Agronomy Research **23**(S1), 195–207, 2025
https://doi.org/10.15159/AR.25.031

Performance and emissions of an agricultural diesel engine with hydrogen injection under different load modes

R. Smigins[1,*], K. Amatnieks[1], A. Birkavs[1] and S. Kryshtopa[2]

[1]Latvia University of Life Sciences and Technologies, Institute of Engineering and Energetics, J. Cakstes blvd. 5, LV3001 Jelgava, Latvia
[2]Ivano-Frankivsk National Technical University of Oil and Gas, Department of Automobile Transport, Carpathians Street 15, UA76019 Ivano-Frankivsk, Ukraine
[*]Correspondence: ruslans.smigins@lbtu.lv

Received: January 25th, 2024; Accepted: April 15th, 2025; Published: April 28th, 2025

Abstract. Excessive use of fossil fuels in transport sector in the last decades stimulated rise in global energy consumption in such way leaving harmful effects on human health and environment. The scale of decarbonization of transport sector in the next decade could be challenging for European Union (EU) as demand for renewable energy, like wind, solar and hydro, will definitely rise. The aim of this study is to find whether hydrogen could be optimal solution for emission reduction in agricultural machinery. In this regard, research was carried out with KOHLER KDI 1903 M diesel engine looking on main performance parameters, as also regulated emissions operating engine with conventional diesel fuel and different hydrogen injection volumes under different loads. Fuel consumption was measured with AVL KMA Mobile device, while emissions was determined using AVL SESAM FTIR exhaust gas analytical system. During the tests, it was observed that the addition of a higher hydrogen concentration provides more substantial benefits that includes a larger impact on fuel consumption and carbon dioxide (CO_2) emissions. Other emissions such as carbon monoxide (CO) emissions had smaller but positive impact, while the addition of hydrogen gas had various impact on nitrogen oxide (NO_x) emissions. At the same time decrease in particulate matter (PM) emissions was observed with higher hydrogen concentrations and more substantial impact was observed during higher load conditions and higher hydrogen concentration.

Key words: diesel engine, emissions, hydrogen addition, performance, torque.

INTRODUCTION

Increased demand for vehicles and excessive use of fossil fuels in transport sector in the last decades stimulated rise in global energy consumption in such way leaving harmful effects on human health and environment. In that case a number of policies designed and implemented to reduce GHG emissions from road transport. Most important is an ambitious global action plan, called Paris Climate Agreement, accepted in 2015 by 196 countries aimed to limit the global warming to 1.5 °C (UN-FCCC, 2015) and most of these nations also signed of the Glasgow Climate Pact at COP26 in 2021 with an unprecedented reference to the role of fossil fuels in the climate crisis. In this regard, road transport plays a significant role in creation of emissions counting around 760 million tonnes of emitted O_2 in the EU in 2022 increased by 24% since 1990 (Destatis, 2024).

The scale of decarbonization of transport sector in the next decade could be challenging for European Union (EU) as demand for renewable energy, like wind, solar and hydro, will definitely rise. This issue is particularly relevant for battery electric vehicles (BEV), the number of which grows significantly based on EU plans to limit the production of vehicles with internal combustion engines already in 2035. This continuous growth of BEV could help mitigate the emissions from on-road applications and practically such vehicles charged with renewable electricity are the only technology able to reduce air pollutants to zero (Philibert, 2018). At the same time there are still many transportation modes, which cannot be easily electrified (e.g., trucks, marine, aviation) (Delgado et al., 2023) as requires high amount of energy, which is not possible to store and transport using existing batteries without significant increase of the weight of them. Thus, the demand for liquid fuels will definitely remain from 2035 and onwards until another suitable solution will be found. However, the choice of the right fuel is not as simple task as it seems as reduction of all most important emissions is not so obvious even using different alternatives (Kryshtopa et al., 2021).

The usage of hydrogen in internal combustion engines (ICEs) is a promising solution looking on a whole life cycle perspective (Baldinelli et al., 2024), which could not only help to improve ecological indicators, but also ensure development of hydrogen usage technologies for ICEs (Kryshtopa et al., 2024). Hydrogen could be considered as the cleanest fuel with a minimal impact on the environment (Abanades, 2012; Obergruber et al., 2018) showing many different properties allowing to achieve more complete combustion and reduction of emissions: higher calorific value and burning velocity, wider flammability range, low diffusivity, etc. As hydrogen does not involve carbon atom as it is in case of liquid fuels, therefore reduction of CO and CO_2 emissions is more visible (Karagoz et al., 2015). Although hydrogen can be injected directly or indirectly showing advantages for each of those methods, the most popular option for using hydrogen in existing diesel ICEs without significant investments, is hydrogen assisted dual-fuel technology allowing to use compressed natural gas (CNG) equipment that has been known for years (Smigins, 2017; Smigins et al., 2020). At the same time, it should be remembered that the proportion of hydrogen should be as high as possible to achieve the desired effect when using two fuels.

