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EXPERIMENTAL INVESTIGATIONS OF HYDROGEN EFFECTS ON PERFORMANCE AND EMISSIONS OF RENEWABLE DIESEL FUELED RCCI

Romualdas JUKNELEVIČIUS *

Vilnius Gediminas Technical University, Vilnius, Lithuania

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Abstract. The article presents the study of hydrogen effects on performance, combustion and emissions characteristics of renewable diesel fueled single cylinder CI engine with common rail injection system in RCCI mode. The renewable diesel fuels as the HRF are the HVO and it blend with petrol diesel further named PRO Diesel, investigated in this study. The purpose of this investigation was to examine the influence of the LRF – hydrogen addition to the HRF on combustion phases, engine performance, efficiency, and exhaust emissions. HES was changed within the range from 0 to 35%. Hydrogen injected through PFI during intake stroke to the combustion chamber, where it created homogeneous mixture with air. The HRF was directly injected into combustion chamber using electronic controlled unit. Tests were performed at both fixed and optimal injection timings at low, medium and nominal engine load. After analysis of the engine bench results, it was observed that lean hydrogen – HRF mixture does not support the flame propagation and efficient combustion. While at the rich fuel mixture and with increasing hydrogen fraction, the combustion intensity concentrate at the beginning of the combustion process and shortened the ignition delay phase. Decrease of CO, CO_2 and smoke opacity was observed with increase of hydrogen amounts to the engine. However, increase of the NO concentration in the engine exhaust gases was observed.

Keywords: hydrogen, RCCI, HVO, NExBTL, PRO Diesel, MFB, combustion, emission, abnormal combustion.

Introduction

Diesel engines cause the environmental pollution and therefore considerable efforts has thus been designated toward reducing of the pollutions as it have negative effects on the environment and human health. The exhaust emission after treatment systems are employed to meet the stringent emission regulations, however these devices are expensive and increase the fuel consumption. Therefore in-cylinder technologies directed to maintain the engine efficiency meanwhile reduce emissions have therefore been the focus of intense research (Reitz & Duraisamy, 2015). During the subsequent studies, it was concluded that different fuel blends should be used at different operating conditions, i.e., a high cetane fuel at light load and a low cetane fuel at high load. Therefore, it is desirable to have the capability to operate with fuel blends covering the range from the high cetane to the low cetane, depending on the operating regime. Kokjohn, Hanson, Splitter, and Reitz (2009) proposed the strategy with the injection of low CN fuel (low reactivity fuel) in the intake port, and direct injection of high CN fuel (high reactivity fuel), later has been called RCCI.

Finish scientists together with Neste Corporation developed the own, oxygen-free, low-emission, renewable diesel fuel NExBTL produced from second-generation feedstock's. During production of HVO or NExBTL, hydrogen is used to remove the oxygen from the vegetable oil, after which catalytic isomerization into branched alkanes is done to get paraffinic hydrocarbons (Pirjola et al., 2017). During the hydro treating of triglycerides at the first step, free fatty acids formed from the triglyceride molecules in presence of hydrogen (Sotelo-Boyás, Trejo-Zárraga, & de Jesús Hernández-Loyo, 2012). In the second step, hydrogenation takes place to saturate the oleic and linoleic acids, because the side chain of palmitic acid is already completely saturated. Decarbonylation and decarboxylation form hydrocarbons having one carbon atom less than the parent FFA does whereas hydrodeoxygenation removes the oxygen atom keeping the same carbon atoms as in the original FFA. In this way, the fully saturated hydrocarbon alkanes (paraffins) are comprised in the range of C_{15} – C_{18}.

Unblended NExBTL meets EN 15940:2016 requirements for paraffinic diesel fuels and European diesel fuel

*Corresponding author. E-mail: *romualdas.juknelevicius@vgtu.lt*

standard EN 590:2013 in all respects except density, which is below the lower limit of 820 kg/m^3 (Engman et al., 2016). For the tests of this study there was used the PRO Diesel purchased from Neste petrol station in Lithuania. PRO Diesel is blend of 15% (vol.) NExBTL with fossil diesel fuel. The properties of hydrogen according to Verhelst and Wallner (2009), NExBTL and PRO Diesel according to the Neste product data sheet and Aatola, Larmi, Sarjovaara, and Mikkonen (2008) presented at the Table 1.

The results of tests performed by Sugiyama et al. (2012), Singh, Subramanian, and Singal (2015), Ewphun et al. (2017), Pirjola et al. (2017), Bhardwaj et al. (2015) revealed that the high CN and the low aromatics fraction of the HVO reduced emissions, and is capable to improve BSFC. These and other studies (Aatola et al., 2008; Erkkila et al., 2011; Imperato, Tilli, Sarjovaara, & Larmi, 2011; Lehto et al., 2011; Murtonen, Aakko-Saksa, Kuronen, Mikkonen, & Lehtoranta, 2009; Pflaum, Hofmann, Geringer, & Weissel, 2010) conducted with the CI engines fueled with HVO showed that HVO reduce NO_x, soot emissions and deposit formation in the cylinder, therefore HVO has beneficial fuel for the CI engine. The utilization of hydrogen with other fuels in diesel engine under dual fuel RCCI mode could provide solutions to reduce carbon-based emissions (Kalsi & Subramanian, 2017). Investigations of Baltacioglu, Arat, Ozcanli, and Aydin (2016), Barrios, Domínguez-Sáez, and Hormigo (2017), Senthil Kumar (2003), Singh Bika, Franklin, and Kittelson (2008), Zhou, Cheung, and Leung (2014), Hilbers et al. (2015), Szwaja and Grab-Rogalinski (2009) performed on CI engine with addition of different amount of hydrogen show that emissions and performance parameters are dependent on injection timing of DF (petrol or renewable), it's duration, *BMEP, MFB* and engine speed. The reactivity of the pilot fuel plays an important role in control of the combustion characteristics of the RCCI engine. Kalsi and Subramanian (2017) concluded on the reviewed studies of other authors, that pilot biodiesel fueled engine under RCCI mode resulted in higher mean effective pressure with as compared to pilot petrol diesel fueled engine. Therefore particularly HRF – HVO and PRO Diesel coupled with the LRF – hydrogen (low CN), is well suited for the RCCI strategy and thus it makes interest of this study. In addition, there are gaps in knowledge dealing of hydrogen co-combustion with HVO in the CI engine, as the experiments performed either with sole HVO, or with addition of hydrogen to the petrol DF.

