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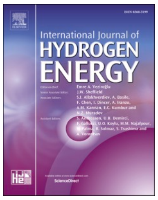

Experimental study of the performance of a SI-engine fueled with hydrogen-natural gas mixtures

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ABSTRACT

Green hydrogen has become more attractive as a fuel for engines to reduce greenhouse gas emissions. By mixing it with natural gas (NG), the modification work on the engine can be minimized but the carbon dioxide emissions from combustion can still be decreased. In this paper, an experimental study was accomplished to investigate the performance of a spark-ignition engine fueled with hydrogen-natural gas blends by either keeping a constant ignition timing or changing it. Up to 25 mol-% hydrogen was mixed into natural gases with different compositions and the methane number and Wobbe index were calculated and compared to the requirements set by Euromot. The results show that up to 15 mol-% hydrogen can be blended into NG to meet the limits of Euromot. However, when 25 mol-% hydrogen was mixed into NG the methane number varied between 56 and 64 depending on the gas composition. This would most likely cause knock for a mixture consisting of higher hydrocarbons but during the executed tests knock was never a problem. Furthermore, it was detected that the methane number alone cannot tell the knock tendency of a gas in a certain engine and an additional condition is needed such as the hydrogen level. An adjusted ignition timing was also preferable compared to a constant one to keep the engine component temperature at a moderate level.

1. Introduction

Climate change is a great concern because of increased consumption of fossil energy and other human activities. To overcome this challenge, research and development in future fuels and energy systems are on high priority to find new ways to decrease the greenhouse gas emissions [1]. During recent years, hydrogen has become attractive due to its potential as a fuel and energy carrier, its capability for energy storage, and its use as a carbon-neutral feedstock [2]. By starting to utilize green hydrogen, produced from renewable energy, the key target for the European Union to be climate-neutral by 2050 is a step closer [3].

Hydrogen is a colourless and odourless gas, which does not release any carbon dioxide (CO_2) when it is burnt [4]. It can be applied in fuel cells and internal combustion engines (ICE), where hydrogen fuel cells achieve high efficiency and low emissions [5]. Natural gas (NG) is a common fuel for ICEs, but there are some challenges when burning NG like the low flame speed, poor lean-burn capability compared to hydrogen, and the ignitability of methane [6]. To handle these issues, an additional fuel can enhance the characteristics of natural gas combustion, where hydrogen is an efficient gas for this purpose [7]. When hydrogen is used as a single fuel, the disadvantages are its low volumetric energy density and high adiabatic flame temperature [7,8]. Mixing a small amount of hydrogen into natural gas provides an opportunity to exploit the positive properties of hydrogen without making any major changes on the natural gas engines that already exist [9].

The addition of hydrogen into natural gas decreases hydrocarbon (HC), carbon monoxide (CO), and carbon dioxide emissions, while the amount of nitrogen oxides (NO_x) increases [10–14]. The NO_x concentration can though, be reduced through lean combustion and delaying of the ignition timing due to a lower temperature in the cylinder [11,12]. This was also noted in an experimental study by Xu et al. [13], who investigated the combustion and emissions of a port-injection spark-ignition (SI) engine fueled with compressed natural gas-hydrogen blends at various hydrogen fractions (0–25 vol-%). If a leaner fuel-air mixture was used, the NO_x emissions were lowered but at the same time the ignition timing had to be optimized to achieve a high thermal efficiency. This was applied when more than 20 vol-% hydrogen was added into natural gas. Other outcomes of the study were that addition of hydrogen raised the maximum cylinder pressure and heat release rate, while it decreased the HC and CO emissions.

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An important parameter for SI-engines is the ignition timing since it affects the quality of the burning fuel in the cylinder and in this way the pollutant emissions from the engine [15]. If the ignition timing is retarded when hydrogen is mixed with natural gas, the NO_x and CO emissions can be reduced, while the power, torque, and fuel consumption efficiency may increase [15,16]. The injection timing is also vital with increased amount of hydrogen, where an advance injection timing is preferable due to a more complete combustion and higher efficiency values [15]. This depends on that hydrogen has five times larger flame speed than methane and a wider flammability range, leading to a shorter burning duration [17,18].

The extended flammability limits mean that the engine can operate at poorer conditions using a higher air/fuel ratio (λ, lambda) and a proper mixing of the air-fuel occurs in the cylinder since hydrogen has a high diffusion coefficient [8,19]. The net fuel consumption is also reduced when running at leaner conditions, which was shown in an experimental study made by Lee et al. [20]. In this work, a H_2-NG mixture, consisting of 30 vol-% hydrogen, was fed into a SI-engine at idle conditions and the outcome was that the fuel consumption could be decreased with more than 25% for the H_2-NG blend compared to when the engine was running on pure natural gas. However, when a higher lambda is used, the temperature in the cylinder decreases, leading to a lower combustion temperature and affects the engine thermal efficiency and torque negatively [21].