The importance of the hydrogen additive amount is also confirmed by Liew (Liew et al., 2010), who conducted study with 6-cylinder, turbocharged Cummins ISM370 diesel engine. He confirmed that the effect of the addition of hydrogen gas (H_2) on combustion process is more visible based on the load and the added amount of hydrogen, showing that relatively large amount of H_2 at higher loads could substantially increase peak pressure and reduce combustion duration.

Shirk also came to similar conclusions (Shirk et al., 2008) testing 1.3 L, 66 kW compression ignition engine on a chassis dynamometer with hydrogen flow rates equivalent to 0%, 5%, and 10% of the total fuel energy. He observed that relatively small amounts of H_2 can be used in light-duty diesel engines, but the benefits on combustion performance and emissions are also relatively small.

Santoso (Santoso et al., 2013) also did not find significant benefits in H_2 introduction at the flow rate of 21.4, 36.2, and 49.6 L min^{-1} testing direct injection diesel engine in dual fuel mode under constant load (10 Nm) and engine speed (2,000 min^{-1}). At the same time, he observed efficiency decrease at low load with hydrogen enrichment.

Less pollution and better performance was observed also by Saravanan (Saravanan & Nagarajan, 2008), who tested single cylinder stationary diesel engine. Tests showed reduction of NO_x emissions more than 5 times using 90% hydrogen enrichment with 70% engine load.

Akbalik (Akbalik & Arpa, 2024) investigated water vapor and hydrogen injection into a single-cylinder diesel engine Antor 4LD 820 LY3 on engine performance and exhaust emissions. He found out increase in engine power and decrease in specific fuel consumption, as also NO_x emissions at higher engine speeds using hydrogen injection.

In general, many studies have been carried out on hydrogen addition in diesel engines, especially in diesel dual-fuel technology engines. When analysing previous research, it can be established that the addition of hydrogen gas to diesel engines can have a positive impact on greenhouse gas emissions depending on the concentration of hydrogen gas versus diesel fuel and engine load. Typically, when running an engine in a dual fuel mode, hydrogen is used to replace the base fuel, so as a result less fossil fuel is consumed. With that, the carbon-based emissions tend to decrease. The properties of hydrogen as well as the concentration of gas affects the combustion process and emissions.

The goal of this research was to analyse the impact of various small concentrations of hydrogen on exhaust gas emissions and fuel consumption by using identical concentrations in different engine speed and load conditions, thus observing a broader spectre from low to high load and different concentrations of hydrogen gas in relation to intake air and fuel.

MATERIALS AND METHODS

Kohler KDI 1903M agricultural engine was used for the research at the Alternative Fuels Research Laboratory of the Latvia University of Life Sciences and Technologies. Engine parameters can be observed in Table 1.

Table 1. Kohler KDI 1903M parameters

Parameter	Value	Unit
Power	31 (42) @2600 min^{-1}	kW (hp)
Torque	133 @1,500 min^{-1}	Nm
Displacement	1,861	cm^3
No. of cylinders	3	-
Bore	88	mm
Stroke	102	mm
Fuel injection	Mechanical rotary pump, direct injection	-
Cooling	Liquid cooling	-
Intake system	Naturally aspirated, 2 intake valves per cyl.	-

As a fuel for engine used commercially available diesel fuel complied with standard EN 590 with a renewable component of 7% added to diesel fuel. The engine was operated with conventional diesel fuel and different, constant hydrogen injection volumes (5, 10, 15 and 20 L min^{-1}) at constant testing modes (1,500 min^{-1} and 2,500 min^{-1} at 5 kW, 10 kW and 15 kW). The flow of hydrogen gas was controlled using digital mass flow meter calibrated for hydrogen use with a measurable flow range from 0 to 50 litres per minute.

For the hydrogen flow control a rotameter with an identical flow range was used. The resulting device (see Fig. 1) allows for a stable and repeatable hydrogen flow adjustment and measurement. The hydrogen gas was supplied with a constant pressure of 0.1 MPa. After the digital mass flow meter, the gas was supplied to the engine intake manifold and further dispersed in the cylinders via the vacuum created by the intake strokes. Hydrogen used in the tests was provided by Linde Gas Latvia. The parameters of hydrogen gas used can be observed in Table 2.

