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# Influence of hydrogen addition on performance and ecological parameters of a spark-ignition internal combustion engine at part load typical for urban traffic

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## ABSTRACT

The presented research was conducted in order to determine the effect of hydrogen as an addition to the air-fuel mixture supplying a spark-ignition internal combustion engine. To carry out the tests, slight modifications were made to the engine structure, consisting in enabling the use of the necessary measuring equipment and adapting the engine to perform tests on the test stand. The applied modifications made it possible to measure the performance parameters generated by the engine, as well as to determine the composition of the emitted exhaust gases. The tests were carried out for a gasoline-powered engine, for a gasoline-powered engine using external exhaust gas recirculation (EGR) and for an engine fueled with gasoline with the addition of hydrogen and using external exhaust gas recirculation (EGR). In order to illustrate the results, they were summarized basing on a series of tests performed, and the effect of exhaust gas recirculation, hydrogen addition and a combination of exhaust gas recirculation and hydrogen addition on the performance and ecological parameters of the tested engine was determined. The conducted research and the obtained conclusions allowed for an unequivocal determination of the legitimacy of using hydrogen as a fuel additive for aconventional spark-ignition internal combustion engine in terms of utility and ecology.

**Keywords:** spark-ignition engine, hydrogen, EGR, exhaust gases.

## INTRODUCTION

When analyzing the development of the automotive industry, it is worth mentioning that the fundamental share of motor vehicles, and in particular motor vehicles, in both passenger and freight transport. The invention of the combustion engine initiated the development of this branch of science [1]. As a result, the spark-ignition combustion engine was also invented [2]. On their basis, the first car was invented and the automotive industry developed dynamically [3]. In modern terms, cars are used on a huge scale, and the everyday functioning of society depends on them to a significant extent through public transport, cargo transport, the passenger and freight transport services sector and private cars. It is estimated that there are less than 1.5 billion cars currently in use, and about half of them are powered by spark-ignition engines [4]. Unfortunately, the performance parameters of car engines are constantly deteriorating, affecting both their performance and ecological parameters [5]. There is a loss of efficiency of the engines in use, for example due to their mechanical wear, which leads to a deterioration of their operational and ecological parameters. These parameters, especially ecological ones, are the basis for classifying engines according to their impact on the environment (exhaust emissions). In the face of the scale resulting from the enormity of vehicles traveling every day on roads located all over the world, limiting the negative impact of vehicles on the environment, as well as reducing the consumption of conventional fuels such as diesel oil or gasoline, is a constantly present problem. In view of the above, it is fully justified to look for solutions that will enable a positive impact on each of the above-mentioned parameters (performance and ecological), and a simultaneous positive impact on both the ecological and operational parameters of a spark-ignition combustion engine. Current research shows trends regarding hydrogen combustion systems for use in combustion engines and the introduction of a pre-chamber to improve the parameters of the combustion process [6]. Other studies allow the conclusion that adding hydrogen to the mixture powering a spark-ignition petrol engine results in a significant reduction in CO (carbon monoxide) emissions and an increase in engine efficiency by up to approximately 10% [7]. However, when hydrogen is added to combustion, NO (nitrogen oxides) emissions may increase [8]. When analyzing combustion processes using hydrogen, the expected effects lead to a decrease in the emission of all exhaust components except NO, but it is possible to test this increase depending on the amount of hydrogen [9]. With the appropriate selection of the amount of hydrogen, it is possible to reduce exhaust emissions and thus increase engine efficiency by approximately 4% [10]. Currently, there are many solutions regarding the use of hydrogen as a fuel in new engines, but existing power units are still in use [11]. In these processes, it is important to properly spray the added substances to enable their proper combustion in the engine cylinder [12]. The use of other types of additives to the fuel mixture, e.g. ethanol, leads to a reduction in emissions of harmful exhaust gas components, but NO is still a problem [13]. It should be noted, however, that the use of ethanol leads to a more significant increase in the overall efficiency of the engine, but at the same time it leads to an increase in emissions of some exhaust gas components [14].