The purpose of this research is to conduct the analysis of the effect of neat hydrogen on the performance, efficiency and emissions parameters of a CI engine operating under RCCI combustion strategy at constant speed, at the Low, Medium, and Nominal Loads and with fixed single injection of HRF.

1. Experimental set-up and procedure

Tests were performed at the Institute of Thermal Machinery of Czestochowa University of Technology, in Poland. The single cylinder stationary compression ignition engine Andoria S320 equipped with the high pressure common rail fuel pump Bosch CR/CP1S3 driven by the 2.2 kW electric motor GL-90L2-4. The other electric motor was used as the starter for the CI engine. After startingh up the CI engine, it delivers energy by two driving V-belts to a power generator. The generator – dynamometer provides the load of the CI engine with accurancy of ±1.75 Nm. The synchronous generator was set to operate at the constant speed of 965 rpm ± 0.83%. Displacement of the engine – 1810 cm^3, compression ratio – 17, rated power – 13.2 kW. The completely experimental installation presented at the Figure 1.

Each experiment was conducted at the various *IMEP*. The *IMEP* managed by changing the amount of the LRF and HRF supplied to the combustion chamber. The LRF – hydrogen supplied together with air into the intake manifold out of the balloon with a one-stage pressure regulator

Table 1. Fuel properties (Neste Certificate of Analysis, 2017; Neste PRO Diesel Product Data Sheet, 2017; Verhelst & Wallner, 2009; Aatola et al., 2008)

Properties	Test method	NExBTL (HVO)	PRO Diesel	Hydrogen
Chemical formula	–	$C_{15}H_{32}$ – $C_{18}H_{38}$	$C_{10}H_{22}$ – $C_{18}H_{38}$	H_2
Composition, %wt	ASTM D5291	84.8 C, 15.2 H	85.8 C, 14 H	100
HVO (NExBTL), %vol	–	100	15	–
Density, kg/m³ at 15°C and 1.01 bar	EN ISO12185	779.4	826	0.08985
Lower heating value, MJ/kg	ASTM D4809	43.737	43.2	120
Stoichiometric air-fuel ratio, kg/kg	–	14.9	14.56	34.2
Heating value of stoichiometric mixture, MJ/kg	–	2.75	2.78	3.40
Heating value of stoichiometric mixture, MJ/Nm³	–	3.52	3.73	3.00
Auto ignition temperature at STP,°C	–	204	~ 210	585
Flammability limits at NTP, %vol	–	–	0.6–7.5	4–75
Cetane number	ASTM D6890	74.3	60	5–10
Aromatics, %wt	EN ISO12916	0.3	13	–
Carbon to hydrogen ratio (C/H)	–	5.6	6.1	–

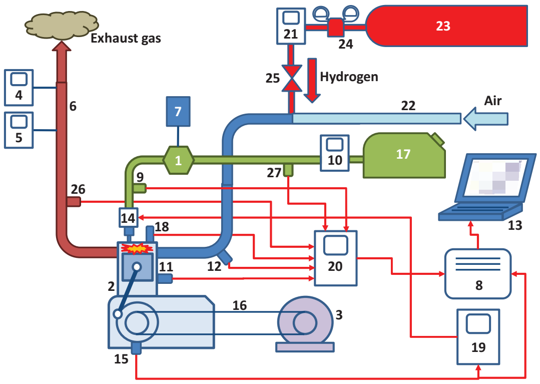

Figure 1. Experimental installation. 1 – DF pump, 2 – CI engine, 3 – Generator, 4 – Smoke analyser, 5 – Emission analyser, 6 – Exhaust pipe, 7 – DF pump drive el. engine, 8 – Data acquisition system, 9 – DF pressure sensor, 10 – DF flow meter, 11 – Engine temperature sensor, 12 – Inlet air temp. sensor, 13 – PC – SAWIR, 14 – DF common rail injector, 15 – CA encoder, 16 – Drive belt, 17 – DF tank, 18 – In-cylinder pressure sensor, 19 – DF injection controller, 20 – Amplifiers & A/D converters, 21 – Hydrogen flow meter, 22 – Air intake pipe, 23 – Hydrogen balloon, 24 – Hydrogen one-stage pressure regulator, 25 – Hydrogen firebreak arrestor, 26 – Exhaust gas temperature sensor, 27 – DF temperature sensor

to reduce its pressure to 1 bar, which was the pressure of the hydrogen gas supply line. A firebreak valve was installed just upstream of the air intake manifold to prevent flashback phenomenon. In cylinder, homogeneous air – hydrogen mixture under the elevated heat and pressure self-ignited by injected HRF, following the RCCI combustion strategy. The consumption of HRF measured by stopwatch. The accuracy of the HRF consumption measurement was 0.5%.