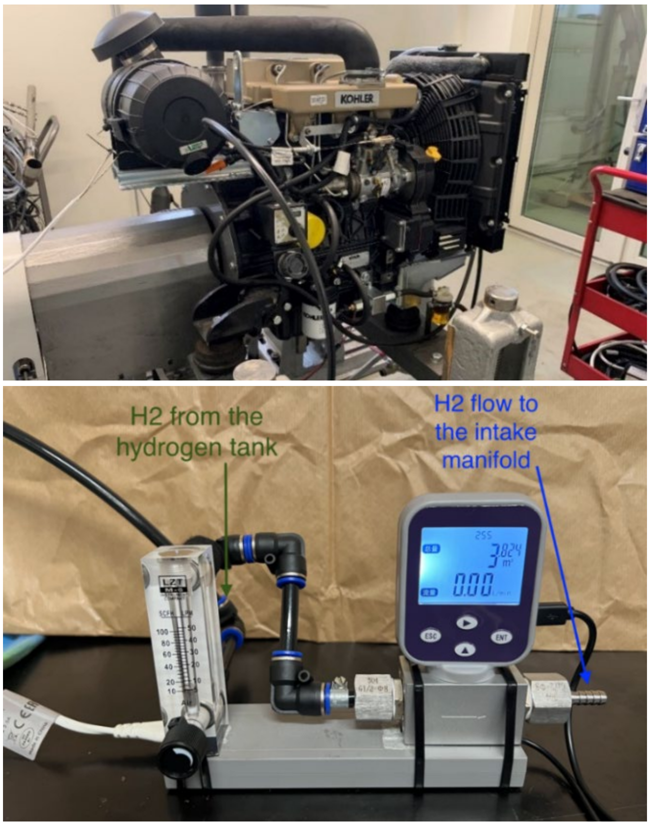

Figure 1. Engine with a test bench and hydrogen flow meter.

Table 2. Hydrogen gas properties

Parameter	Value	Unit
Density	0.0838	kg·m^{-3}
Autoignition temperature	858	K
Minimum ignition energy	0.02	mJ
Flame velocity	265–325	cm s^{-1}
Flammability limits (volume in air)	4–75	%
Purity	99.99	%
Heating value	119.9–141.9	MJ kg^{-1}
Hydrogen tank pressure	20	MPa
Manifold injection pressure	0.1	MPa

Tests with previously mentioned engine were realized on the SIERRA CP-Engineering engine test bench with an AC dynamometer. CADET control system used to control test bench, where the ABB 4 drive system was applied to load equipment more precise. Engine torque was obtained from the test bench using the load cell method. Emissions were recorded by the AVL SESAM FTIR system, where they were analysed by an infra-red spectrometer. In overall, AVL SESAM FTIR allows to fix 24–27 gases simultaneously, from which most part of components is measured, but some components are calculated from the process. The parameters for the test bench can be observed in Table 3. During the tests all gases were fixed, and more detailed analysis were done for regulated (NO_x, CO, CO_2, PM) emissions. AVL KMA Mobile fuel consumption measuring device with measuring range from 0.35–150 L h^{-1} and measurement error - 0.1% was used for fuel consumption measurements.

Each reading was repeated five times and after that the results were averaged to reduce uncertainty. The accuracy of measurements is shown in the graphs using statistical analysis with the assumption that 95% of results should be within 2 standard deviations of the result (± 2σ). Microsoft Excel software with the statistical analysis ToolPak add-in was used for calculating the mean (average) value and standard deviation. For use in graphs, the standard deviation was doubled. The mean value calculated using the statistical analysis provides a 95% confidence level that corresponds with the 2 standard deviations.

Table 3. Test bench parameters

Parameter	Value	Unit
Sierra CP Engineering 51.5 kW AC Dynamometer		
Absorbing power	50	kW
Absorbing torque	140	Nm
Inertia	0.068	kgm^2
Engine speed	7,500	min^{-1}
Electric current	140	A
Current type	3-phase	-
Drive type	Four quadrant regenerative drive	-
Measurement uncertainty	5	%
AVL SESAM FTIR spectrometer for exhaust gas analysis		
Sample gas flow	10	L min^{-1}
Response time	1	s
Measured gas components	CO, CO_2, H_2O, NO, NO_2, N_2O, NH_3, CH_4, C_2H_2, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_6, C_2H_5OH, CH_3OH, CH_3CHO, CHO, HCOOH, SO_2, IC_5, NC_5, NC_8, HNCO, HCN, COS, AHC, NO_x, NMHC, HCD, HCG, HCE	-
Measurement uncertainty	0.11–1.4	%

The maximum flow value of 20 L min^{-1} was chosen because it was the highest concentration of hydrogen that the engine could utilise without modifications to injection timing and engine parameters. Further increasing hydrogen concentration resulted in audibly observable engine knocking or increased engine speed at the lowest operating conditions (idle speed with no added load) that have not been analysed in this research. The selected maximum flow rate has been further divided into multiple segments, resulting in the flow rates (5, 10, 15 and 20 L min^{-1}) that have been tested. As a result, both hydrogen rich (H2 concentration in relation to diesel fuel is high) and hydrogen lean (H2 concentration in relation to diesel fuel is low) mixtures would be obtained in both high load and low load conditions.

RESULTS AND DISCUSSION

During the experiment the engine output power and engine speed were kept as constant variables. The addition of hydrogen gas resulted in the necessity to lower the amount of fuel delivered. As a result, the added hydrogen replaces diesel fuel in the fuel-air mixture resulting in a decrease in fuel consumption. The combustion properties of hydrogen mixed with the change in the fuel-air mixture result in a shift in emission gas concentration.

