Article citation info:
Longwic R, Tatarynow D, Kuszneruk M, Wozniak-Borawska G. Preliminary tests of a Diesel engine powered by diesel and hydrogen. Combustion Engines. 2023;195(4):35-39. https://doi.org/10.19206/CE-169485

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Combustion Engines
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Preliminary tests of a Diesel engine powered by diesel and hydrogen

ARTICLE INFO

Received: 1 June 2023
Revised: 10 July 2023
Accepted: 11 July 2023
Available online: 22 July 2023

This article discusses the possibilities of powering a commonly used diesel engine with renewable fuels. It analyses scientific studies that clearly indicate that the use of hydrogen is a potentially future-proof option due to its potential to reduce specific fuel consumption and improve performance and increase thermal efficiency. The research was carried out on a laboratory bench designed to test a diesel engine fueled by different fuels. A proprietary hydrogen injection system with dedicated control software was used. Hydrogen injection pressures of 0.15, 0.18, 0.20 MPa and hydrogen injector opening times of 2.5, 3.0, 3.5 ms, respectively, were set as control parameters. The rapidly varying engine operating parameters were recorded and the parameters calculated from them were analysed.

Key words: *hydrogen, combustion, diesel engine, indication, test stand, fuel*

1. Introduction

The well-known effects of excessive pollutant emissions such as global warming, higher sea levels, smog or a health crisis are driving the drive towards climate neutrality [1]. This goal can be achieved, among other things, through the use of alternative fuels. This is why engines powered by renewable energy sources are currently gaining more and more interest. These include hydrogen, which is an environmentally friendly fuel with a zero carbon footprint that contributes to cleaner combustion. There is a huge dynamic of interest in hydrogen on a global scale. In the report 'Geopolitics of the Energy Transformation The Hydrogen Factor', according to Francesco La Camera Director-General International Renewable Energy Agency, hydrogen sources are expected to cover up to 12 per cent of global energy consumption by 2050 [14].

According to the European Automobile Manufacturers Association (ACEA), the European Union has 560 passenger cars and 81 commercial vehicles per 1000 inhabitants. Diesel-powered light commercial vehicles continue to dominate in most EU countries, with as much as 91.2% of the commercial vehicle fleet in the EU running on diesel. A similar situation (96.3%) applies to heavy goods vehicles. In the second quarter of 2022, the market share of passenger cars powered by both petrol and oil was still 55.8% despite the declines [12, 13].

It is, therefore important that conventional diesel engines can eventually be adapted to run on hydrogen, e.g. while leaving the pilot diesel injection in place. A great deal of research work is being carried out in this area. The use of hydrogen as a fuel for diesel engines is a complex issue. Ceraat et al. [2] carried out experimental studies in which they showed that increasing the amount of hydrogen improves the combustion process and reduces the carbon content in the fuel-air mixture, leading to lower CO_2 and CO emissions. It has been noted that soot content decreases with an increase in hydrogen by up to 20%.

Similarly, Juknelevičius et al. [5] showed that the introduction of hydrogen fuel has a positive effect on exhaust emissions, smoke and CO emissions. Combustion becomes smoother, smoke and CO emissions decrease, while HC emissions increase. In [15], it was found that with the enrichment of the mixture with hydrogen, there is a significant reduction in specific CO_2 emissions (the maximum reduction in emissions is observed at 62% in the presence of 46% hydrogen). It was noted that soot emissions decrease significantly with the addition of hydrogen and are 0.28 g/kWh, 0.20 g/kWh and 0.16 g/kWh at 16% H_2, 36% H_2 and 46% H_2, respectively. In contrast, the amount of soot emitted without hydrogen addition was 0.66 g/kWh. According to Santoso et al. [16], at constant load and engine speed, the addition of hydrogen to the intake manifold results in a reduction in diesel consumption.

Work has shown that hydrogen is a potentially future-proof option because it reduces specific fuel consumption [3, 4, 6, 7], increases engine performance, improves efficiency and thermal efficiency [8–10]. It has also been found that, by increasing the dosage of diesel, more hydrogen can be supplied without adversely affecting the working process [11, 17–19].