Pollutants in the exhaust gas were analyzed using *Bosch* and *Maha* (smoke) analyzers. In-cylinder pressure *(p)* was recorded by quartz pressure sensor *Kistler* 6061B installed instead of the preheating plug. The uncertainty of the pressure sensor ±0.5% of full scale, pressure measurement range 0–25 MPa, sensitivity of the sensor 25 pC/bar. The crank angle (CA) measured by encoder *Kistler* type 2612C, with speed range up to 15 000 rpm. The data acquisition converter *Measurement Computing Corporation* PCI-DAS 6036 was used in line with PC software *SAWIR* – System of the Indicator Chart on Real Time Analysis.

The injection timing, loads corresponding *IMEP* and equivalence ratio (λ) at various composition of combustible mixture presented at the Table 2. The injection timing φ_1 for HVO operation (Table 2, test no. 1) was determined at the position of 50% MFB, which corresponds to the peak of indicative pressure in cylinder. The injection timing φ_2 (Table 2, test no. 2) was determined with the lowest HES = 13%, again at the combustion of 50% MFB. The same injection timing φ_2 was used for the rest of tests with hydrogen fractions of 22%, 29% and 35%. The similar procedure with targeting of 50% MFB within the range of 8–12 deg CA was repeated with PRO Diesel. During the operation with PRO Diesel injection, timings φ_1 and φ_2 were determined again.

2. Results of the research and discussion

The analysis of the experiments presented in the study based on in-cylinder pressure data acquisition. The 200 consecutive engine-working cycles of each combustible mixture and HES collected for the analysis. The term HES could be replaced by premixed energy ratio – PER, which is commonly used in some articles related to the RCCI startegy. Both HES and PER are defined as the energy ratio of the LRF versus the total delivered energy (Benajes, Molina, García, & Monsalve-Serrano, 2015). At the each specific HES, the total energy delivered to the cylinder was kept constant during the tests. In order to keep the constant total energy, the mass of LRF and HRF was adjusted as required to compensate the differences in LHV. The impact of HES on combustion properties and combustion duration of the engine operating with the HVO and PRO Diesel at three engine loads studied.

Table 2. SOI, loads, IMEP and equivalence ratio (λ) at various composition of combustible mixture

Test no.	Composition of combustible mixture	SOI (φ), BTDC	Loads	IMEP, kPa	λ
1	HVO+H_2 0%	**φ_1 = 18°**	LL	344.9	3.78
2	HVO+H_2 (13–35%)	**φ_2 = 18°**	LL	376.0–376.7	3.80–3.31
3	HVO+H_2 0%	24°	ML	519.8	2.22
4	HVO+H_2 (13–30%)	24°	ML	494.8–538.5	2.15–1.93
5	HVO+H_2 0%	28°	NL	651.8	1.55
6	HVO+H_2 (12–24%)	28°	NL	645.8–691.5	1.43–1.42
7	PRO Diesel+H_2 0%	18°	LL	367.6	3.37
8	PRO Diesel+H_2 (17–34%)	18°	LL	406.0–417.7	3.75–3.07
9	PRO Diesel+H_2 0%	26°	ML	533.2	1.99
10	PRO Diesel+H_2 (13–26%)	26°	ML	579.7–620.1	1.91–1.88
11	PRO Diesel+H_2 0%	28°	NL	590.1	1.41
12	PRO Diesel+H_2 (13–24%)	28°	NL	652.9–717.8	1.37–1.28

Typically, the reactivity in RCCI combustion mode is characterized by global reactivity and reactivity stratification (Li, Yang, Goh, An, & Maghbouli, 2014). Most of the subsequent studies are performed using double and triple injection pulses of HRF. Such injection strategy with varied LRF/HRF ratio provides the global and reactivity stratification. However, Li, Jia, Liu, and Xie (2013) investigated the RCCI startegy with single injection timing φ from 30° to 15° BTDC, while Benajes, Molina, García, Belarte, and Vanvolsem (2014) from 37° to 7° BTDC and Liu et al. (2014) from 43° to 35° BTDC. In this article only the global reactivity was studied, which determined by the amount of LRF and HRF and single injection timing φ (from 28° to 18° BTDC) of HRF, which was determined at the position of 50% MFB corresponding to the peak of indicative pressure in cylinder at the lowest HES at each load (Table 2). SOI was fixed with the further HES at the certain load.

Figure 2 illustrates the variation of in-cylinder maximum pressure with various HES at LL, ML and NL. The increase trend of in-cylinder maximum pressure noticed with increase of HES within all range of loads. The increase of in-cylinder maximum pressure at LL was negligible – 5.5%, it was 7.9% at ML and 14.3% at NL with HVO. The presence of hydrogen increased the maximum pressure at LL by 7.0%, at ML by 14.7% and by 18.2% at NL with PRO Diesel. The negligible influence of hydrogen fraction at the LL and partially at the ML can be explain by the low volume fraction of the hydrogen in the combustion chamber, which was below of the LFL of hydrogen (Table 1).