As it is visible in the graph displayed in Fig. 2, the engine torque remains largely unchanged during the tests with added hydrogen gas. Since the engine speed and load were fixed parameters, and the changes have been implemented to the fuel injection system, and parts of the diesel fuel have been replaced with hydrogen gas, such result could be expected. Since other engine mechanical output parameters such as engine speed and load were unchanged, it is reasonable to expect that parameters like torque will also remain unchanged. This gives valuable information that adding a hydrogen injection system to existing internal combustion engines will not result in a decrease in engines mechanical output parameters.

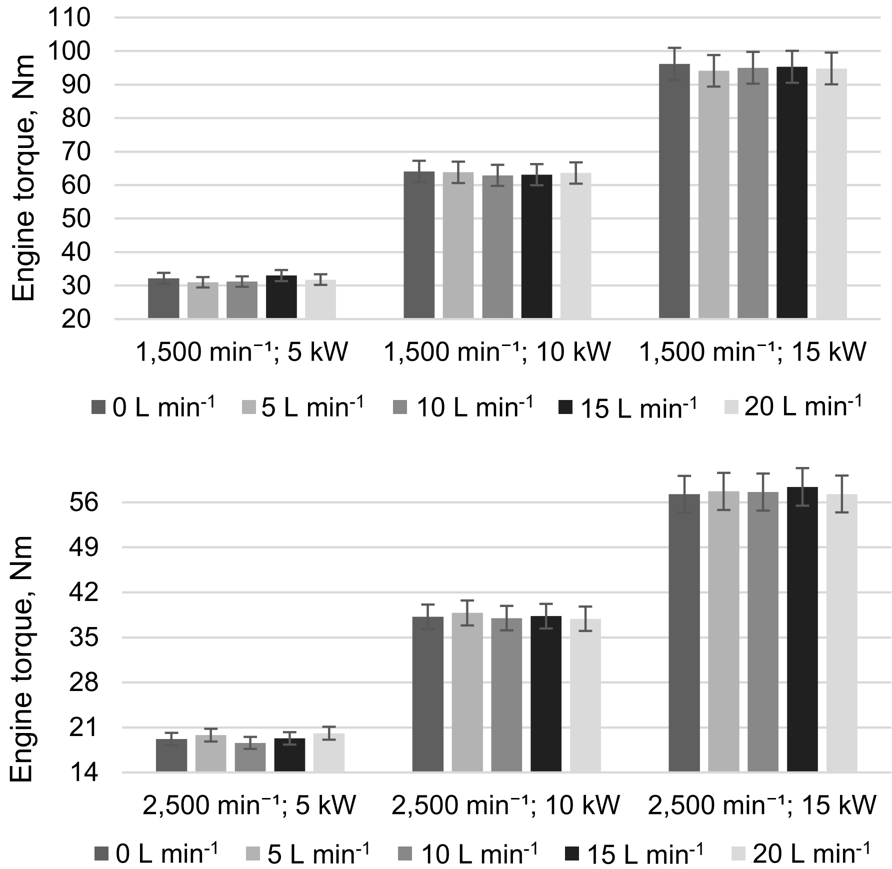

Figure 2. Variation of engine torque under different load modes and hydrogen flow rates.

As it is seen in Fig. 3, the addition of hydrogen gas resulted in a decrease in fuel consumption in all observed engine speed and load conditions. The largest decrease in fuel consumption at all engine speed and load conditions was observed with the addition of 20 L min^{-1} of hydrogen. The largest decrease (up to 41%) in fuel consumption was observed at 1,500 min^{-1} with the added load of 5 kW. With the same addition of 20 L min^{-1} of hydrogen at 2,500 min^{-1}, the reduction of fuel consumption reached nearly 21%.

The smallest reduction in fuel consumption was obtained at 2,500 min^{-1} with 15 kW load and with the addition of 10 L min^{-1} of hydrogen gas (only 3%) as the amount of the hydrogen gas supplied is a fixed value, independent of the amount of diesel fuel injected at the same time. At higher engine speeds and load conditions when the overall fuel and intake air consumption is increased, the overall amount of diesel fuel, air and oxygen that is replaced with the additional hydrogen gas is smaller, resulting in both a lower percentual decrease in fuel consumption and emissions. For comparison, at 1,500 min^{-1} in all load conditions, the same flow rate of hydrogen gas was used, 5, 10, 15 and 20 L min^{-1}, but the fuel consumption as well as the flow of air and oxygen necessary for the combustion process have increased resulting in a decrease in hydrogen gas concentration.