Considering the increasingly widespread trends in fueling combustion engines with hydrogen, it is justified to choose the presented direction of research. It should be noted that, among the commonly used spark-ignition engines, current development trends have resulted in the entry into the area of application of single-fuel combustion engines powered by hydrogen. The possibility of using fuel additives in the form of fueling a mixture of gasoline and hydrogen in gasoline engines is currently treated to a largely marginal extent, and it should be mentioned that the possibility of partially fueling currently used engines with the addition of hydrogen without the need to introduce changes in the design of the drive units themselves may prove to be an excellent solution enabling smoothing the process of replacing gasoline engines with hydrogen engines with a gradual, rather than abrupt, transition to the latter fuel. In this research study, it was decided to use an additional factor influencing the application of NO emissions. This factor was intended to reduce the impact of the change in combustion rate caused by the addition of hydrogen on NO emissions [15, 16]. Given the advancement of the design of modern spark ignition (SI) engines, it is reasonable to consider the impact of the addition of hydrogen to the fuel-air mixture on the operational and ecological parameters, the impact of the use of EGR (Exhaust Gas Recirculation) and the combination of both elements and determine whether their combination results in a synergy effect [17]. After the literature analysis, EGR was used as a parameter to reduce the increase in NO. Hydrogen addition for use in an existing engine. The idea of the research was to check the impact of the addition of modified EGR hydrogen on the operational and ecological parameters of this engine without the need to introduce changes to its design.

It should be clearly noted that the use of hydrogen to power combustion engines is economically justified only if the use of hydrogen is a product that is unnecessary from the point of view of the technological processes carried out or comes from renewable energy sources. Hydrogen in industrial terms is identified in different color variations basing on how it is obtained, namely hydrogen produced from conventional energy sources, hydrogen produced from renewable energy sources, hydrogen produced using nuclear energy and atmospheric hydrogen. It should be noted that hydrogen is quite common in the natural environment because it is part of water molecules, but in this condition, it cannot be used as an engine fuel. The following types of hydrogen are distinguished [18]:

- black hydrogen – produced in the process of gasification of a conventional energy source such as hard coal,
- brown hydrogen – produced in the gasification process of a conventional energy source such as brown coal,
- gray hydrogen – produced in the methane gas reforming process,

- blue hydrogen – produced in the process of methane gas reforming or coal gasification combined with the capture of carbon dioxide emitted into the environment,
- yellow hydrogen – produced in the electrolysis process powered by solar energy,
- green hydrogen – produced in the electrolysis process powered by renewable energy sources other than solar energy,
- turquoise hydrogen – produced in the methane pyrolysis process, which enables the use of renewable energy sources,
- red, purple or pink hydrogen produced in the electrolysis process powered by energy generated from nuclear fuels.

It should be noted that in gasoline-powered combustion engines it is possible to use hydrogen in the form of both high-purity gas (without pollutants) as well as gas containing certain admixtures, which is not possible in the case of hydrogen fuel cells requiring gas with at most a residual amount of pollution [19, 20]. Therefore, hydrogen from any of the sources listed above can be used in spark ignition engines, regardless of its degree of purity [21].

## METHODS

The research described later in the article was carried out on a specially prepared research engine. A spark-ignition internal combustion engine was used for the tests. It was modernized for use as a research engine. The engine consisted of a cylinder head used in 169A4000 engines serially installed in Fiat Panda II cars (1.2 8V engine) in the version with variable valve timing. The research engine uses the engine block and crankshaft of the 350A1000 engine as standard in Fiat Grande Punto engines (1.4 8V engine), also in the version with variable valve timing. In order to carry out the tests concerning both the engine's ecological parameters and its operational parameters, an external exhaust gas recirculation system was additionally used, enabling the supply of exhaust gases to the inlet manifold of the tested engine. The engine on the test stand, prepared for testing, is shown in the Figure 1.

To measure the operational and ecological parameters of the engine, it was placed on a test stand equipped with equipment enabling real-time measurement of the following parameters:

- rotational speed of the engine crankshaft,
- torque generated by the engine,
- exhaust gas composition in the engine exhaust manifold,
- exhaust gas composition in the intake manifold using EGR,
- gasoline consumption,
- hydrogen consumption,
- pressure indicated in the combustion chamber,
- ignition timing.