2. Materials and Methods

2.1. Test stand

The tests were carried out in the Laboratory of the Department of Motor Vehicles of the Lublin University of Technology. The test object was a 1.3 MultiJet compression-ignition engine installed in a Fiat Qubo car. Parameters and technical data of the engine are presented in Table 1. The test environment is shown in Fig. 1.

Table 1. Main characteristics of Fiat Qubo vehicle used for the tests

Parameter	Unit
Engine capacity	1248 cm^3
Cylinder diameter	69.6 mm
Piston stroke	82 mm
Compression ratio	16.8:1
Max power	55 kW CEE/75 KM CEE
Max torque	190 Nm CEE/kg m CEE
Idle speed	850 ±20 rpm
Rotational speed at maximum torque	1500 rpm
Injection system/fuel supply	Common Rail/diesel

Fig. 1. Test bench: 1 – 1.3 Multijet engine, 2 – Fiat Qubo, 3 – Dynorace DF4FS-HLS chassis dynamometer, 4 – computer with software: AVL Indicom, MultiEcuScan and dedicated gas control software, 5 – MAHA MET 6.3 exhaust gas analyzer, 6 – MultiCon CMC-99 data logger, 7 – AVL IndiMicro 602 measuring system, 8 – ZPR 1-B/S fuel consumption meter

During the tests, the engine was fueled with diesel and hydrogen, the dosage of which was adjusted using dedicated control software. Traction tests were carried out using a Dynorace DF4FS-HLS chassis dynamometer. The test rig is shown in detail in the block diagram (Fig. 2). The test vehicle can be supplied with diesel fuel from the vehicle's main tank and other liquid fuel mixtures from an installed auxiliary tank, which allows rapid replacement of the test fuel. The entire process is managed by ECU1 (Electronic Control Unit 1). Fuel consumption was then measured using a flow meter which took into account the return overflow from the injectors and high-pressure pump. Fuel was then fed sequentially to the high-pressure pump, the fuel tank and the injectors. In addition, the stand was adapted to supply the engine with hydrogen gas. The hydrogen fuel supply line originates in a hydrogen storage tank, and the flow pressure can then be set via the I-regulator. The pressurized hydrogen then enters the flow meter with the possibility of recording it in real time. Reducer II has the task of stabilizing the hydrogen operating pressure (this is a control parameter). From this point, two options are possible for feeding the engine. The first is to feed the fuel to the main rail, from which the hydrogen is distributed to four injectors. Each one assigned to a specific cylinder. In the second option, fuel is fed directly from the reducer II via two injectors mounted between the turbocharger and the air cooler. The block diagram shows the electrical signal measurement paths through which the hydrogen injection controller (ECU2) receives information from the sensors on the temperature, hydrogen pressure, and temperature of the reducer II and then controls the gas injectors.

The control and measurement track allows the recording of parameters of engine operation under dynamic conditions, measurement of fuel consumption and environmental and energy parameters. The AVL IndiMicro 602 measurement system, together with the AVL IndiCom software, allows the recording of rapidly changing in-cylinder pressures and the analysis of injection parameters. Ecological measurements are made using the MAHA MET 6.3 exhaust-gas analyzer, the measuring probe of which is installed upstream of the catalytic converter. The analyzer measures HC, CO, CO_2, O_2, NO_x, λ, PM and smoke opacity. Other actual engine operating values were recorded using the Multiecuscan OBD II (On Board Diagnostics) diagnostic interface.