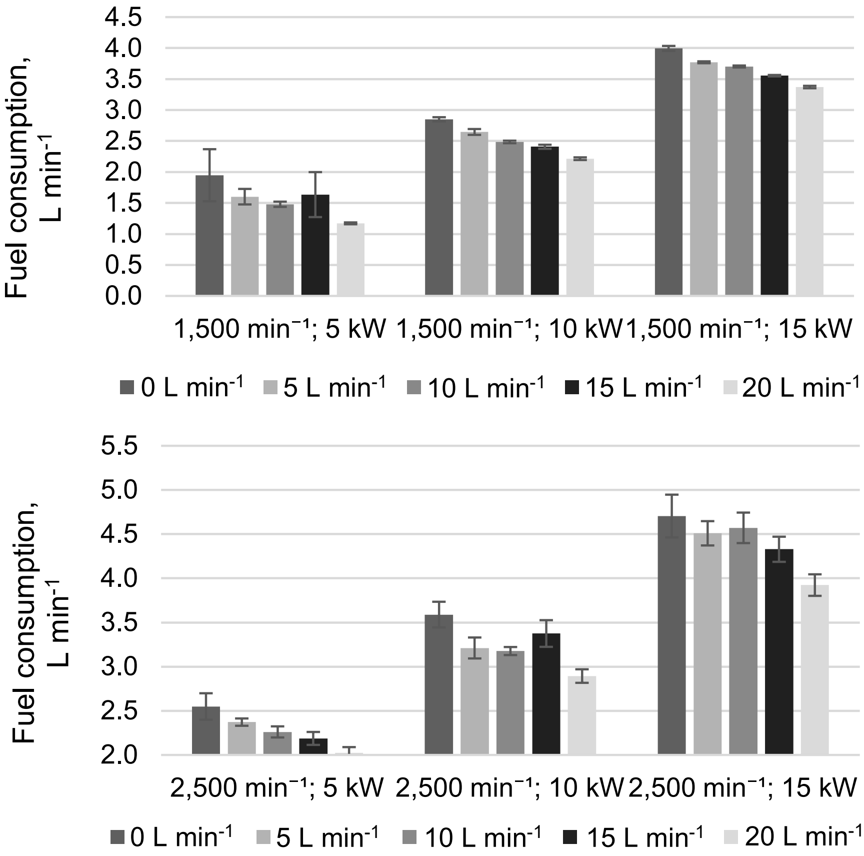

Figure 3. Variation of fuel consumption under different load modes and hydrogen flow rates.

As it is seen in Fig. 4, CO_2 emissions reduced in all engine speed and load conditions. The maximum reduction of CO_2 emissions (up to 28%) was observed at 1,500 min^{-1}, with 5 kW of load and 20 L min^{-1} of hydrogen. With increased engine speed of 2,500 min^{-1} and at the same 5 kW load condition, the reduction in CO_2 emissions was significantly smaller (15.3%). This can be explained by the fact, that the hydrogen gas concentration is decreased. The biggest impact on CO_2 emissions observed with higher concentrations of H_2 gas.

The addition of only 5 L min^{-1} of hydrogen gas resulted in the smallest decrease in CO_2 emissions. At 2,500 min^{-1} with 15 kW of load, the 5 L min^{-1} addition of hydrogen resulted with a 0.7% decrease in CO_2 emissions. The reduction of CO_2 emissions in the exhaust gasses can be explained with the fact that diesel fuel is being removed from the engine and replaced with hydrogen gas. Since hydrogen gas does not contain carbon elements, the overall reduction in carbon-based emissions was observed. When the hydrogen gas concentration in the air-fuel mixture increased, the effect became more visible.

Comparing both the changes in CO_2 emissions and fuel consumption, it was observed that the graphs have a similar tendency - the bigger the impact of hydrogen gas on fuel consumption, the more it affects CO_2 emissions. Again, the carbon particles are being removed from the air-fuel mixture, and the lesser the hydrogen concentration, the less effect on CO_2 emissions the gas has.