The flammability limits of the hydrogen-air mixture are changing with increase of temperature and pressure. The experiments show that LFL decrease with increasing temperature (Schroeder & Holtappels, 2004). The linear function of LFL described in the temperature range up to the actual SOC, which was in the temperature range of 404–424 °C with both fuels during the experiment performed by author. At this temperature, the LFL decreased to 1.5% of hydrogen volume fraction. However this decrease of LFL do not contribute the SOC of hydrogen as the temperature is still too low (404–424 °C) and not sufficient for auto-ignition of hydrogen. The increase of pressure have the opposite effect as temperature does. With increase of pressure up to 50 bar the LFL increased from 4% to 5.6% and further no changes has been noticed with increase of pressure (Schroeder & Holtappels, 2004; Schroeder, Emonts, Janssen, & Schulze, 2004). Considering above mentioned, at the moment of the SOC the pressure was 3.52 MPa (35.2 bar) and the LFL was 3.0–3.1% of hydrogen volume fraction. Therefore we can conclude that only when this LFL was achieved, hydrogen effectively co-combusted with injected HRF. Before that, the lean mixture of air – hydrogen with HRF burns incompletely and does not make positive effect on the combustion intensity and engine performance (Verhelst & Wallner, 2009). The lean hydrogen – air mixture does not support the flame propagation and results in rather low hydrogen combustion efficiency (Saravanan, Nagarajan, & Narayanasamy, 2007). The same explanation related to the poor performance of p_{max} with low HES and rich fuel mixtures at ML and NL.

At the lean mixture (Table 2, test no. 1, 2, 7, 8) the combustion of hydrogen with HVO and PRO Diesel is hydrogen assisted and combustion of hydrogen is sluggish, therefore increase of in-cylinder pressure (Figures 2, 3 and 4) with increase of HES is negligable. The in-cylinder pressure data presented at the Figures 3 and 4 with the positions of SOC of corresponding mixtures. The SOC was taken at the crank angle at which the curve of the ROHR changes its value from the minus side to plus one. For the accuracy of the evaluation 200 single-cycle in-cylinder pressure diagrams were recorded. Therefore, the SOC was averaged over 200 combustion cycles. However, the p_{max} (Figure 2) and in-cylinder pressure (Figures 3 and 4) for PRO Diesel at the ML was higher than that of HVO at the whole test range of hydrogen fraction starting from 0%, because the SOI (Table 2) and SOC with PRO Diesel at ML takes place earlier than with HVO and the pressure-rise in this case faster.

The heating value of PRO Diesel stoichiometric mixture (on both volume and weight basis) is higher than that of HVO (Table 1) and in-cylinder pressure should be higher. However, the CN of HVO has advantage against PRO Diesel, the auto-ignition delay with HVO is shorter and pressure-rise faster. Therefore, at the NL when the SOI

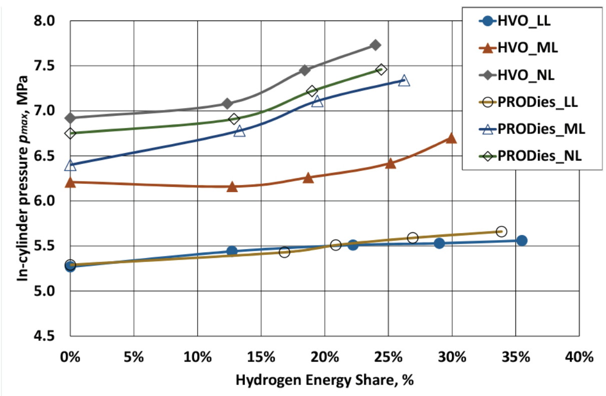

Figure 2. In-cylinder max pressure p_{max} at Low, Medium and Nominal Loads and HES

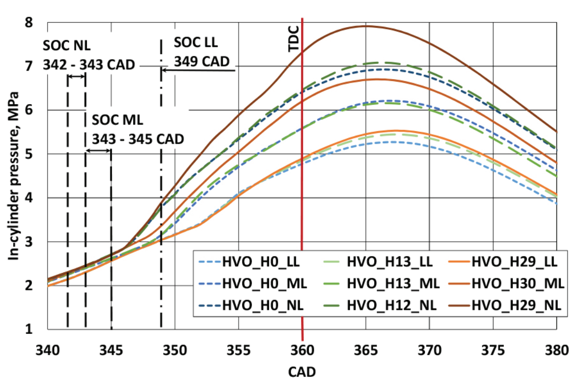

Figure 3. In-cylinder pressure dependence on CAD and position of SOC at various loads and HES with HVO

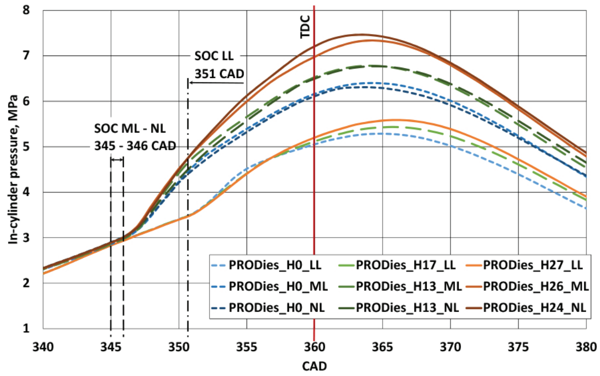

Figure 4. In-cylinder pressure dependence on CAD and position of SOC at various loads and HES with PRO Diesel