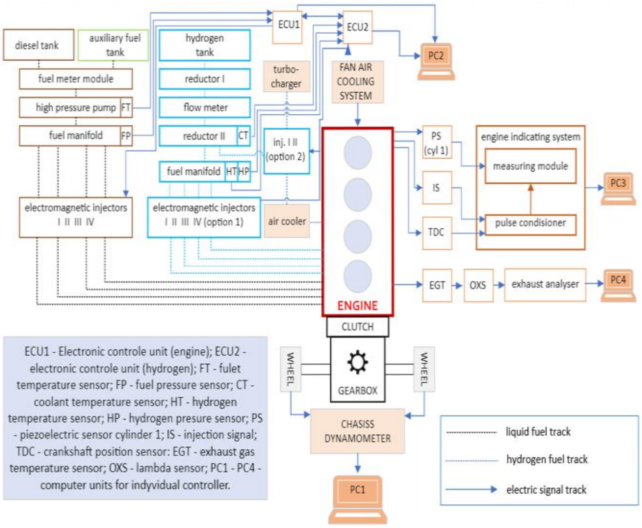


Fig. 2. Block diagram of the test bench

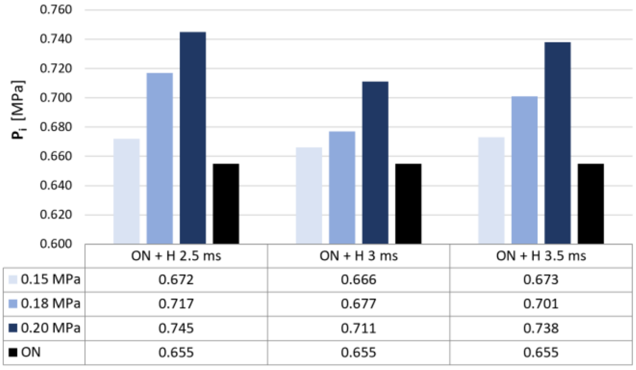
2.2. Course of tests

Tests were carried out with the vehicle running on a chassis dynamometer in fourth gear (closest to direct ratio) at a constant speed of 2600 rpm. The vehicle was subjected to rolling movement resistance. Measurements were carried out for two variants of engine fueling, i.e. diesel and diesel with hydrogen injection into the intake manifold. Hydrogen was injected sequentially according to the ignition sequence 1-3-4-2 (first option shown in Fig. 2) at the opening of the intake valves on successive cylinders. The operating pressures of the hydrogen addition were determined experimentally, based on preliminary tests described in [9], and were set successively at – 0.15 MPa, 0.18 MPa and 0.20 MPa. In addition, the hydrogen injection time was changed for each pressure value; it was 2.5 ms, 3.0 ms and 3.5 ms, respectively.

3. Results

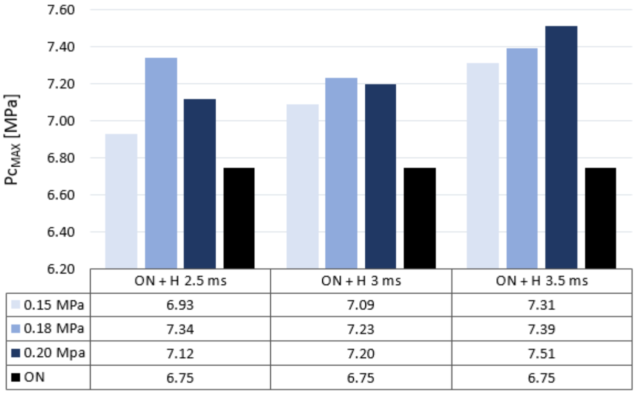
The graphs show the values of the average indicating pressure, maximum combustion pressure, and maximum combustion pressure build-up rate. Also highlighted are the values for the position of the accelerator lever, amount of fuel injected, air flow, hydrogen flow and amount of fuel consumed.

During the combustion of diesel with hydrogen, the recorded values of the average index pressure increased. The observed increase had a linear trend and depended mainly on the set pressure on the operating regulator. The highest values were reached at 0.20 MPa. Hydrogen injection with an injector opening time of 2.5 ms and an injection pressure of 0.20 MPa resulted in a higher average index pressure of 13.7% than diesel combustion. The exact results are included in the table below the graph (Fig. 3). In the case of maximum combustion pressure, higher values were recorded with increasing hydrogen pressure and increasing the opening time of the hydrogen injectors, as shown in Fig. 4. Under the set test conditions, the maximum value of 7.51 MPa achieved gave an 11.2% increase compared to the combustion of diesel alone. Parallels were noted in the case of the maximum combustion pressure rate. At the maximum set hydrogen injection rate, a 20% increase was recorded compared to the combustion of diesel alone (Fig. 5).