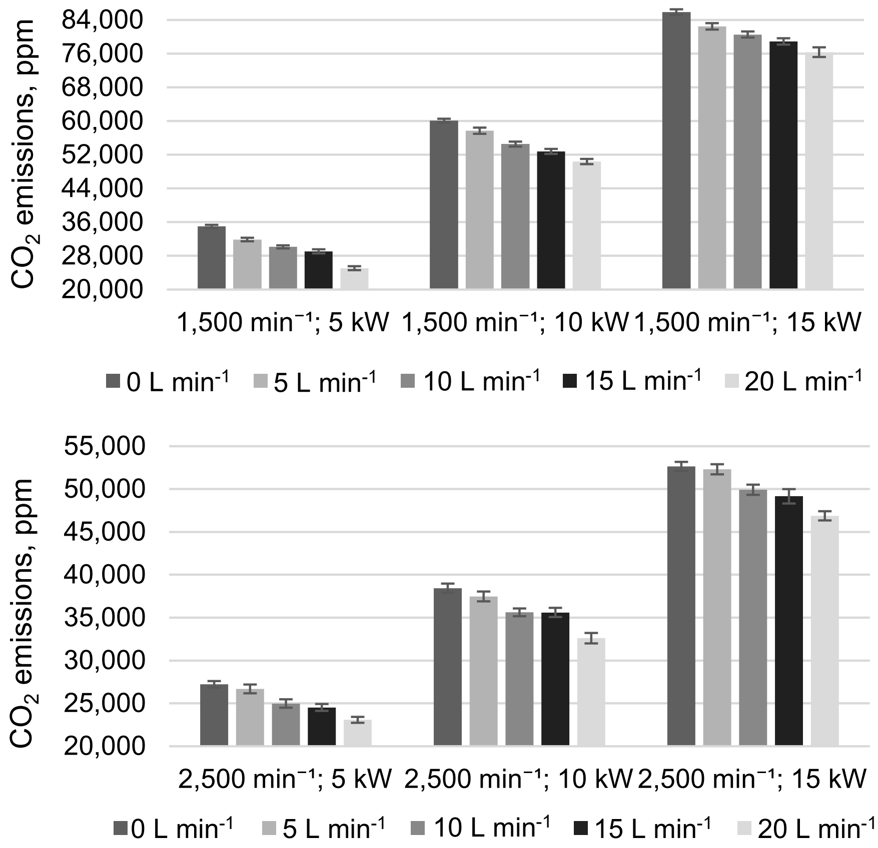

Figure 4. Variation of CO_2 under different load modes and hydrogen flow rates.

As it is seen in Fig. 5, CO emissions also was reduced in all engine speed and load conditions. The largest decrease was observed at 1,500 min^{-1} with 15 kW of added load showing decrease up to 55%. At 2,500 min^{-1} with 15 kW of load the addition of 5 L min^{-1} of hydrogen gas showed a slight increase in CO emissions (up to 3.2%).

Carbon monoxide is a by-product of incomplete combustion. In diesel fueled engines, CO forms during combustion inside the cylinder in zones where the air-fuel mixture is lean, and the insufficient mixing of oxygen and diesel fuel is realized. Since four stroke diesel engines are direct injection, and the fuel injection is realized close to the top dead centre, the formation of both fuel rich and fuel lean areas could be observed. In the case of fuel rich areas, the lack of oxygen prevents the complete oxidation of carbon inside the fuel, but in the case of fuel-lean areas the lower combustion rate and temperature negatively impacts the oxidation of carbon (Tutak et al., 2023).

Since hydrogen has faster flame speed than diesel fuel, it can increase the temperature inside the cylinder, especially during the end of combustion, resulting in a more complete combustion and oxidation of carbon particles. Additionally, since the amount of diesel fuel is reduced, the formation of fuel-rich areas also can be reduced, further aiding reduction of CO emissions (Zareei et al., 2024).

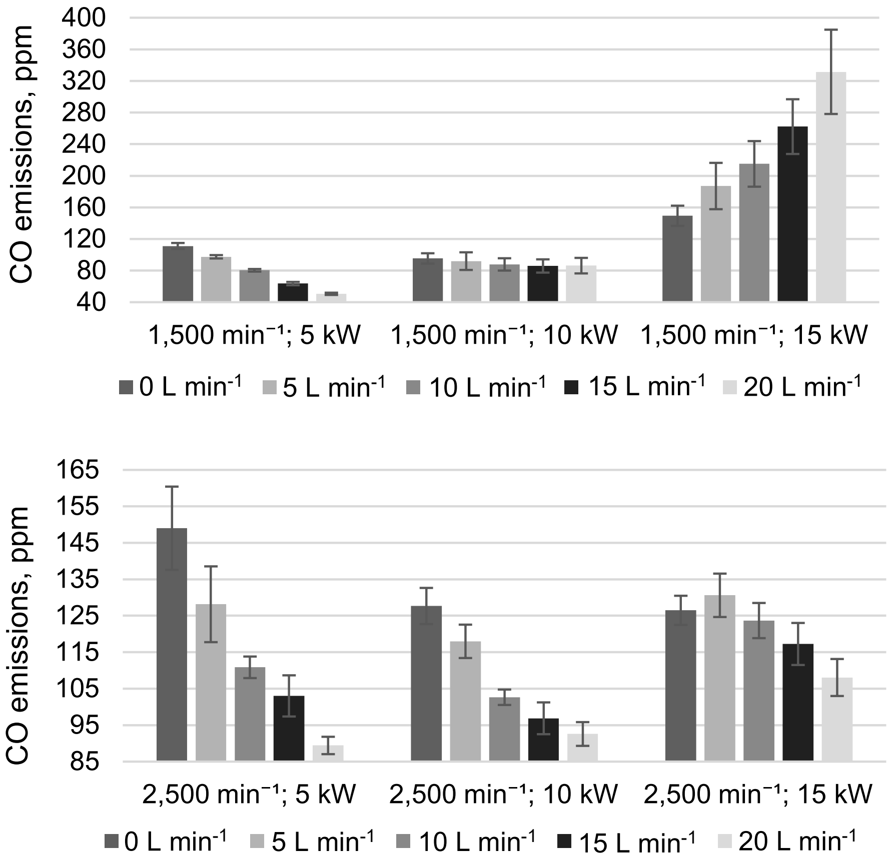

Figure 5. Variation of CO emissions under different load modes and hydrogen flow rates.