The risk of uncommon combustion features, such as pre-ignition, knock, and backfire can also happen when hydrogen is blended into natural gas [7]. Pre-ignition is a premature combustion prior to controlled ignition, caused by hot spots such as overheated valves, spark plugs, hot residual gases, or lubricant droplets [22]. Backfire is similar to pre-ignition but the timing when the anomaly occurs is different, where pre-ignition starts during the compression stroke with closed intake valves and backfire takes place with intake valves open [22,23]. This results in combustion and pressure rise in the intake manifold, which can damage and destroy the intake system [23]. Autoignition or knock is commonly used to denote end-gas autoignition which happens spontaneously followed by a rapid release of the remaining energy, generating high-amplitude pressure waves so-called oscillations [22,23]. Prolonged operation under intense knock conditions can cause serious damage to the engine and increase the emissions [23]. An engine running on a hydrogen-natural gas mixture becomes more sensitive to knock if higher engine speeds, loads, and compression ratios are used [7]. Even the amount of added hydrogen is crucial, where Flekiewicz et al. [24] had observed that knock occurs when more than 40% hydrogen was mixed into natural gas.

Methane number (MN) is a well-established definition of the knock resistance of gaseous fuels, and it is used by engine manufacturers to describe the gas quality [25]. A gas consisting of 100% methane has a MN of 100 and when higher hydrocarbons such as ethane, propane, butane, and pentane are added the methane number decreases, meaning that the engine becomes more sensitive to knock [26,27]. Carbon dioxide can increase the MN above 100 if the gas contains only methane, while hydrogen reduces it, and the impact of nitrogen is negligible [25,27]. Engine manufacturers are often using their own calculation tool to determine the methane number of a fuel gas and they also put requirements on the maximum allowed amount of certain components to be able to achieve the best performance of the engine [28–31]. According to Euromot, which is the European association of internal combustion engine manufacturers, the methane number shall be 70.0 or higher for natural gas at the exit points in the European gas distribution system to ensure that engines manufactured by Euromot reach their optimal performance [32]. Another specification set by Euromot is that the Wobbe index (WI) shall be between 49.0 and 52.7 MJ/m^3, where Wobbe index means the interchangeability between gaseous fuels in the way that two gases with different compositions but equal Wobbe index can be replaced with each other since they release the same amount of energy [32,33].

There are many experimental investigations [4,9,11–17,19,21] which have studied the performance of SI-engines by mixing hydrogen into natural gas. In this work, the purpose is the same but natural gases with different methane numbers have also been explored to give a better understanding of the relationship between gas composition and methane number. Another unique item in this work is the size of the experimental engine, which is a 20-cylinder spark-ignition engine with a mechanical power of 12 MW. This engine can be used in power plants, where the gas is directly coming from the gas grid, which can have an shifting gas composition depending on location [26,34]. In the future, there is a possibility that hydrogen will be injected directly into the gas grid [26] and therefore, it is important to study the behaviour of the engine which is fed with different amounts of hydrogen and varied natural gas compositions.

2. Material and methods

2.1. Experimental setup and procedure

The experimental tests were carried out on a Wärtsilä 20V31SG engine, which is a 4-stroke, spark-ignition, twenty-cylinder, turbocharged, water-cooled, and lean-burn engine, where each cylinder has a precombustion chamber located in the cylinder head. The engine details are shown in Table 1.

The tests were performed at the engine laboratory in Bermeo, Spain, in February 2022. Natural gas was taken from the Spanish gas grid and blended with hydrogen taken from a trailer, consisting of high-pressure gas bottles. A pressure reduction valve was used to lower the hydrogen pressure to get a slightly higher pressure compared to the natural gas pressure. In some cases, a gas with a low methane number was desired which could be achieved by mixing propane into natural gas, whereafter hydrogen was blended into the gas mixture. Propane was taken from a pressurized liquified petroleum gas (LPG) tank by increasing the LPG pressure with a pump and vaporizing it to gas with a heat exchanger that used thermal oil as a heating medium. The mixed gas was fed to the gas valve unit (GVU), which controlled the inlet gas pressure, and then fed into the engine. Fig. 1 shows a schematic sketch of the fuel system.

To get the correct ratio of natural gas, propane, and hydrogen, mass flow meters and control valves were installed in the pipelines. A flow meter of the type Promass F300 from Endress + Hausser was utilized to measure the mass flow of natural gas and propane, while Emerson's model CMFS075 M measured the hydrogen mass flow. The composition of natural gas coming from the gas grid, as well as the gas mixture was analysed with Agilent gas chromatograph of the model 490 Micro GC.