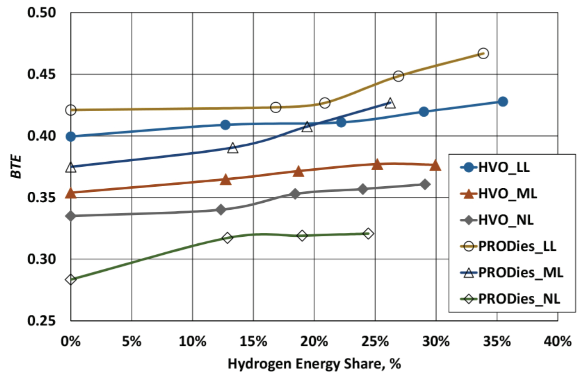

Figure 5. The dependence of BTE on fuel used, loads and HES

was the same at HVO and PRO Diesel, in-cylinder pressure was higher with HVO.

The *BTE* increased steadily with increase of the HES with both tested fuels (Figure 5), and that increase was more significant with PRO Diesel noticed. The efficiency of the engine was higher with PRO Diesel, because of the higher heating value of stoichiometric mixture (Table 1) and shorter ignition delay (Aatola et al., 2008). The negligible lower auto ignition temperature of HVO (204 °C) than PRO Diesel (210 °C), do not influenced the auto-ignition delay. The biggest influence on the *BTE* was made by increased mass flow rate of the hydrogen as the response to the decreased total fuel mass flow rate. The *BTE* increased by 5.0–6.5% with HVO at whole range of loads, and by 6.5% at the LL and by 13.2–13.9% at the higher loads with PRO Diesel, as the increasing hydrogen fraction affects the combustion intensity more tangible when rich burn with $\lambda = 1.42–1.43$ for HVO and $\lambda = 1.28–1.37$ for PRO Diesel.

The *BSFC* decreased steadily with increase of the HES with both tested fuels as presented at the Figure 6. Due to the increase of LRF – hydrogen, the *BSFC* decreased, because the hourly heat value of the hydrogen directly correlated with HES, while the *BSFC* of HRF decreased with increase of HES. The higher *BSFC* of PRO Diesel at the NL can be attributed mainly to the higher mass flow rate of liquid fuel – PRO Diesel. The *BSFC* decreased by 18–22% for HVO and by 19–23% for PRO Diesel with increase of the mass flow rate of hydrogen and HES. The substitution of HRF by LRF makes positive affect on the *BSFC*.

The HRF used during tests has lower C/H ratio in compare to the petrol DF: PRO Diesel by 4.7% while HVO by 8.2%. On top of that, the increased hydrogen increment rate caused further decrease of C/H ratio and that causes reduction of CO and CO_2 emission (Figures 7 and 8) in the exhaust gas as well as reduction of its smokiness as shown at the Figure 9 (Aldhaidhawi, Chiriac, Bădescu, Descombes, & Podevin, 2017; Barrios et al., 2017; Rocha, Pereira, Nogueira, Belchior, & Tostes, 2016). Other reason is that, increase of HES makes better-homogenized mixture of air and LRF, which leads to the decrease of smokiness.

The addition of LRF up to 10–12% HES do not effect NO with both HRF, however with the further HES