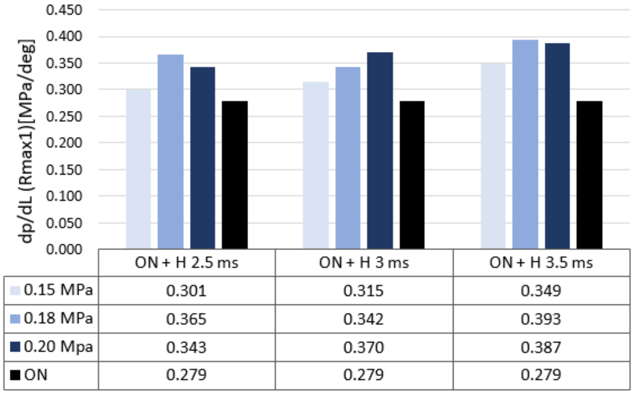
	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
■ 0.15 MPa	0.672	0.666	0.673
■ 0.18 MPa	0.717	0.677	0.701
■ 0.20 MPa	0.745	0.711	0.738
■ ON	0.655	0.655	0.655

Fig. 3. Indicative mean effective pressure – diesel-hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times



	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
■ 0.15 MPa	6.93	7.09	7.31
■ 0.18 MPa	7.34	7.23	7.39
■ 0.20 Mpa	7.12	7.20	7.51
■ ON	6.75	6.75	6.75

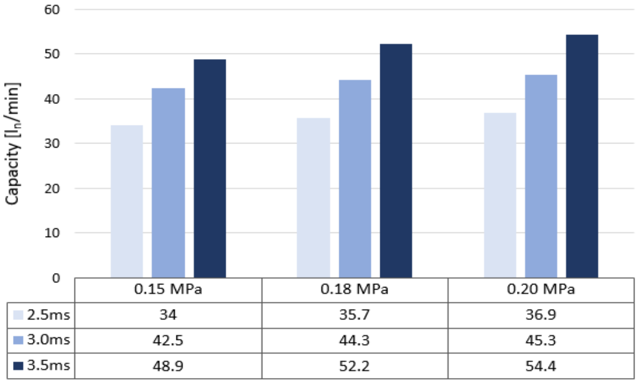
Fig. 4. Maximum combustion pressure – diesel-hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times



	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
■ 0.15 MPa	0.301	0.315	0.349
■ 0.18 MPa	0.365	0.342	0.393
■ 0.20 Mpa	0.343	0.370	0.387
■ ON	0.279	0.279	0.279

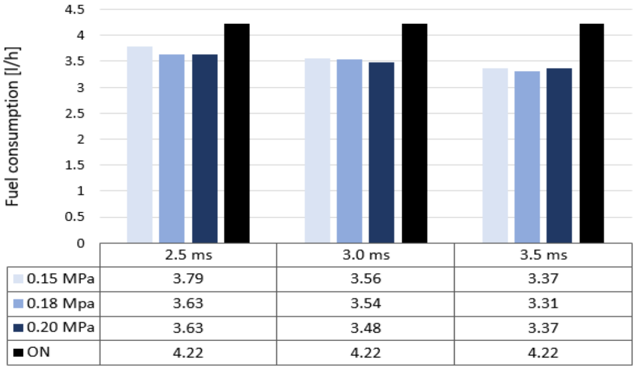
Fig. 5. Maximum build-up rate of combustion pressure – diesel-hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times

An analysis was carried out of the recorded values of hydrogen flow when co-combustion it with diesel fuel. By setting the hydrogen injection control map to an opening time of 2.5 ms, the observed increase in hydrogen flow with respect to pressures of 0.15 and 0.18 MPa was up to 1.7 dm^3/min. On the other hand, each time the injector opening time increased by 0.5 ms, the hydrogen flow increased by an average of about 8 dm^3/min (Fig. 6). As the hydrogen flow increased, the average diesel fuel consumption decreased. The largest reduction in diesel fuel consumption was recorded at the hydrogen injector opening setting of 3.5 ms and a pressure of 0.18 MPa and was 3.31 dm^3/h. This was compared with a value of 4.22 dm^3/h of average diesel consumption alone. At this static test measurement point, this is 0.91 dm^3/h less diesel consumption (Fig. 7).