The goal of the tests was to examine the engine performance when adding up to 25 vol-% hydrogen into natural gas without modifying the already existing design and performance optimizations of the engine. Natural gas consisting of 25 vol-% hydrogen can still be classified as natural gas, meaning that this is the maximum amount of hydrogen which can be mixed into NG and the same rules and regulations can be applied [35,36].

The tests were conducted at a constant speed of 750 rpm, where the NO_x emissions were kept constant by adjusting the charge air pressure and thus affecting the combustion duration. This is due to the fact that addition of hydrogen increases the NO_x emissions, but by using a higher

Table 1
Test engine specifications.

Item	Value
Engine type	4-stroke
Cylinder configuration	20V
Bore x Stroke	310 x 430 mm
Nominal speed	750 rpm
Break Mean Effective Pressure (BMEP)	29.6 bar
Mechanical power	12000 kW

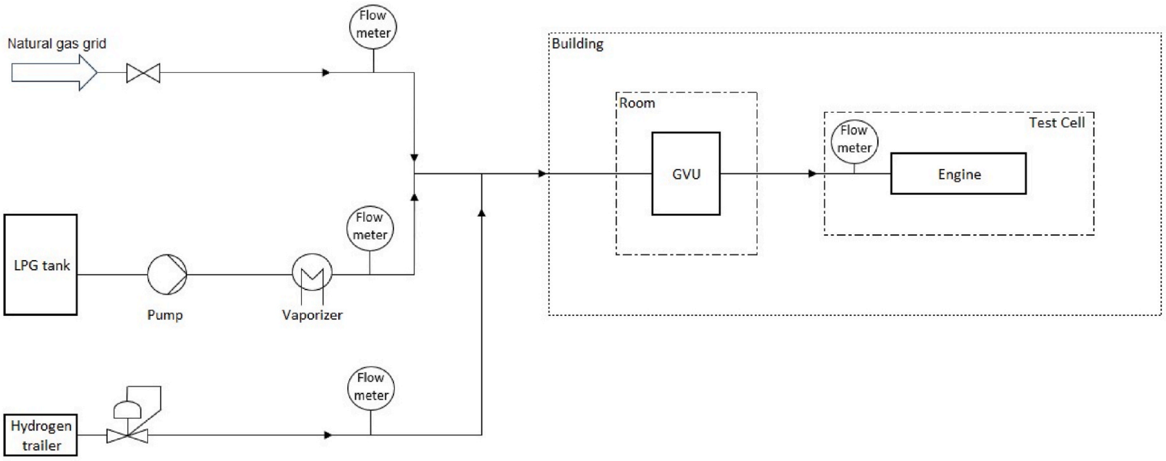

Fig. 1. Schematic sketch of the fuel system in the study.

lambda the combustion temperature decreases as well as the emissions [37]. In this study, three test series are presented, Table 2, where the ignition timing was kept constant in the first one and it was changed in the second and third one. Since hydrogen has a fast-burning velocity meaning that the combustion is sped up [7], a variation in the ignition timing can be needed to keep the combustion in a suitable position despite changing fuel composition. The engine was running at 100% load in the two first series and data measurement points were taken when 0, 10, 15, 20, and 25 mol-% hydrogen had been added into natural gas, meaning that they have the same gas composition. Before each test point was taken, the engine had stabilised for about 15–25 min at the given input data to get reliable values. Parameters such as mass flows, charge air pressure, cylinder pressure, prechamber temperature, and exhaust emissions were collected at each measurement point [38]. More details about the used instrumentations are listed in Table 3.

In the third test series, the engine was run at 90% load to prevent a too high pressure in the cylinders. In this series, the purpose was to examine the performance of the engine when hydrogen is mixed into a natural gas with low methane number. Propane was first blended into NG to achieve a methane number of 76, whereafter 16.6 (Case 1) and 25 (Case 2) mol-% hydrogen was added. In addition, 25 mol-% hydrogen was mixed with a natural gas composition that had a MN of 70 (Case 3) and 65 (Case 4). According to Euromot, the methane number shall be above 70 to ensure proper operation of an engine [32], which was the reason why MN 70 was chosen. There was also an interest to see if the engine could handle a gas composition with a lower methane number than the recommended value and 65 was used in this case. The same parameters were measured in the third test series as in the two first ones [38], and Table 4 shows the gas compositions used in all series, as measured by the Agilent gas chromatograph.

2.2. Calculations

2.2.1. Methane number and Wobbe index

The methane number for the gas compositions was calculated according to EN16726:2015 [39] which is the method that Euromot refers to. Euromot has specified that the Wobbe index requirements set by them are determined at reference conditions of 15 °C and 101.325 kPa [32,40], and these values have been used in this study. The approach for calculating the Wobbe index is presented in more detail in the article by Ingo et al. [41] and the equations are according to ISO 6976:2016 [42].

Table 2
Test series conducted in the study, the control methods that were used on the engine, as well as the engine load.

