidation of the diesel-CNG and diesel-HVO fuel mixture in the dual mode compared to the diesel/HVO mode.



(a)



(b)



(c)

Fig. 4. **PM concentration in the exhaust gas:** a – 1500 rpm; b – 1900 rpm; c – 2300 rpm

Conclusions

The results presented in this paper were obtained on a modified (originally Cummins ISBe4 light truck diesel engine) engine operating in dual mode. The results of experiments carried out at different operating speeds and loads in a combination of different fuels and dual-fuel operation show that it is possible to reduce the produced CO_2 emissions in the exhaust gases in a specific application technically relatively easily and economically at relatively low costs. Dual engines can thus become suitable drive units for trucks and other suitable applications in the nearest future.

Acknowledgements

This work was supported by the Student Grant Competition of the Technical University of Liberec under project No. SGS-2022-5035.

Author contributions

Conceptualization, A.D., R.P., J.P. and D.N.P., methodology, A.D., R.P., J.P. and D.N.P., experiment A.D., R.P., J.P. and D.N.P., data analysis, A.D., R.P., J.P. and D.N.P., writing – original draft preparation; writing – review and editing, A.D., R.P., J.P. and D.N.P. All authors have read and agreed to the published version of the manuscript.

References

[1] DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL: on the promotion of the use of energy from renewable sources. In: Brusel, Belgium: Official Journal of the European Union, 11 December 2018. Accessible from: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri = uriserv:OJ.L_.2018.328.01.0082.01.ENG

[2] Tutak W., Jamrozik A., Bereczky A., Lukács K. Effects of injection timing of diesel fuel on performance and emission of dual fuel diesel engine powered by diesel/E85 fuels. Transport 2018, 33, pp. 633-646.

[3] Jurkovic M., Kalina T., Skrúcaný T., Gorzelanczyk P., L'upták V. Environmental Impacts of Introducing LNG as Alternative Fuel for Urban Buses – Case Study in Slovakia. Promet-Traffic Transp. 2020, 32, pp. 837-847.
[4] Łagowski P. The Effect of Biofuel on the Emission of Exhaust Gas from an Engine with the Common Rail System. Arch. Automot. Eng. 2021, 90, pp. 33-44.
[5] Mikulski M., Ambrosewicz-Walacik M., Duda K., Hunicz J. Performance and emission characterization of a common-rail compression-ignition engine fuelled with ternary mixtures of rapeseed oil, pyrolytic oil and diesel. Fuel 2020, 148, pp. 739-755.
[6] Rimkus A., Stravinskas S., Matijošius J. Comparative Study on the Energetic and Ecologic Parameters of Dual Fuels (Diesel–NG and HVO–Biogas) and Conventional Diesel Fuel in a CI Engine. Appl. Sci. 2020, 10, 359.
[7] Dittrich A., Beroun S., Zvolsky T. Diesel gas dual engine with liquid LPG injection into intake manifold. In Proceedings of the 17th International Scientific Conference on Engineering for Rural Development, Jelgava, Latvia, 23–25 May 2018; pp. 1978-1983.
[8] Gatts T., Liu S., Liew C., Ralston B., Bell C., Li H., Gatts T., Liu S., Liew C., et al., An experimental investigation of incomplete combustion of gaseous fuels of a heavy-duty diesel engine supplemented with hydrogen and natural gas, Int. J. Hydrogen Energy 37 (9), 2012, pp. 7848-7859.
[9] Zhao W.S., Yang W.M., Fan L.Y., Zhou D.Z., Ma X.Z. Development of a skeletal mechanism for heavy-duty engines fuelled by diesel and natural gas, Appl. Therm. Eng. 8 (123), 2017, pp. 1060-1071.
[10] Papagiannakis R.G., Kotsiopoulos P.N., Zannis T.C., Yfantis E.A., Hountalas D.T., Rakopoulos C.D. Theoretical study of the effects of engine parameters on performance and emissions of a pilot ignited natural gas diesel engine, Energy 35 (2), 2017, pp. 1129-1138.
[11] Sombatwong P., Thaiyasuit P., Pianthong K. Effect of pilot fuel quantity on the performance and emission of a dual producer gase diesel engine, Energy procedia 34, 2013, pp. 218-227.
[12] Sahoo B.B., Sahoo N., Saha U.K. Effect of engine parameters and type of gaseous fuel on the performance of dual-fuel gas diesel engines-A critical review, Renew. Sustain. Energy Rev. 13, 2009, pp. 1151-1184.
[13] Papagiannakis R.G., Hountalas D.T., Rakopoulos C.D. Theoretical study of the effects of pilot fuel quantity and its injection timing on the performance and emissions of a dual fuel diesel engine, Energy Convers. Manag. 48, 2007, pp. 2951-2961.
[14] Banapurmath N.R., Tewari P.G., Hosmath R.S. Experimental investigation of a four-stroke single-cylinder direct injection diesel engine operated on dual fuel mode with producer gas and Honge oil and its methyl ester (HOME) as injected fuels, Renew. Energy 33, 2008, pp. 2007-2018.
[15] Ramadas A.S., Jayaraj S., Muraleedharan C. Dual fuel mode operation in diesel engines using renewable fuels: rubber seed oil and coir-pith producer gas, Renew. Energy 33, 2008, pp. 2077-2083.
[16] Abdelaal M.M., Hegab A.H. Combustion and emission characteristics of a natural gas-fueled diesel engine with EGR, Energy Convers. Manag. 64, 2012, pp. 301-312.
[17] Abdelaal M.M., Rabee B.A., Hegab A.H. Effect of adding oxygen to the intake air on dual-fuel engine performance, emissions, and knock tendency, Energy 61, 2013, pp. 612-620.
[18] Cheenkachorn K., Poompipatpong C., Ho C.G. Performance and emissions of a heavy-duty diesel engine fuelled with diesel and LNG (liquid natural gas), Energy 53, 2013, pp. 52-57.
[19] Liu Z., Fei S. Study of CNG/diesel dual-fuel engine's emissions by means of RBF neural network, J. Zhejiang Univ. Sci. 5 (8), 2004, pp. 960-965.
[20] Paykani A., Saray R.K., Shervani-Tabar M.T., Mohammadi-Kousha A. Effect of exhaust gas recirculation and intake pre-heating on performance and emission characteristics of dual-fuel engines at part loads, J. Cent. South Univ 19 (5), 2012, pp. 1346-1352.
[21] Hegab A., La Rocca A., Shayler P. Towards keeping diesel fuel supply and demand in balance: dual-fuelling of diesel engines with natural gas, Renew. Sustain. Energy Rev. 70, 2017, pp. 666-697.
[22] Mikulski M., Wierzbicki S., Smieja M., Matijosius J. Effect of CNG in a fuel dose on the combustion process of a compression-ignition engine, Transport 30 (2), 2015, pp. 162-171.
[23] Brabec P., Laurin J. Alternativní paliva pro silniční nákladní vozidla – výhled do roku 2030 (Alternative fuels for road trucks – outlook to 2030). Výzkumná zpráva. Technická univerzita v Liberci, Katedra vozidel a motorů, 2022, 87 s. (In Czech)