The initially determined and adopted rotational speed was set using the engine control system. The torque generated by the engine was measured using the AMX-200 brake. The brake enabled continuous measurement of the generated torque, and its cooling system was based on liquid cooling. The exhaust gas composition was measured using two independently operating exhaust gas

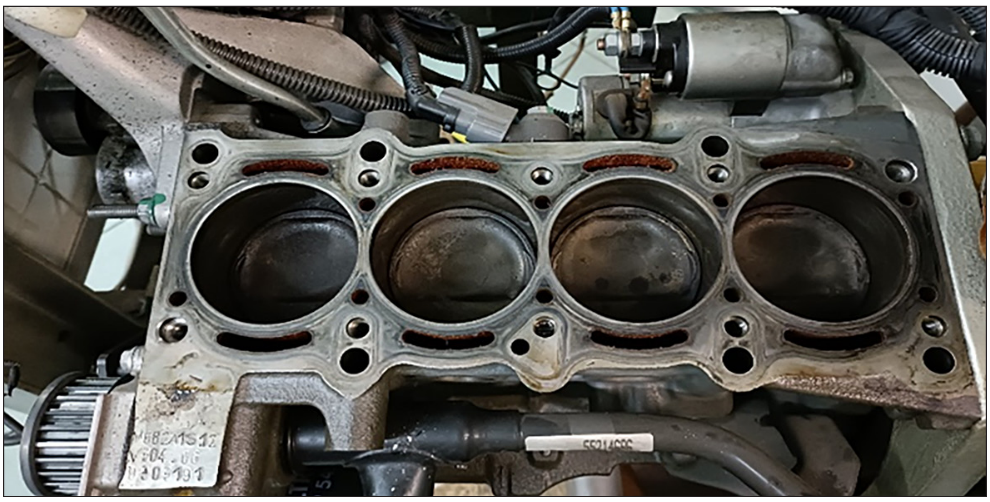

**Figure 1.** Tested spark ignition engine (during the construction of the test stand – engine without cylinder head)

analyzers, one of which was used for measurement in the exhaust manifold and the other in the intake manifold (using EGR). The TWC (three way catalyst) was used in the exhaust gas discharge system. Gasoline consumption was measured in terms of its mass loss when the engine was running in given conditions, while hydrogen consumption was measured by measuring the change in gas pressure in the pressure tank, considering the temperature of the tank's outer surface. Temperature-corrected hydrogen mass measurement was used. During the measurements, the temperature was kept as constant as possible, which allowed the measurement uncertainty to be minimized to a value that did not affect further analyses. The measurement of the pressure indicated inside the cylinder was made using an Optrand pressure sensor, taking into account the positioning of the engine crankshaft position angle resulting from the readings of the encoder enabling the identification of a change in the engine crankshaft position angle every 1° (360 pulses/revolution) and with the identification of a full revolution (1 pulse/revolution). The test stand where the research was carried out is shown in Figure 2. Exhaust gases taken after the TWC were used due to their greater neutrality compared to those before the catalytic converter. Additionally, collecting exhaust gases after the catalytic converter makes it possible to eliminate the impact of higher exhaust gas pressure in the case of higher loads, and thus allows for expansion of research in the future. The diagram of the measurement system used is shown in the Figure 3.

During the measurements, a constant crankshaft speed of the tested engine was set at 2360 ± 10 rpm and a constant throttle opening angle of 15% was determined. The measurements were performed in several steady-state engine operating conditions using the following modifiers:
- engine powered only by gasoline,
- engine powered by gasoline with a little amount of hydrogen added,
- engine powered by gasoline with a large amount of hydrogen added,
- gasoline-powered engine with a little amount of hydrogen and EGR,
- gasoline-powered engine with a large amount of hydrogen and EGR.

Little amount of hydrogen is less than 1% of the mass of the fuel mixture and large amount of hydrogen added it is 1–2% of the mass of the fuel mixture. For each measurement, the values necessary to determine the engine's performance parameters (torque and rotational speed) and ecological parameters (exhaust gas composition) were recorded. Additionally, pressure measurements were made to enable preliminary identification of the cause of differences in individual parameters occurring between the measurement