Test series	NO_x emission control	Ignition timing control	Engine load
First test series	Constant	Constant	100%
Second test series	Constant	Adjusted	100%
Third test series	Constant	Adjusted	90%

Table 3
Specification of instrumentation used in the study.

Unit	Model	Measurement range	Accuracy
Natural gas flow meter	Endress + Hausser Promass F300	0–2500 kg/h	± 0.35%
Propane gas flow meter	Endress + Hausser Promass F300	0–300 kg/h	± 0.35%
Hydrogen gas flow meter	Emerson CMFS075 M	0–200 kg/h	± 0.25%
Gas mixture flow meter (total)	Emerson CMF200 M	0–2300 kg/h	± 0.35%
Charge air pressure	Danfoss MBS 3350	0–10 bar	± 0.5%
Cylinder pressure	Kistler 6124A1S3-3	0–300 bar	± 1%
Prechamber tip temperature	Pentronic Thermocouple Type K	−40–1000 °C	±1.5%

Exhaust gas analyser

Unit	Model	Measurement range	Accuracy[1)]
NO_x	Horiba Mexa One	0–500 ppm	± 1%
HC		0–2000 ppm	± 1%
CO		0–5000 ppm	± 1%
CO_2		0–25 vol-%	± 1%

[1)] The accuracy is 1% of full scale.

2.2.2. Efficiency

The engine power was obtained by measuring the voltage and current from the generator that was connected to the engine. Voltage and current transformers of class 0.1 were connected to Arqtec AQ-P215 class 0.2, which provided the electrical power. The generator losses were then calculated based on input data from the generator manufacturer, whereafter the mechanical engine power could be determined according to equation (1).

$$P = P_E + P_{loss} \tag{1}$$

Where, P corresponds to the engine mechanical power [kW], P_E is the electrical power [kW], and P_{loss} represents the generator losses [kW].

Engine efficiency was calculated by dividing the engine mechanical power with the product of the gas mass flow and the lower heating value (LHV) of the gas mixture according to equation (2).

Table 4

Gas composition for the test series, where the unit is in mol-%.

First and second test series					
Component	0% H_2	10% H_2	15% H_2	20% H_2	25% H_2
Methane	92.37	83.11	78.50	73.97	68.87
Ethane	5.20	4.64	4.36	4.11	3.88
Propane	0.92	0.83	0.79	0.74	0.70
i-Butane	0.18	0.16	0.15	0.14	0.13
n-Butane	0.17	0.16	0.15	0.14	0.13
i-Pentane	0.03	0.03	0.02	0.02	0.02
n-Pentane	0.02	0.02	0.02	0.02	0.02
Carbon Dioxide	0.32	0.29	0.27	0.26	0.25
Nitrogen	0.78	0.72	0.65	0.62	0.57
Hydrogen	0.00	10.05	15.09	19.97	25.42

Third test series				
Component	Case 1	Case 2	Case 3	Case 4
Methane	77.74	69.55	67.60	64.65
Ethane	2.70	2.41	2.38	2.31
Propane	2.66	2.36	4.08	6.05
i-Butane	0.13	0.12	0.14	0.18
n-Butane	0.08	0.07	0.08	0.10
i-Pentane	0.00	0.00	0.00	0.00
n-Pentane	0.00	0.00	0.00	0.00
Carbon Dioxide	0.00	0.00	0.00	0.00
Nitrogen	0.08	0.07	0.06	0.06
Hydrogen	16.61	25.17	25.38	26.29

$$\eta = \frac{P}{\frac{\dot{m}}{3600} \bullet LHV_m} \bullet 100\% \quad (2)$$

Where, η represents the efficiency, $\dot{m}$ is the total gas mass flow [kg/h], and LHV_m is the lower heating value on mass basis of the gas mixture [kJ/kg], which was calculated from equation (3).

$$LHV_m = \frac{LHV_V}{\rho} \quad (3)$$

Where, LHV_V is the lower heating value on volume basis of the gas mixture [kJ/m^3] and ρ is the gas mixture density [kg/Nm^3]. The LHV_V and density of the gas mixture were obtained from the Agilent gas chromatography, which has calculated the values based on the analysed gas compositions given in Table 4.

2.2.3. The default CO_2 emission factor

The default carbon dioxide emission factor is calculated per energy content in the fuel blend. To determine the CO_2 emission factor, it was assumed that a complete combustion occurred meaning that all carbon in the feed flow reacts with oxygen and carbon dioxide is formed as the below reaction (4) shows:

$$C + O_2 \rightarrow CO_2 \quad (4)$$

According to Statistics Finland [43], the default oxidation factor in combustion for natural gas is 1.0, and the emission factor can be calculated as following:

$$EF_{CO_2} = \frac{\frac{x_C \bullet \dot{m}}{M_C} \bullet M_{CO_2} \bullet 1000}{P} \quad (5)$$

Where, EF_{CO_2} represents the CO_2 emission factor [g/kWh], x_C refers to the mass carbon content in the feed flow ($\dot{m}$), M_C is the molar mass of carbon; 12.0107 kg/kmol [42], and M_{CO2} is the molar mass of carbon dioxide; 44.0095 kg/kmol [42]. The carbon content in the feed flow (x_c), mass flow ($\dot{m}$), and mechanical power (P) were received from the test points.