Fig. 6 shows changes of PM emissions, where a decrease in PM was observed with higher hydrogen concentrations and more substantial impact during higher load conditions.

Similar to other emissions observed during the tests, the most significant impact on PM emissions was observed with larger concentrations of H_2 gas. At 1,500 min^{-1} with 20 L min^{-1} of hydrogen and 15 kW of added load a 37.2% reduction in particle matter was observed. Overall, with 20 L min^{-1} of hydrogen in both engine speed modes tested a reduction of over 25% was observed, however, with smaller concentrations of hydrogen (at 1,500 min^{-1} with 5 kW of load and 10 L min^{-1} of hydrogen), a maximum increase in PM emissions of up to 3% was obtained.

Particulate matter results from an incomplete combustion of hydrocarbon fuels and forms inside the engine during combustion process. Soot particles make up approximately 50% of particulate matter. Diesel engines produce particulate matter mainly because of the local fuel-rich areas that have incomplete combustion. Since the addition of hydrogen gas reduces both the injected fuel quantity and creates a more homogenous air-fuel mixture, lower particulate matter emissions can be achieved (Hosseini et al., 2023).

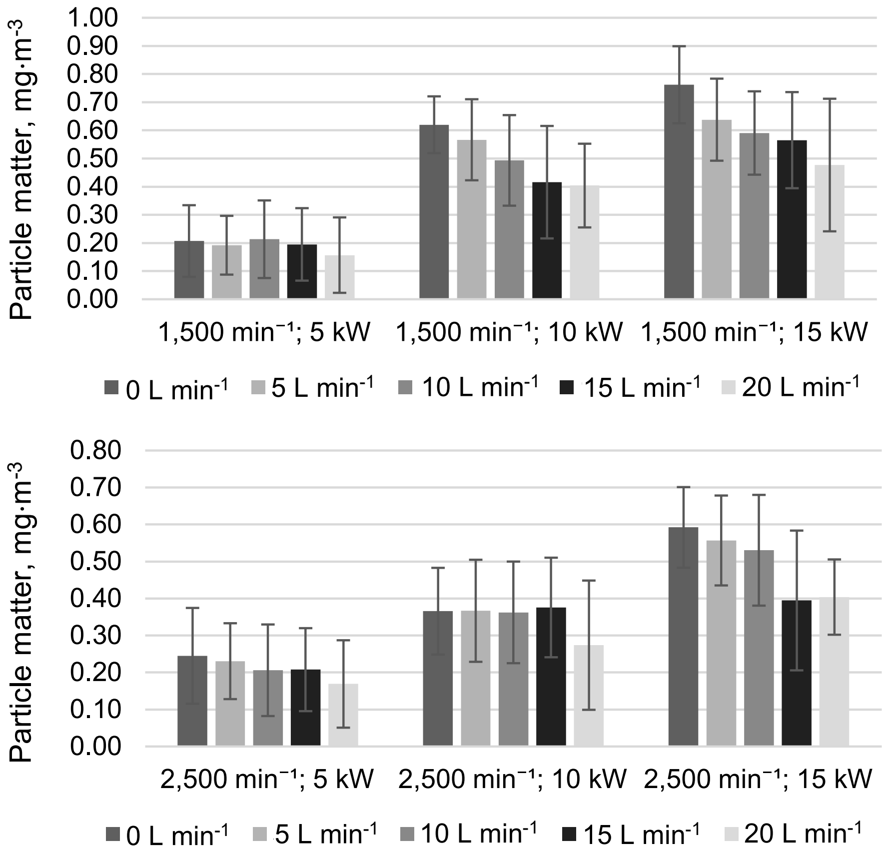

Figure 6. Variation of PM emissions under different load modes and hydrogen flow rates.

The addition of hydrogen gas has various impact on NO_x emissions (see Fig. 7). At the engine speed of 2,500 min^{-1} with 5 kW of added load the addition of hydrogen gas resulted in a reduction in NO_x emissions (up to 13.2%). This reduction can be explained by the fact that hydrogen replaces the diesel fuel in the combustion process, resulting in a leaner combustion process. Additionally, at high engine speed with low load conditions the temperature of combustion is reduced (White et al., 2006). As it is known, NO_x formation happens at high combustion temperatures. As a result, with operational conditions that contain higher engine speed and low load conditions (as the situation with 2,500 min^{-1} with 5 kW load), a decrease in NO_x emissions was achieved.

Additionally, since the hydrogen is added to the engine trough the intake manifold, the added hydrogen gas results in a lower concentration of oxygen that further limits the formation of NO_x (Tsujimura & Suzuki, 2017). Saravanan (Saravanan & Nagarajan, 2008) also found that at full load NO_x emission increases despite to decrease of particulate matter by 50%.

Alternatively, at higher engine load conditions, such as the ones displayed at the engine speed of 1,500 min^{-1} in all load conditions, as well as at 2,500 min^{-1} with 10 and 15 kW of added load, was observed that the NO_x emissions tend to increase. This happens as at higher load conditions the addition of hydrogen gas to the combustion process results in an increase in both the peak in-cylinder pressure and peak heat release (Dimitriou & Tsujimura, 2017). As a result, the chemical processes related to NO_x production are stimulated and more NO_x emissions are produced at these conditions.