	0.15 MPa	0.18 MPa	0.20 MPa
■ 2.5ms	34	35.7	36.9
■ 3.0ms	42.5	44.3	45.3
■ 3.5ms	48.9	52.2	54.4

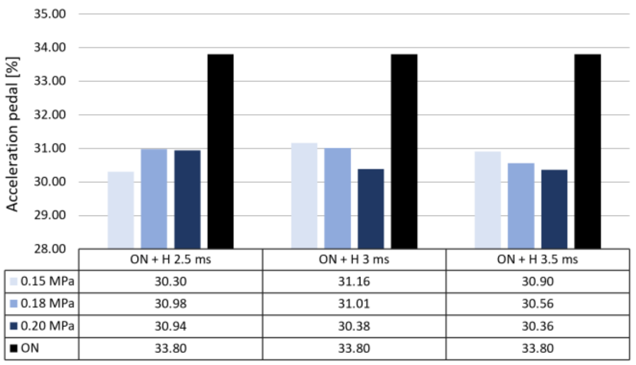
Fig. 6. Hydrogen flow – diesel-hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times



	2.5 ms	3.0 ms	3.5 ms
■ 0.15 MPa	3.79	3.56	3.37
■ 0.18 Mpa	3.63	3.54	3.31
■ 0.20 MPa	3.63	3.48	3.37
■ ON	4.22	4.22	4.22

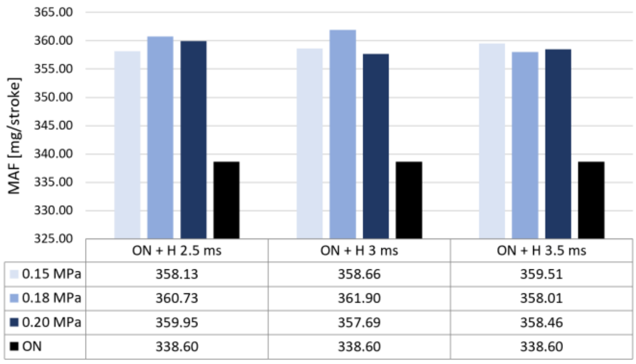
Fig. 7. Fuel consumption – diesel/hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times

It was observed that the addition of hydrogen had an effect on the set angle of the accelerator lever (Fig. 8), where, when driving in fourth gear at 2600 rpm, the value of the accelerator lever swing decreased as the hydrogen injection pressure increased. At a setting of 3.5 ms and a pressure of 0.20 MPa, the difference with the diesel test was 11%. It was also noted that there was an increase in air mass demand to burn the diesel-hydrogen mixture. During one duty cycle, the test engine required on average 6% more air to burn the fuel mixture (Fig. 9). The average amount of diesel fuel injected during one duty cycle of the combustion engine under test was 13.1 mm^3/stroke. Re-estimating this value in ECU1 (Fig. 2) in parallel with ECU2 (Fig. 2) by adding hydrogen to the combustion process, a decrease of 2 mm^3/w on average was observed, as shown in Fig. 10.