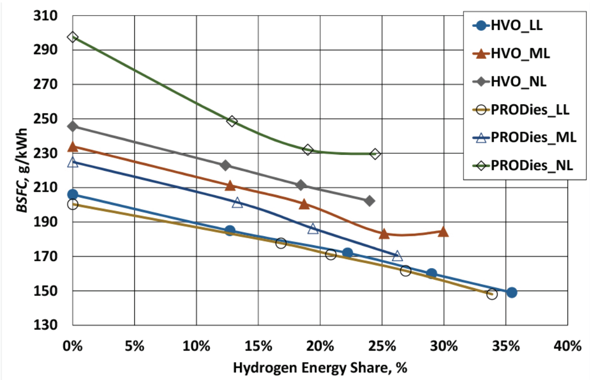

Figure 6. The dependence of *BSFC* on fuel used, loads and HES

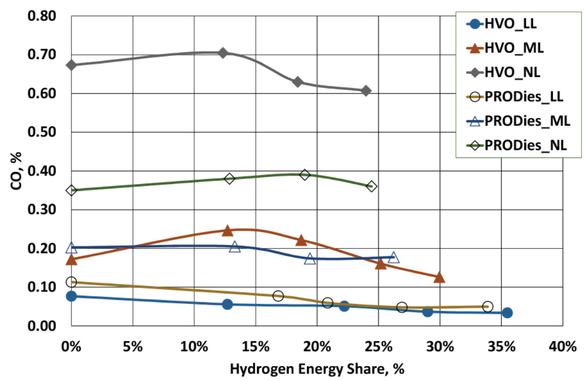

Figure 7. The dependence of CO on fuel used, loads and HES

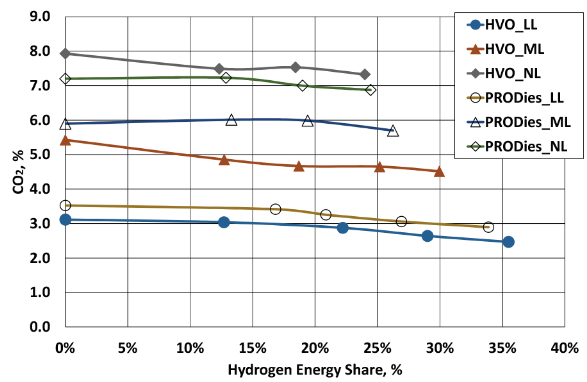

Figure 8. The dependence of CO_2 on fuel used, loads and HES

increase of more than 15% NO increased significantly (Figure 9). At the LL, the increase of NO is negligible at the whole test range of HES because the lean hydrogen – air mixture does not support the flame propagation and results in low combustion temperature. Senthil Kumar (2003) and Singh Bika et al. (2008) at the low HES of 5% observed the reduction of NO_x. This reduction is due to the slower combustion caused by a shorter ignition lag that contributes to advanced ignition, which decreases the combustion rate just after the SOC (Grab-Rogalinski & Szwaja, 2016).

The amount of smokiness depends on the CN, soot particles formation and burning rate set up by diffusion phase at the final combustion stages depending on the chemical structure and amount of the fuel injected (Labeckas, Slavinskas, & Mažeika, 2014). However, with increase of hydrogen fraction, the combustion became more intensive at the premixed phase, the burning rate at the diffusion phase as well as the CD makes shorter and that can be related to the significant decrease of smokiness with increase of HES (Figure 10). The smokiness measured for the HVO was lower that for PRO Diesel, because of chemical structure and physical properties of the fuel, i.e. lower density and kinematic viscosity than that of PRO Diesel. According to investigations (Chen, Wang, Roberts, & Fang, 2013), the HVO presents smaller SMD than PRO Diesel and better-homogenized mixture guiding to the lower smokiness.

The MFB profile was determined on the basis of the absolute pressure trace for the each combustion event. For the accuracy of the evaluation, 200 single-cycle in-cylinder pressure diagrams averaged. Then the rate of MFB was calculated. Assuming, that the cumulative heat release is directly proportional to the mass of the fuel burnt, then, the ROHR directly correspond to the dimensionless rate of MFB. From the MFB profile, the 10%, 50% and 90% MFB were determined. The CD of CA0–10 was defined as the CA interval from the SOC to the CA of 10% MFB, while CD of CA10–90 was defined as the CA interval from the 10% MFB to the CA of 90% MFB. The combustion duration of CA0–10 (Figure 11) and CA10–90 (Figure 12) calculated at each *IMEP* and with each hydrogen fraction for HVO and PRO Diesel according to the MFB profiles. Additionally, the location of the maximum rate of MFB, the locations of the 50% MFB and the maximum rate of MFB were determined.

The test results show that increase of the hydrogen fraction have an impact on the fuel reactivity distribution, which determines the shortened auto-ignition delay (lag). The auto-ignition is the chemical reaction, which releases the energy at the such rate, which is sufficient to sustain combustion without any external energy source. It was expressed by the initial combustion duration of CA0–10 (Figure 11) due to the high premixed combustion rate and development of higher laminar speed of hydrogen flame (Szwaja, 2011). While the auto-ignition delay time is defined as the time intervals of chemical and the physical