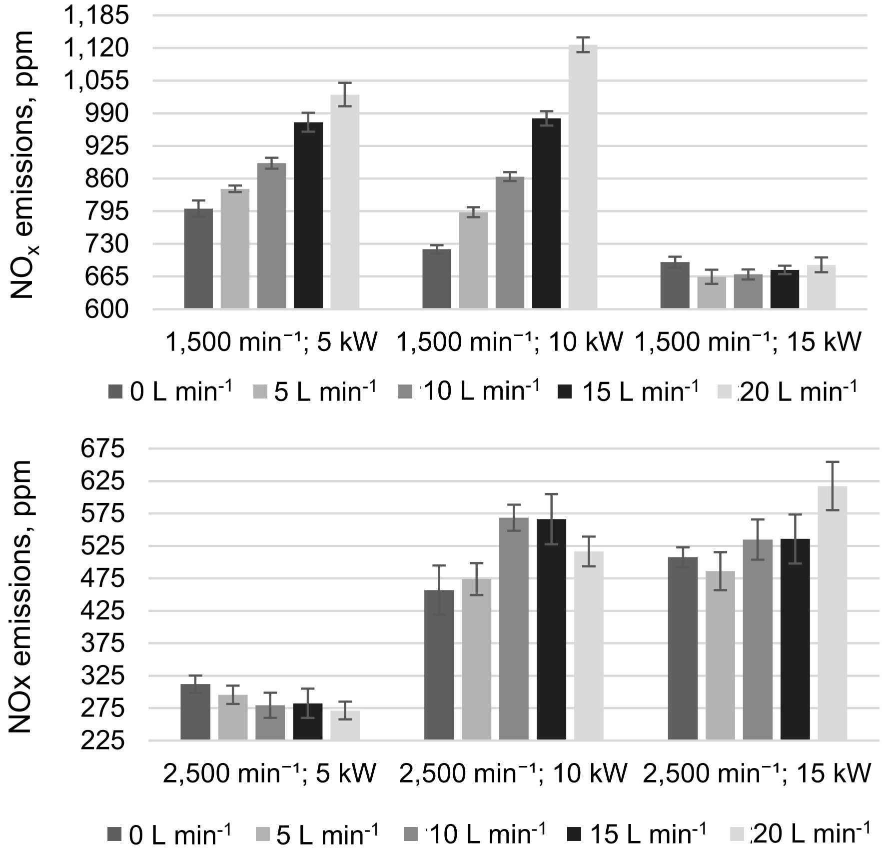

Figure 7. Variation of NO_x emissions under different load modes and hydrogen flow rates.

The most significant increase in NO_x emissions was observed at 1,500 min^{-1} with 10 kW of added load and 20 L min^{-1} of added hydrogen. At this experimental mode, the 36.2% increase in NO_x emissions was obtained.

CONCLUSIONS

Overall, the addition of hydrogen gas to a diesel internal combustion engine can provide multiple benefits, including a reduced fuel consumption, a more complete combustion, and lower greenhouse gas emissions, but the main conclusions are as following:

1. The addition of hydrogen gas to the combustion process and replacing diesel fuel with hydrogen gas has no significant impact on engine output parameters such as torque and the ability to handle load.
2. Higher concentrations of hydrogen gas have more significant impact on emissions and fuel consumption.
3. Hydrogen gas can be used to partially replace diesel fuel, resulting in a decrease in diesel fuel consumption of up to 41%.
4. Addition of hydrogen gas results in a decrease in CO_2 emissions by up to 28.3% at 1,500 min^{-1}, with 5 kW of load and 20 L min^{-1} of hydrogen.

5. Hydrogen gas can impact the combustion process, resulting in up to 55% decrease in CO emissions. At higher load conditions, a slight increase of 3.2% was observed.

6. At higher concentrations of 20 L min^{-1} of hydrogen, up to 37.2% reduction of particle emissions was observed, but with lower concentrations at lower load conditions, an up to 3% increase was observed.

7. At low load conditions and high engine speed when the engine moves high amounts of air and the combustion temperature is lower, an up to 13.2% reduction in NO_x emissions was observed.

8. At higher load conditions, an up to 36.2% increase in NO_x emissions was observed.

The most important negative drawback of hydrogen injection in an internal combustion diesel engine is the increase of NO_x emissions that could be observed during high engine load conditions where the temperature and pressure during combustion is increased. In situations like this, a method for slowing down the combustion process by removing excess heat would be beneficial.

Further research on the impact of hydrogen gas on combustion properties, emissions and fuel consumption is planned.

ACKNOWLEDGEMENTS. The article was supported by Latvia University of Life science and Technologies, ERAF project Nr. 1.1.1.8/1/24/I/002 'LBTU Doctoral Support and Development Initiative'.

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