	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
0.15 MPa	30.30	31.16	30.90
0.18 MPa	30.98	31.01	30.56
0.20 MPa	30.94	30.38	30.36
ON	33.80	33.80	33.80

Fig. 8. Acceleration pedal position – diesel-hydrogen co-combustion for selected hydrogen pressures and hydrogen injector opening times

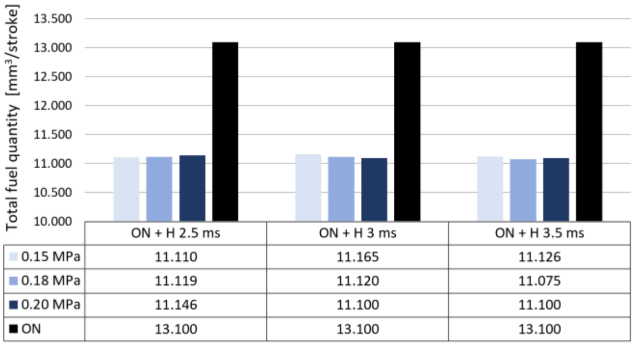


	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
0.15 MPa	358.13	358.66	359.51
0.18 MPa	360.73	361.90	358.01
0.20 MPa	359.95	357.69	358.46
ON	338.60	338.60	338.60

Fig. 9. Mass air intake (MAF) for three injector opening times and three hydrogen injection pressures – diesel-hydrogen co-combustion

4. Conclusions

Indicating the engine tested for diesel-hydrogen co-combustion clearly shows that the rapidly varying in-cylinder combustion parameters analyses are improving. The recorded real values indicated that, as the hydrogen injection time and pressure increase, the air requirement for the correct combustion process increases. In addition, it was observed that the ECU1 reacts by decreasing the set amount of diesel fuel injected during a single duty cycle for each additional fuel injection. The control parameters determined were injection time and hydrogen pressure. Their control range was so small that the correction of the amount of diesel injected by ECU1 over their entire range was practically unchanged. Correct adjustment of the amount of diesel to hydrogen is crucial for stabilizing the working processes of the combustion engine under power.



	ON + H 2.5 ms	ON + H 3 ms	ON + H 3.5 ms
0.15 MPa	11.110	11.165	11.126
0.18 MPa	11.119	11.120	11.075
0.20 MPa	11.146	11.100	11.100
ON	13.100	13.100	13.100

Fig. 10. Amount of diesel fuel injected during one cycle of the diesel-hydrogen co-combustion engine for selected hydrogen pressures and hydrogen injector opening times

A study of a diesel engine fueled with hydrogen allowed the control parameters for the addition of renewable fuel to be determined so as to reduce the consumption of fossil fuel, i.e. diesel. When driving the test vehicle in 4th gear at an engine speed of 2600 rpm, the best fast-variable in-cylinder parameters were achieved when the injector was opened for 3.5ms at 0.20 MPa. Adjusted in this way, ECU2 reduced diesel consumption by an average of 21.5%. Analysis of the results indicates that the search for alternative power sources for existing and technologically refined internal combustion engines is in the right direction. Further research will focus on the search for further control parameters that will directly translate into improvements in the energy and environmental values of the engine studied.

Nomenclature

ACEA	European Automobile Manufacturers' Association
CO	carbon monoxide
CO_2	carbon dioxide
ECU	engine control unit
H	hydrogen
HC	hydrocarbons
MAF	mas air flow
NO_x	nitrogen oxides
OBD	on board diagnostics
O_2	oxygen
PM	solid particles
λ	excess air factor

Bibliography

[1] Bruyninckx H. Health in focus: moving towards zero emissions means healthier lives in Europe. Bulletin EEA, 2022. https://www.eea.europa.eu/en/newsroom/editorial/health-in-focus-moving-towards-zero-pollution-means-healthier-lives-in-europe

[2] Ceraat A, Pana C, Negurescu N, Nutu C, Mirica I, Fuiorescu D. Effect of hydrogen use on diesel engine performance. IOP Conf Ser Mater Sci Eng. 2016;161:012075. https://doi.org/10.1088/1757-899X/161/1/012075

[3] Chojnowski J, Karczewski M. Analysis of the market structure of long-distance transport vehicles in the context of retrofitting diesel engines with modern dual-fuel systems. Combustion Engines. 2022;188(1):13-17. https://doi.org/10.19206/CE-142167