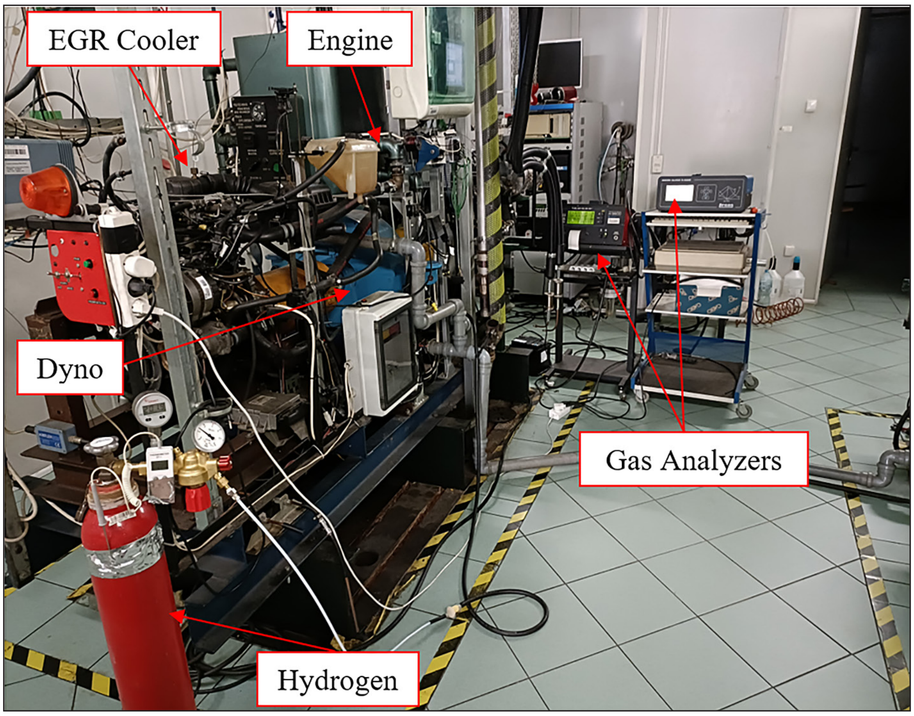


**Figure 2.** Test stand

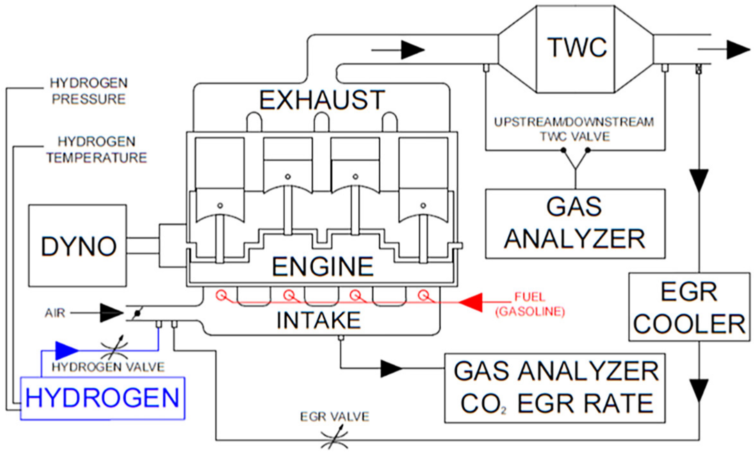


**Figure 3.** The diagram of the measurement system

series. The obtained results are presented later in the article. The rotational speed was measured by the engine control system with an accuracy of 1 rpm and torque was measured using an AMX-200 brake with an accuracy of 0.1 Nm. The exhaust gas composition was measured using a Radiotechnika AI9600 exhaust gas analyzer. Its measurement accuracy is 0.01% for CO and $O_2$, 0.1% for $CO_2$ and 1 PPM for HC (hydrocarbons) and NO. The measurements were carried out in continuous mode, they constantly analyze the measured parameters, and the consumption of gasoline and hydrogen were determined as average values from the entire measurement with an accuracy of 0.0001 g/s. Measurements were carried out as several-minute trials with average values during the entire measurement. The ignition advance angle was manually selected to achieve the highest torque for the selected rotational speed range (2360 ± 10 rpm). The engine speed was selected due to the maximum torque generated by the engine in this range. Such engine operation is typical of a small passenger car driving in city traffic. The excess air ratio was constantly monitored during the measurements and kept within the range (before TWC) of 1.007 ± 0.002.