2.2.4. Relative change

The relative change has been calculated for most of the test points according to equation (6).

$$C = \frac{x_2 - x_1}{x_1} \bullet 100\% \quad (6)$$

Where, C is the relative change [%], x_1 is the initial value, and x_2 is the final value.

In this study, the initial value, x_1, has been assumed to be the parameters for the gas composition which does not contain any hydrogen. The final value, x_2, is the parameters for the gas compositions where 10%, 15%, 20%, or 25% hydrogen has been mixed with natural gas.

3. Results and discussion

3.1. Effect of ignition timing on charge air pressure

Hydrogen was mixed with natural gas and fueled into a SI-engine. A challenge with hydrogen is its high flame temperature and speed which causes higher combustion temperature and favours the formation of NO_x [12]. In the performed test series, the NO_x emissions were kept constant by adjusting the charge air pressure. It was observed that the charge air pressure increased with a higher hydrogen content, as illustrated in Fig. 2, to keep the NO_x emissions at a stable level. The charge air pressure was highest for the first test series, which had a constant ignition timing, while it was lower in the second series where the ignition timing was changing. A higher charge air pressure can cause earlier turbocharger speed derating at higher altitudes and in worst case result in misfiring, meaning that a too high charge air pressure is not desired [44].

3.2. Effect of ignition timing on efficiency

The engine efficiency was also increased when more hydrogen was added as shown in Fig. 3. The reason is the faster combustion because hydrogen has a higher laminar flame speed than methane [15,16]. The more hydrogen that was added, the less enhanced the efficiency improvement, where the increase was small from 20 to 25 mol-% injected hydrogen. For the whole range, from 0 to 25 mol-% added hydrogen, the efficiency rise was about 1.8% in the first test series and 1.5% in the second. In previous studies [10,12,14], it has been observed that lambda, engine speed, and ignition timing have an impact on efficiency and by optimising these parameters a higher efficiency can be achieved when adding hydrogen into natural gas. In the performed tests, the engine speed was the same for both test series, while the ignition timing was constant in the first series and adjusted in the second. Lambda was different in both series since it increased with raised charge air pressure.

3.3. Constant vs. adjusted ignition timing

Although the highest efficiency was received with constant ignition timing, which was used in the first test series, the temperature of the components became higher with this setting. A higher temperature can cause hot spots, which in the worst case can lead to pre-ignition [22]. In Fig. 4a) the prechamber tip temperature is shown as a function of hydrogen content for the first and second test series. By changing the ignition timing, which was done in the second test series, the temperature remains on a moderate level over the whole hydrogen range. It was also observed that the cylinder peak pressure increased more in the first test series compared to the second series as the hydrogen level increased, refer to Fig. 4b) where the given pressure is the average peak pressure for all 20 cylinders. It is therefore preferable to change the ignition timing when running on hydrogen-natural gas mixtures, which is the reason why the third test series was using an adjusted ignition timing.

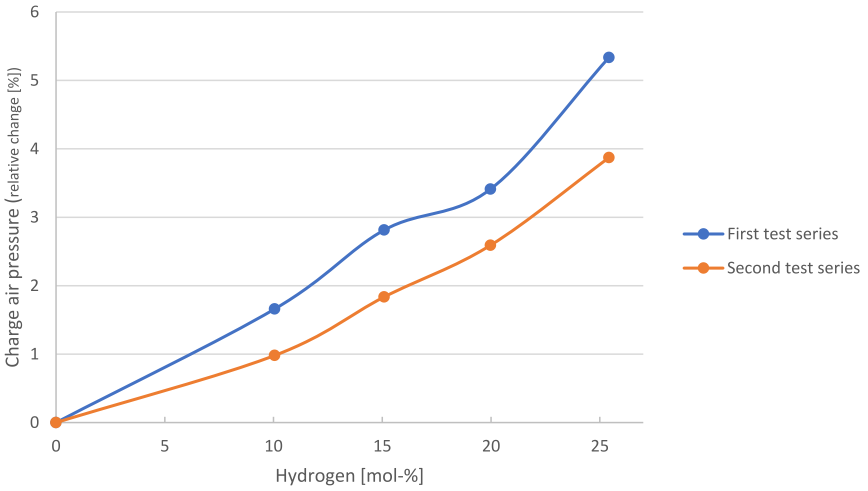

Fig. 2. Charge air pressure at constant NO_x for the first and second test series at varying hydrogen content.