[4] Das S, Kanth S, Das B, Debbarma S. Experimental evaluation of hydrogen enrichment in a dual-fueled CRDI diesel engine. Int J Hydrogen Energ. 2022;47(20):11039-11051. https://doi:10.1016/j.ijhydene.2022.01.125

[5] Juknelevičius R, Rimkus A, Pukalskas S, Matijošius J. Research of performance and emission indicators of the compression-ignition engine powered by hydrogen – Diesel

mixtures. Int J Hydrogen Energ. 2019;44(20):10129-10138. https://doi.org/10.1016/j.ijhydene.2018.11.185

[6] Koten H. Hydrogen effects on the diesel engine performance and emissions. Int J Hydrogen Energ. 2018;43(22):10511-10519. https://doi:10.1016/j.ijhydene.2018.04.146

[7] Köse H, Ciniviz M. An experimental investigation of effect on diesel engine performance and exhaust emissions of addition at dual fuel mode of hydrogen. Fuel Process Technol. 2013;114:26-34. https://doi:10.1016/j.fuproc.2013.03.023

[8] Kumar CB, Lata DB. Effect of di-tert butyl peroxide (DTBP) on combustion parameters and NO_x in dual fuel diesel engine with hydrogen as a secondary fuel. Int J Hydrogen Energ. 2021;46(5):4507-4525. https://doi.org/10.1016/j.ijhydene.2020.10.235

[9] Longwic R, Borawska GW, Tatarynow D, Sander P, Gita A. Analysis of the combustion process of a diesel engine fuelled by diesel and hydrogen. Laribi MA, Carbone G, Jiang Z. (eds). Advances in Automation, Mechanical and Design Engineering. SAMDE 2021. Mechanisms and Machine Science. 2021;121. Springer, Cham. https://doi.org/10.1007/978-3-031-09909-0_9

[10] Longwic R, Woźniak G, Sander P. Compression-ignition engine fuelled with diesel and hydrogen engine acceleration process. Combustion Engines. 2020;180(1):47-51. https://doi.org/10.19206/CE-2020-108

[11] Mickevicius T, Labeckas G, Slavinskas S. Experimental investigation of biodiesel-n-butanol fuels blends on performance and emissions in a diesel engine. Combustion Engines. 2022;188(1):90-95. https://doi.org/10.19206/CE-142030

[12] Report ACEA. New car registrations by fuel type. European Union. 06.2022.

[13] Report ACEA. Vehicles in use, Europe 2022. 01.2022.

[14] Report „Geopolitics of the Energy Transformation The Hydrogen Factor” IRENA, Geopolitics of the Energy Transformation: The Hydrogen Factor, International Renewable Energy Agency. Abu Dhabi 2022.

[15] Sandalci T, Karagöz Y. Experimental investigation of the combustion characteristics, emissions and performance of hydrogen port fuel injection in a diesel engine. Int J Hydrogen Energ. 2014;39(32):18480-18489. https://doi.org/10.1016/j.ijhydene.2014.09.044

[16] Santoso WB, Bakar RA, Nur A. Combustion characteristics of diesel-hydrogen dual fuel engine at low load. Energy Proced. 2013;32:3-10. https://doi.org/10.1016/J.EGYPRO.2013.05.002

[17] Siadkowska K, Barański G, Sochaczewski R, Wendeker M. Experimental investigation on indicated pressure and heat release for direct hydrogen injection in a dual fuel diesel engine. Adv Sci Tech. 2022;16(3):54-66. https://doi.org/10.12913/22998624/149300

[18] Stelmasiak, Z., Larisch, J., Pietras, D., Issues related to naturally aspirated and supercharged CI engines fueled with diesel oil and CNG gas. Combustion Engines. 2017;169(2):24-31. https://doi.org/10.19206/CE-2017-205

[19] Zhou JH, Cheung CS, Leung CW. Combustion, performance, regulated and unregulated emissions of a diesel engine with hydrogen addition. Appl Energ. 2014;126:1-12. https://doi.org/10.1016/j.apenergY.2014.03.089

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