## RESULTS AND DISCUSSION

As a result of measurements carried out on an engine powered only by gasoline and without the use of EGR, maintaining the engine speed of 2360±10 rpm and opening the throttle at 15%, the torque generated by the engine was 33.8 Nm. During this measurement, the average gasoline consumption was 0.7189 g/s. The ignition timing for this measurement series was 30° before the piston's upper return position. For each test, the composition of exhaust gases collected behind the TWC is presented. The values in the table are the accuracy indicated by the analyzer.

In the next step, analogous values were measured, but the engine was fueled with gasoline with the addition of a little amount of hydrogen. At constant rotational speed and throttle opening as in the previous measurement, a torque of 34.2 Nm was obtained. The average gasoline consumption was 0.7198 g/s and the average hydrogen consumption was 0.0067 g/s. The ignition advance angle did not change in comparison to the first measurement series.

To measure analogous values, but with the engine powered by gasoline with the addition of a large amount of hydrogen and with the same rotational speed and throttle opening angle, a torque of 34.2 Nm was obtained. The average gasoline consumption was 0.7000 g/s and the average hydrogen consumption was 0.0107 g/s. In terms of obtaining the same torque value as in the previous measurement, it should be noted that the ignition advance angle has changed, which in this case was 26°.

In the case of measurements with a little and large amount of hydrogen used as a gasoline additive and the simultaneous use of EGR, as well as maintaining a rotational speed of 2360 ±10 rpm and a throttle opening of 15%, a torque of 33.8 Nm and 34.0 Nm was obtained, respectively, at a little and a large amount of added hydrogen along with EGR. In the case of a little amount of added hydrogen and EGR, the average gasoline consumption was 0.6871 g/s and the average hydrogen consumption was 0.0055 g/s.

For the measurement with the addition of a large amount of hydrogen together with EGR, the average gasoline consumption was 0.6561 g/s and the average hydrogen consumption was 0.0118 g/s. The ignition timing was 48° for the addition of a little amount of hydrogen and EGR and 40° for the addition of a large amount of hydrogen and EGR. The composition of exhaust gases for each measurement is presented in Table 1.

To determine the percentage of EGR, the following relationship was used [22, 23]:

$$X_{EGR} = \frac{CO_{2i}}{CO_{2o} - CO_{2i}} \cdot 100 \quad (1)$$

where: $CO_{2i}$ – carbon dioxide in the intake of manifold, $CO_{2o}$ – carbon dioxide in the manifold outlet.

The $CO_{2i}$ and $CO_{2o}$ parameters were the carbon dioxide content in the exhaust gases in the intake manifold and exhaust manifold, respectively, using exhaust gas recirculation. During the measurements, the EGR level was kept constant, which was set at 20% and determined based on continuous comparison of the indications of these parameters on exhaust gas analyzers.

Taking into account the variable value of the ignition advance angle and, therefore, a certain unreliability of the torque generated by the engine during subsequent measurement series, a comparison of the efficiency value achieved by the engine during each test was used. For this purpose, based on the average consumption of gasoline or gasoline and hydrogen for each measurement, the work generated by the combustion of designated masses of each fuel was determined. For this purpose, the product of the mass of a given fuel and its calorific value was used. The calorific values were assumed to be 43 MJ/kg for gasoline and 120 MJ/kg for hydrogen. In order to determine the effective power for each of the measurements, the following relationship was used:

$$P = \frac{M \cdot n}{9549} \quad (2)$$

where: $M$ – torque, $n$ – rotation speed.

For the above relationship, the torque value for each measurement was assumed as M, and the engine crankshaft rotational speed of 2360 ±10 rpm was assumed as n. The obtained work and effective engine power values are presented in Table 2. Basing on the presented relationships, the overall engine efficiency was determined for each measurement series. To determine the efficiency, the following relationship was used:

$$\eta = \frac{P}{W} \cdot 100 \quad (3)$$

where: $P$ – power, $W$ – work.

The obtained values of engine efficiency for each of the measurements performed are presented in Table 3.