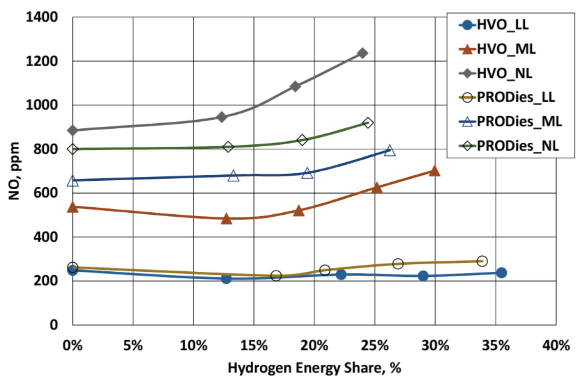

Figure 9. The dependence of NO on the load and HES

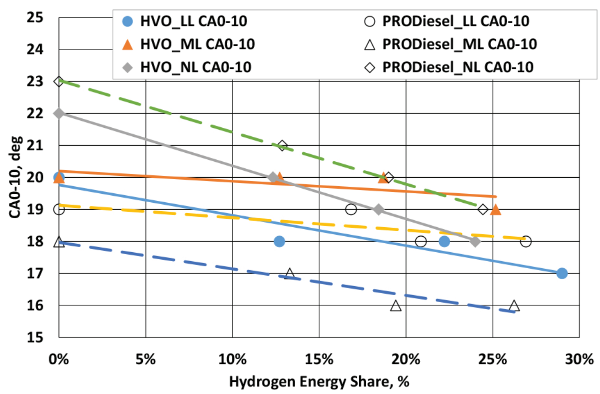

Figure 11. The combustion delay of 0–10% MFB at tested HES of HVO and PRO Diesel

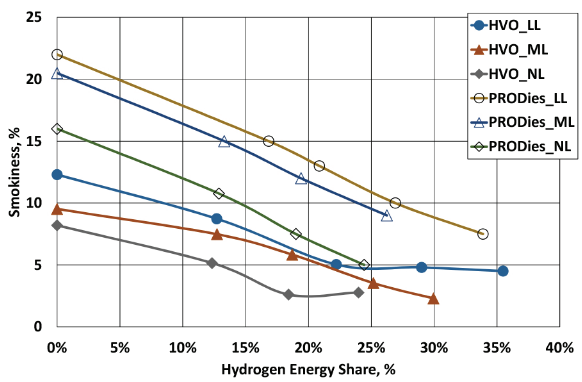

Figure 10. The dependence of smokiness on the load and HES

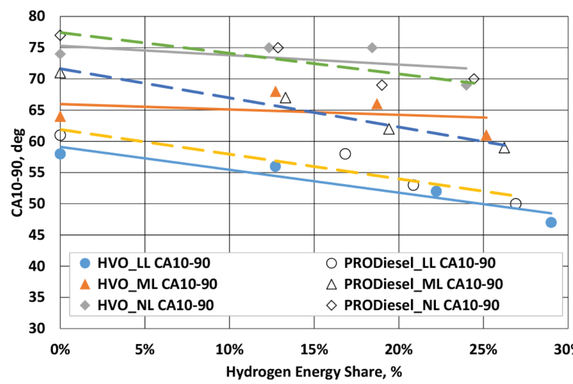

Figure 12. The combustion delay of 10–90% MFB at tested HES of HVO and PRO Diesel

processes for ignition. Physical process includes the heat conduction, diffusion and mixing of reactants and chemical process based on pre-flame reactions, radical concentration governed by chemical kinetics. Thus auto-ignition delay time is important in developing RCCI strategy and it has been frequently used to validate chemical kinetic mechanisms (Tang, Zhang, & Huang, 2014).

It was found that combustion starts with the auto-ignition of the injection of HRF. Then, the temperature and pressure rise starts the flame propagation across the lean zones of the combustion chamber. As the LRF/HRF ratio increased, due to the high penetration of hydrogen into the mixture, the mixing time makes shorter and the first combustion stage expressed by CA0–10 lowered. As the HRF injection timing was fixed at the lowest HES at each load, the further increase of HES shortened auto-ignition delay over combustion process (Li, Jia, Liu, & Xie, 2013). Increase of hydrogen fraction also reduces the main combustion duration CA10–90 (Figure 10) which was accelerated by the first combustion phase CA0–10. The combustion duration of CA0–10 varying with PRO Diesel within the range of 16–23 CAD, while with HVO it was shorter: 17–22 CAD. The main CD of CA10–90 with increase of HES was reduced by 12–16% with both tested fuels.

Different trend of the combustion duration of CA0–10 was noticed at the ML with PRO Diesel in compare to HVO. The CD of PRO Diesel was significantly shorter than that with HVO at ML, while at other two loads (LL and NL) it was vice versa. It occurs due to the different SOI at ML, though at other loads the SOI was the same with both HRF (Table 2). The SOI with HVO was 24° BTDC while with PRO Diesel it was more advanced – 26° BTDC. Thus, it additionally confirms that SOI is another tool for adjustment of the performance of RCCI engine tested by several authors (Benajes et al., 2015; Li et al., 2014; Li, Jia, Chang, Xie, Reitz, 2016; Reitz & Duraisamy, 2015).

Conclusions

The analyses of the test and simulation results revealed the following conclusions:

- Dual fuelling with increase of HES enhances the p_{max} of all tested loads as the result of the considerably higher heating value of hydrogen, higher flame velocity and increasing reaction rates. However, the lean LRF/HRF mixture does not support the flame propagation due to the too low hydrogen volume fraction, which was insufficient to reach the LFL and results the negligible increase of in-cylinder maximum pressure.
- The efficient hydrogen co-combustion with injected HRF starts with increased HES at ML (HES = 30%) and NL (HES = 29%), corresponding to the LFL = 3.0–3.1% of hydrogen.
- With increase of HES, the specific fuel consumption decreased by 18–22% for HVO and by 19–23% for PRO Diesel owing to the higher heating value of the mixture. The substitution of HRF by LRF makes positive affect on the *BSFC*.
- The *BTE* increased by 5.0–6.5% with HVO at whole range of loads, and by 6.5% at the LL and by 13.2–13.9% at the higher loads with PRO Diesel. The increasing LRF/HRF ratio provides the higher reactivity, it enhances the combustion intensity more tangible at the rich burn with $\lambda = 1.42–1.43$ for HVO and $\lambda = 1.28–1.37$ for PRO Diesel. However, at that range remarkably increases the NO.
- The reduction of smokiness, CO and CO_2 emission levels were observed with increased hydrogen increment rate, as a result of improved combustion and replacement of the certain hydrocarbon fraction. The increase of HES enhances the temperature, ROHR and contributes the increase of the NO. The HES = 15–20% was found as the optimal percentage with respect to NO emissions.
- With increase of the LRF/HRF ratio, the fuel mixing time makes shorter due to the high penetration of hydrogen into the mixture, and the first combustion stage expressed by CA0–10 shortened, as the auto-ignition delay makes shorter. Increase of the LRF/HRF ratio leads to decrease the combustion duration of CA10–90 owing to its high flame velocity and enhanced combustion characterisitics.
- The maximal rate of MFB was higher with HVO than with PRO Diesel, therefore the CA0–10 was shorter. The CN of HVO is higher and the auto-ignition delay is shorter than PRO Diesel.
- The abnormal combustion appeared with the hydrogen volume fraction of 5.0–5.5% at the ML and 6.51–7.15% at the NL, as the SOI of the HRF was fixed. Therefore, the control of the SOI and the amount of HRF is one of challenges for RCCI combustion, especially at rich burn and high loads. With the early injection of 26° BTDC at the ML with PRO Diesel was noticed the shorter combustion duration of CA0–10 in compare to the lean burn of HVO and PRO Diesel.