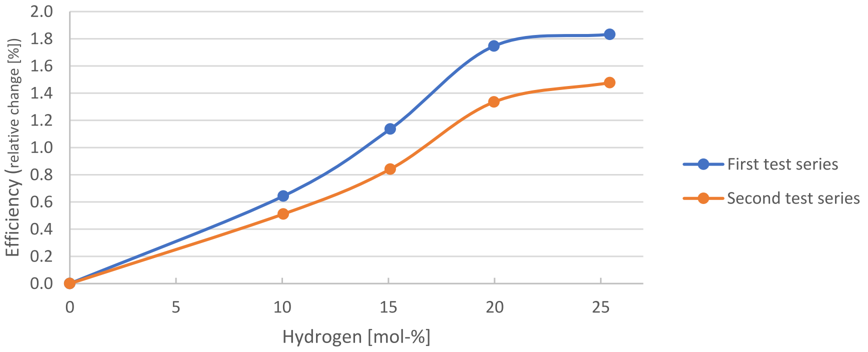

Fig. 3. Engine efficiency relative change as a function of the hydrogen content in natural gas for the first and second test series.

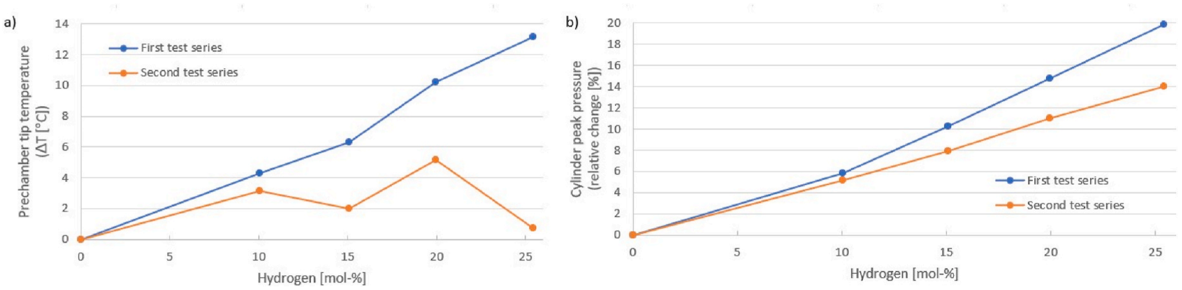

Fig. 4. a) Prechamber tip temperature and b) cylinder peak pressure as a function of hydrogen content in natural gas for the first and second test series.

3.4. Effect on HC and CO emissions

The main target with blending hydrogen into natural gas is to get lower greenhouse gas emissions. It was noted a reduction of the hydrocarbon and carbon monoxide emissions due to lower carbon content in the fuel, as well as faster and more complete combustion. A more complete combustion means that the formation of carbon dioxide is favourable, which depends on the increased combustion temperature caused by hydrogen addition [14]. Fig. 5 shows the HC and CO emissions as a function of hydrogen content for the first and second test series. The biggest decrease was observed for carbon monoxide which was about 35% for both test series, while the total hydrocarbon emissions reduced 11% in the first series and 15% in the second. The values of the relative change have been calculated based on the HC and CO content at 5% oxygen at dry conditions with the unit mg/Nm^3.

3.5. Effect on default CO_2 emission factor

In Fig. 6 the calculated default CO_2 emission factor is illustrated as a function of hydrogen content in natural gas for the first and second test series. The reduction was about 10% for both test series.

In previous studies [10–14], the same trend with a reducing value in CO, HC, and CO_2 emissions has been observed, where the reduction for HC and CO_2 has been up to 50% when the load has varied [14]. However, the CO and HC emissions depends strongly on lambda, where the mixture shall neither be too rich or too lean to receive an optimal drop in

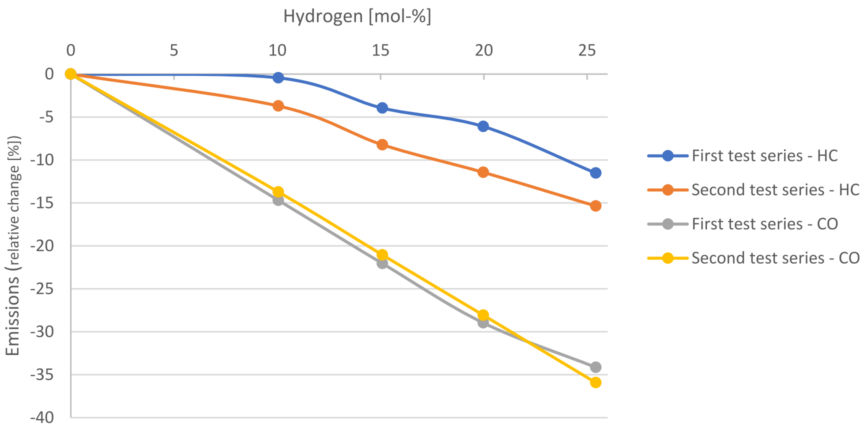

Fig. 5. Hydrocarbon and carbon monoxide emissions as a function of the hydrogen content in natural gas for the first and second test series.