**Table 1.** Composition of exhaust gases for each measurement

| Parameter | Unit | Value (value relative to the value for gasoline [%] | | | | |
|---|---|---|---|---|---|---|
| | | Gasoline (100.00) | Gasoline + little hydrogen | Gasoline + lots of hydrogen | Gasoline + little hydrogen + EGR | Gasoline + lots of hydrogen + EGR |
| CO | % | 0.90 | 0.84 (93.33) | 0.87 (96.67) | 0.79 (87.78) | 0.7 (77.78) |
| HC | PPM | 99 | 96 (96.97) | 87 (87.88) | 225 (227.27) | 176 (177.78) |
| NO | PPM | 2218 | 2430 (109.56) | 2315 (104.37) | 243 (10.96) | 250 (11.27) |
| $CO_2$ | % | 13.9 | 13.6 (97.84) | 13.0 (93.53) | 16.3 (117.27) | 13.0 (93.53) |
| $O_2$ | % | 0.79 | 0.79 (100.00) | 0.76 (96.20) | 0.82 (103.80) | 0.75 (94.94) |

**Table 2.** The work and effective engine power value for each measurement

| Measurement | Work – W [kW] | Power – P [kW] |
|---|---|---|
| Gasoline | 32.29 | 8.36 |
| Gasoline + little hydrogen | 31.76 | 8.47 |
| Gasoline + lots of hydrogen | 31.38 | 8.42 |
| Gasoline + little hydrogen + EGR | 30.21 | 8.36 |
| Gasoline + lots of hydrogen + EGR | 29.66 | 8.41 |

**Table 3.** Engine efficiency for each measurement

| Measurement | *η* [%] (efficiency change [%]) | Increase relative to the initial value [%] |
|---|---|---|
| Gasoline | 25.88 (+0,00) | - |
| Gasoline + little hydrogen | 26.68 (+0.80) | 3.09 |
| Gasoline + lots of hydrogen | 26.83 (+0.95) | 3.67 |
| Gasoline + little hydrogen + EGR | 27.66 (+1.78) | 6.88 |
| Gasoline + lots of hydrogen + EGR | 28.34 (+2.46) | 9.50 |

In order to present the results regarding ecological parameters obtained during the measurements, they were compared and differentiated from the measurement carried out for an engine powered only by gasoline. A summary of the results in graphical form is presented in Figure 4, where semi-transparent blue is only gasoline, orange is gasoline with a little amount of hydrogen, gray - gasoline with a large amount of hydrogen, yellow - is gasoline with a little amount of hydrogen and EGR and blue is gasoline a large amount of hydrogen and EGR.

The conducted research allows for a clear indication that the addition of hydrogen to the fuel-air mixture powering a spark ignition engine and the use of EGR have a positive impact on the operational and ecological parameters of this engine. The use of hydrogen as an additive to gasoline allows for greater overall engine efficiency. This fact is justified by the visible change in the ignition advance angle, which decreases with the increase in the amount of hydrogen added to gasoline. This change allows us to conclude that the average combustion speed of the mixture in the cylinder increases with the increase in the amount of hydrogen added to it. During the tests, an increase in the overall efficiency of the engine was achieved by 3.67% compared to its efficiency when powered only by gasoline (relative to the initial value). The use of EGR allowed for a more noticeable impact on the overall efficiency of the tested engine, which increased by 9.50% compared to the initial efficiency. The test stand on which the measurements were carried out after appropriate preparation of the measuring equipment will additionally allow for determining the impact of the addition of hydrogen on the value of the indicated pressure in the cylinder, but this aspect will be included in further stages of thematically related research work.

The use of hydrogen additives in gasoline also affects the composition of exhaust gases emitted by the tested engine. In the case of the addition of hydrogen, a slight decrease in the amount of CO in the exhaust gas was observed, reaching approximately 7%. During the measurements, a decrease in the amount of HC in the exhaust gas was also recorded, increasing with the amount of hydrogen added and reaching up to 12% with a larger amount of gas added. A slight increase in the amount of NO was observed, reaching approximately 10%, and a slight decrease in $CO_2$ and $O_2$ (oxygen), reaching no more than 6% and 4%, respectively.