The present study demonstrates that improvement of *BTE*, low CO, CO_2 and smokiness is possible using the RCCI strategy. The addition of hydrogen has a greater effect on the beginning stages of combustion than in later stages of combustion when tests performed with fixed SOI of the HRF. Further optimization of RCCI engine parameters such as HRF injection strategy modifications are required to realize the potential of dual-fuel operation. Investigation on the abnormal combustion (knocking) of RCCI with development of the model to detect the knock combustion makes it the subject of the research interest (Li, Yang, & Zhou, 2017).

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VANDENILIO ĮTAKA ENERGINIAMS IR EMISIJOS RODIKLIAMS ALTERNATYVIU DYZELINU VEIKIANČIAME RCCI VARIKLYJE – EKSPERIMENTINIS TYRIMAS

R. Juknelevičius

Santrauka

Straipsnyje pateiktas tyrimas apie vandenilio įtaką vieno cilindro slėginio uždegimo variklio energiniams parametrams ir deginių sudėčiai, kuriame alternatyvūs dyzeliniai degalai įpurškiami akumuliatorine įpurškimo sistema „Common rail“, varikliui veikiant RCCI režimu. Šiame tyrime buvo naudojami aukšto cetaninio skaičiaus alternatyvus dyzelinis degalas HVO ir jo mišinys su dyzelinu, toliau vadinamu PRO Diesel. Šio tyrimo tikslas – išbandyti žemo cetaninio skaičiaus degalo – vandenilio – įtaką aukšto cetaninio skaičiaus alternatyvaus dyzelinio degalo HVO degimo fazėms, variklio veikimo efektyvumui ir deginių kiekiui. Vandenilio energtinė dalis mišinyje buvo keičiama nuo 0 iki 35 %. Vandenilis buvo tiekiamas įsiurbimo fazės metu, įsiurbimo kanalu į degimo kamerą, kurioje jis, susimaišęs su oru, sudaro homogeninį mišinį. Aukšto cetaninio skaičiaus degalas HVO buvo tiesiogiai įpurškiamas į degimo kamerą, įpurškimo momentą ir trukmę valdant elektroniniu būdu. Bandymai buvo atliekami nekeičiant įpurškimo kampo ir nustačius optimalų įpurškimo kampą, esant žemai, vidutinei ir nominaliajai variklio apkrovai. Išnagrinėjus bandymo rezultatus buvo pastebėta, kad, degant liesam vandenilio-HVO mišiniui, liepsna plinta lėtai ir mišinys dega neveiksmingai. Esant riebiam degalų mišiniui ir didinant vandenilio energijos dalį, degimo intensyvumas didžiausias degimo proceso pradžioje ir sutrumpėja uždegimo gaišties trukmė. Buvo pastebėta, kad CO, CO_2 ir kietųjų dalelių sumažėjo didinant vandenilio kiekį, tačiau padidėjo NO koncentracija variklio išmetamosiose dujose.

Reikšminiai žodžiai: vandenilis, RCCI, HVO, NExBTL, PRO Diesel, MFB, degimo procesas, deginių emisija, detonacija.

Notations

Variables and functions
$dp/d\phi$ – pressure-rise;
p – in-cylinder pressure;
p_{max} – in-cylinder maximum pressure;
φ – injection timing (SOI);
λ – air-fuel (equivalence) ratio;

Abbreviations
BTDC – before top dead center;
BSFC – brake specific fuel consumption;
BTE – brake thermal efficiency;
CA – crank angle;
CAD – crank angle degree;

CA 0–10 – initial combustion duration measured by CAD and determined by interval from SOC to 10% MFB;
CA 10–90 – main combustion duration measured by CAD and determined by interval from 10% MFB to 90% MFB;
CD – combustion duration;
C/H – carbon to hydrogen ratio;
CI – compression ignition;
CO – carbon monoxide;
CO_2 – carbon dioxide;
CN – cetane number;
DF – diesel fuel;
HCCI – homogeneous charge compression ignition;
HES – hydrogen energy share;
H0 – HES = 0%;
H16 – HES = 16%;
HRF – high reactivity fuel;
HVO – hydro-treated vegetable oil;
HVO+$H_2$0% – HVO – hydrogen mixture with HES = 0%;
HVO+$H_2$16% – HVO – hydrogen mixture with HES = 16%;
IMEP – indicated mean effective pressure;
LFL – lower flammability limit;
LL – low load;
LRF – low reactivity fuel;
MFB – mass fraction burned;
ML – medium load;
NExBTL – trademark of Neste developed and produced hydro-treated vegetable oil;
NO – nitrogen oxide;
NL – nominal load;
NTP – normal temperature and pressure is defined as conditions at 20° C and 1 atm (101 325 Pa);
PCCI – premixed charge compression ignition;
PFI – port fuel injection;
PRO Diesel – mixture of 15% (vol.) NExBTL with fossil diesel fuel;
PRO Diesel+H_2 0% – PRO Diesel – hydrogen mixture with HES = 0%;
PRO Diesel+H_2 16% – PRO Diesel – hydrogen mixture with HES = 16%;
RCCI – reactivity controlled compression ignition;
ROHR – rate of heat release;
SMD – sauter mean diameter;
SOC – start of combustion;
SOI – start of injection;
STP – standard temperature and pressure is defined as conditions at 0° C and 1 bar (100 000 Pa).