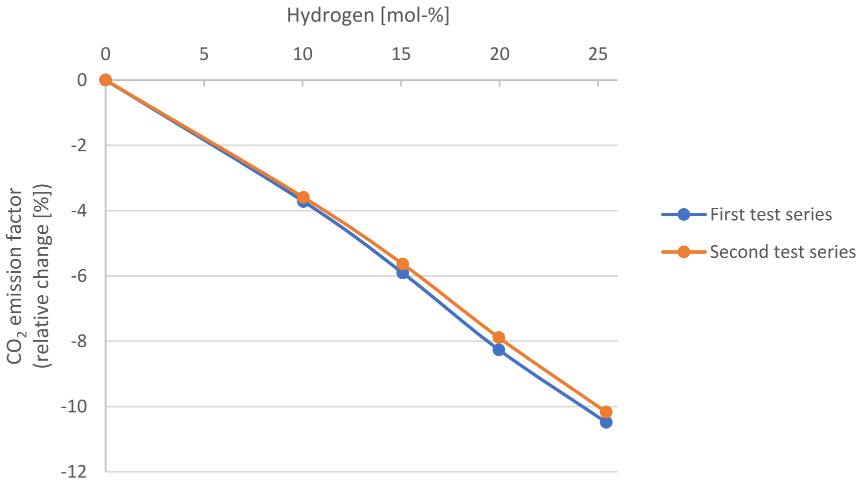

Fig. 6. The default carbon dioxide emission factor as a function of hydrogen content in natural gas for the first and second test series.

greenhouse gas emissions [11,13].

3.6. *Methane number and Wobbe index*

The methane number and Wobbe index were calculated for each measurement point based on the gas composition, where Table 5 shows the hydrogen content and calculated values for the first and second test series, which have the same gas composition. With a higher hydrogen content, the methane number decreases, as well as the Wobbe index. To fulfil Euromot's requirements with a MN higher than 70.0 and a Wobbe index between 49.0 and 52.7 MJ/m^3, 15 mol-% hydrogen can be added. As illustrated in Fig. 3, the engine efficiency was raised with higher hydrogen content and the engine performed well although the methane number went down to 64 and the Wobbe index to 48 MJ/m^3 when 25 mol-% hydrogen was blended into natural gas.

In the third test series which were conducted, propane was first mixed with natural gas to get a lower methane number, whereafter hydrogen was added. A MN of 76 was used in two measurement points, and 16.6 mol-% (Case 1), respectively 25 mol-% (Case 2) hydrogen were injected. The methane number was then lowered to 70 and 65, and ~25 mol-% hydrogen was blended into Case 3 and 4. Table 6 shows the hydrogen content, calculated methane number and Wobbe index. It is only the Wobbe index requirement set by Euromot which is fulfilled for all cases except for Case 4. The methane number is under 70 for all gas compositions, meaning that they do not meet the lower limit of Euromot. Even in this test series the engine performed good, but it shall though be noted that the load was 90% to limit problems with a too high pressure in the cylinders since it increases with more hydrogen content [13]. The amount of added hydrogen can therefore be restricted to the design pressure of the cylinder, and derating can be needed when running at high levels of hydrogen at the maximum cylinder pressure.

As mentioned earlier, methane number is a definition of knock

Table 5
Hydrogen content in the gas mixture, as well as calculated methane number and Wobbe index for the first and second test series.

Parameter	0% H_2	10% H_2	15% H_2	20% H_2	25% H_2
Hydrogen content [mol-%]	0	10	15	20	25
Methane number	79.6	74.4	70.8	67.3	63.6
Wobbe index [MJ/m^3]	51.2	49.9	49.2	48.6	47.9

Table 6
Hydrogen content in the gas mixture, as well as calculated methane number and Wobbe index for the third test series.

Parameter	Case 1	Case 2	Case 3	Case 4
Hydrogen content [mol-%]	16.6	25	25	26
Methane number	68.0	62.2	59.4	55.6
Wobbe index [MJ/m^3]	51.5	50.1	49.4	48.7

resistance of gaseous fuels where a lower MN means that the engine becomes more sensitive to knock [25–27]. An observation from the third test series was that the heat release rate was the same for Case 2–4, meaning that the combustion did not react to the change in methane number [38,45]. If knock had occurred, the heat release would have altered but no difference was noted for these cases, which had a methane number between 56 and 62. Such a low MN would have caused knock for the same engine running on natural gas with no added hydrogen [45]. This indicates that the methane number alone cannot tell the tendency of knock and the gas composition seems to have an impact because hydrogen speeds-up the combustion and there is less time for knock to occur as it happens after a certain delay. Even the ignition timing retarded by a few degrees at 90% load when hydrogen had been added, which also can have increased the knock resistance.