After adding hydrogen and EGR simultaneously, a mutually increased impact of both factors on the exhaust gas composition was achieved. With a little amount of hydrogen and EGR,

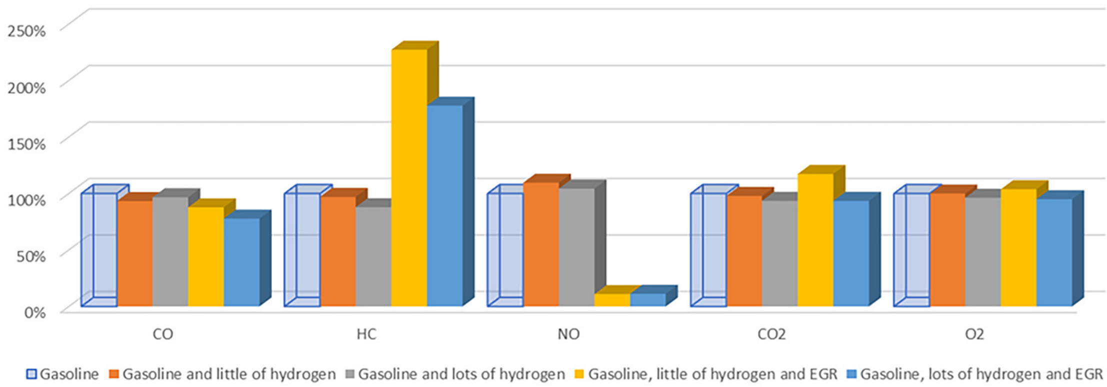


**Figure 4.** Exhaust gas composition for each measurement

a decrease in the amount of CO in exhaust gases by 12%, an increase in the amount of HC by 127%, a significant decrease in NO to only 11%, an increase in the amount of CO2 by 17% and an increase in the amount of $O_2$ by 4%. When using a larger amount of hydrogen in combination with EGR, a partially variable trend in the effect on individual exhaust gas components was observed. Compared to the amount of CO in the exhaust gases, hydrogen and EGR caused a total greater decrease in the amount of this component in the exhaust gases by 22%. The amount of HC in the exhaust gas increased by EGR was partially reduced by hydrogen and increased by 78%. The NO content in exhaust gases remained at a similar level, dropping to 11%. The addition of a larger amount of hydrogen resulted in a decrease in the amount of $CO_2$ and $O_2$ in the exhaust gases to 94% and 95%, respectively, compared to the reference value, i.e. measurement for an engine powered only by gasoline.

The presented results allow for a clear statement that the combined effect of the addition of hydrogen to the fuel-air mixture and the use of EGR allows for a more favorable impact on the operational and ecological parameters of the spark ignition engine. It should be noted that a larger amount of added hydrogen allows for more significant differences that have a positive impact on both operational and ecological parameters.

## CONCLUSIONS

The addition of hydrogen to the air-fuel mixture powering a spark-ignition engine allows it to increase its overall efficiency by approximately 4%. Similar results were obtained in studies by other authors [10, 24]. Combining the addition of hydrogen with EGR allows for a synergistic effect combining both parameters and leads to an increase in efficiency by up to less than 10%. A larger amount of added hydrogen allows for a greater increase in efficiency. The use of a combination of hydrogen addition and EGR allowed to reduce the CO content in the exhaust gases by up to 22%, while the use of only the hydrogen addition allowed to reduce the CO content in the exhaust gases by almost 7%. On this basis, it should be concluded that the addition of hydrogen in combination with EGR allows for a reduction in the CO content in the exhaust gases. The combination of these factors led to an increase in the amount of HC in the exhaust gases, with EGR leading to a significant increase in HC in the exhaust gases, and the addition of hydrogen visibly limits this increase from 127% with a little amount of hydrogen to 78% with a larger amount of hydrogen added to gasoline. The amount of NO in exhaust gases was reduced by up to 89% using hydrogen and EGR, with EGR having a significant impact on this parameter. With a larger amount of added hydrogen and the use of EGR, the CO and $O_2$ content in the exhaust gases was reduced, but these values decreased by no more than 6%. The obtained results do not differ from the research of other authors [24, 25].

The result of the decrease in the content of these exhaust gas components is the addition of hydrogen, which compensates for their increase caused using EGR. The addition of hydrogen in combination with EGR leads to an increase in the operational and ecological parameters of the spark ignition combustion engine. For the tests carried out in the described case, a larger amount of added hydrogen leads to an increased positive impact on the results achieved. Research work aimed at determining the causes of the observed phenomena is a developing research topic currently being carried out in this direction.

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