The Wobbe index and methane number restrictions set by Euromot are based on optimal performance of gas appliances, including safety, energy efficiency, and emissions [32]. In the Euromot position paper [32], it is also stated that up to 20 vol-% hydrogen is accepted if all other technical requirements are met. Among the conducted test runs, 15 mol-% hydrogen was the maximum level which could be added to comply with Euromot's limits. The Wobbe index is not as sensitive to hydrogen as the MN, especially if the NG contains higher hydrocarbons which was the case in the third test series. In this series, the WI was higher for all cases compared to the first and second series when 25 mol-% hydrogen had been mixed into natural gas. On the other hand, the MN limit set by Euromot was not met at any of the measurement points in the third test series and for Case 4, the methane number was as low as 56 and the Wobbe index 47.9 MJ/m^3. No knock was observed though, and the engine worked well which is the target of Euromot's limitations.

The results from the experimental study show that the engine can run on 25 mol-% hydrogen with good performance although the Wobbe index and methane number are not met according to Euromot's requirements. In the future, hydrogen-natural gas mixtures will become more common in the European natural gas grid [26] and this is something that should be taken into consideration when calculating the methane number of a H_2-NG mixture, since a low methane number does not automatically mean that the engine will knock. For example, a deviation in the MN and WI requirements could be made if the fuel gas contains a certain amount of hydrogen to accept these kinds of blends and the hydrogen level would also be good to inform. When the engine was run at low methane numbers, the load was only 90% to prevent a too high pressure in the cylinders. Tests at 100% engine load would be interesting to perform to see if knock appears or if the cylinder pressure raises above the design pressure. Therefore, future studies of low methane number tests are needed to fully understand the knock versus methane number relationship with hydrogen mixtures.

4. Conclusion

The increasing average temperature in the world, resulting in more abnormal weather and natural disasters has led to a growing interest in the hydrogen economy. Hydrogen is the most common element in the earth, and it can be used both as an energy carrier and as a fuel. No carbon dioxide is formed when hydrogen is burnt, which is one of the main reasons why engine manufacturers want to start using it as a fuel for internal combustion engines. To develop these kinds of engines, most focus has been to add a small amount of hydrogen into natural gas which does not require any major changes on the existing engines. In this work, an experimental study was executed to investigate the performance of a SI-engine fueled with hydrogen-natural gas mixtures. The methane number and Wobbe index were calculated for each gas composition and compared to the requirements set by Euromot, which is a MN higher than 70.0 and a Wobbe index between 49.0 and 52.7 MJ/m^3.

Three test series were accomplished, where the ignition timing was kept constant in the first test series, and it was adjusted in the second and third series. The same gas composition was used in the two first test series and 0-25 mol-% hydrogen was mixed with natural gas. In the third test series, the methane number of the natural gas was first lowered to 76, 70, and 65 by adding propane, whereafter 25 mol-% hydrogen was blended into these gas compositions. To fulfil Euromot's limitations, a maximum level of 15 mol-% hydrogen can be added into natural gas to assure that an optimal performance of the engine can be achieved. When more hydrogen was mixed into the NG, the methane number and Wobbe index became out of range in the first and second test series. In the third series with low MNs, the Wobbe index was still within the boundaries, except for the case with the lowest methane number of 56. If this gas blend would have consisted of mainly hydrocarbons and no added hydrogen, the engine would have knocked. During the performed test series, no knock was observed, and the engine performed well in all cases. However, the third test series was conducted at 90% engine load to limit that the cylinder pressure increased too much since a higher hydrogen level raises the pressure in the cylinder.

Looking at the efficiency, it was noted that with a higher hydrogen content the efficiency increased due to hydrogen's fast laminar flame speed which leads to a faster combustion. When a constant ignition timing was used the efficiency raised more than when the ignition timing was changing. The component temperature was though increasing with a higher hydrogen content and constant ignition timing, where a higher temperature can cause hot spots and lead to pre-ignition. Therefore, it is preferable to change the ignition timing when running at hydrogen-natural gas mixtures because with this setting the component temperature can be kept at a moderate level. It was also observed that a quicker and more complete combustion resulted in reduced hydrocarbon and carbon monoxide emissions, as well as carbon dioxide since the total carbon content is less in the gas mixture.

The results from the experimental study were positive and it showed that a low methane number does not automatically lead to engine knock for a gas containing hydrogen. If hydrogen will be injected into the natural gas grid in the future, an additional condition to the MN can be required such as the hydrogen level. This to inform the consumers if the gas is applicable for their needs. Another alternative is to develop the methane number calculation in the way that it can also work for certain quantity ranges of hydrogen.

Declaration of competing interest

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

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