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Research Article

INVESTIGATION OF COMBUSTION, PERFORMANCE AND EMISSION CHARACTERISTICS OF SPARK IGNITION ENGINE FUELLED WITH BUTHANOL – GASOLINE MIXTURE AND A HYDROGEN ENRICHED AIR

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ABSTRACT

In this study, spark ignition engine fuelled with buthanol-gasoline mixture and a hydrogen-enriched air was investigated. Engine performance, emissions and combustion characteristics were investigated with different buthanol (10% and 20% by volume) gasoline mixtures and additionally supplied oxygen and hydrogen (HHO) gas mixture (3.6 l/min) in the sucked air. Hydrogen, which is in the HHO gas, improves gasoline and gasoline-buthanol mixture combustion, increases indicated pressure during combustion phase and decreases effective specific fuel consumption. Buthanol addition decreases the rate of heat release, the combustion temperature and pressure are lower which have an influence on lower nitrous oxide (NO_x) emission in exhaust gases. Buthanol lowers hydrocarbon (HC) formation, but it increases carbon monoxide (CO) concentration and fuel consumption. Combustion process analysis was carried out using AVL BOOST software. Experimental research and combustion process numerical simulation showed that using balanced buthanol and hydrogen addition, optimal efficient and ecological parameters could be achieved when engine is working with optimal spark timing, as it would work on gasoline fuel.

Keywords: buthanol, hydrogen, spark timing, simulation

INTRODUCTION

Environmental pollution is currently one of the biggest problems in the world. Transport is a significant contributor to this problem, therefore, most of the scientific studies are carried out in order to research next generation fuel by modifying ordinary internal combustion engines or developing new ones in order to use renewable energy resources which cause less damage to the environment. The use of renewable resources also produces economic benefits, as most countries are forced to export their raw materials and renewable resources can be produced within the country.

European Union's transport White Paper pays a lot of attention to the development of renewable clean energy, particularly the development of hydrogen. It also notes that hydrogen is not an energy source, but a good energy (including renewable) accumulator, therefore, its wider use is the main objective of each country [1].

Hydrogen production process is not yet sufficiently developed, as considerable energy losses are suffered during the process [2], therefore, it is still rather expensive to use pure hydrogen. However, unique properties of hydrogen, even when it is supplied in small quantities, improve the combustion process in an internal combustion engine. This feature can be used when using different fuel mixtures which, even though they are renewable, cause combustion process deterioration. For example, when using gasoline and butanol mixtures, engine combustion process becomes noticeably slower [3, 4], and hydrogen additive could eliminate this deficiency.

The aim of this work is to research the combustion process and the performance and emission characteristics of a spark ignition engine using gasoline-butanol mixtures and an oxygen and hydrogen (HHO) gas mixture additionally supplied into the intake air.

LITERATURE REVIEW

Small supply of H_2 into the engine's intake air enables the engine to operate with a much leaner air-fuel ratio, thus slightly reducing NO_x, HC and CO, but increasing CO_2 concentration in exhaust gas [5, 6].

By increasing the amount of hydrogen from 5% to 25% (in volume), and with a steady amount of gasoline, the indicated pressure and power of the engine increase due to the improvement of the combustion process [6, 7]. The reason for the power increase is the increased relative amount of hydrogen in fuel, in terms of carbon, as well as its high calorific value. The use of hydrogen in the engine increases flame spread rate and flame front, therefore, even at medium engine speeds, hydrogen molecules in the cylinder form a faster igniting and burning combustible mixture, compared to gasoline, as hydrogen ignition temperature is significantly lower, and the flame spread rate is higher.

When analysing the harmful compounds of exhaust gas, it is noticed that hydrogen content produces a positive effect to the HC emission. The smallest HC content is noticed when supplying 25% of hydrogen without exceeding 3000 min^{-1} speed. NO_x concentration increased in exhaust gas when increasing hydrogen concentration in the combustible mixture, as, during the more efficient hydrogen gas oxidation in the combustion chamber, higher heat content is produced improving the NO_x forming conditions. When increasing hydrogen concentration in the combustible mixture, CO emission decreased due to high temperature in the combustion chamber [7].

There is a noticeable decrease in power when mixing gasoline with biobutanol and using the mixture in the spark ignition engine, when compared to the use of pure gasoline. The reason for the decrease in power is lower calorific value of biobutanol, compared to gasoline (Table 1). Combustion is prolonged when using the gasoline-biobutanol fuel mixture, therefore it is necessary to advance the ignition advance angle in order to achieve optimal combustion [8].

The research of some scientists show that lower HC concentration in exhaust gas can be noticed during the combustion of the gasoline-biobutanol mixture, when compared to the combustion of pure gasoline. This can be explained by a shorter biobutanol molecular carbon chain. Research have also shown that, when increasing biobutanol content in gasoline, NO_x emission decreases by a quarter due to decreased lower calorific value of the mixture, whereas CO emission increases, as temperatures higher than 1000^oC are necessary for CO particles to be able to oxidise to CO_2 [9, 10].

Wang and others (2011) have determined that hydrogen – oxygen mixture (HHO) additive increases engine efficiency and average indicated pressure, compared to the engine running on pure gasoline. HHO additive extends the economic performance limits of an engine, contributes to the decrease in HC and CO concentration, but increases NO_x emission [12].

Table 1. Fuel properties [2, 11]

Parameter		Gasoline	Biobuthanol	Hydrogen
Chemical formula		$C_4 \ldots C_{12}$	C_4H_9OH	H_2
Density (kg/m^3)		~750	~810	~0.09
Lower heating value, MJ/kg		44	33	120
Octane number		95...98	90	130
Elemental composition %	C	86.500	65	-
	H_2	13.475	13.5	100
	O_2	0.025	21.5	-
Stoichiometric AFR		14.6	11.2	34.5
Auto ignition temperature, °C		260...460	343	585

Table 2. Technical data of engine

Parameter	Value
Type	HR 16DE
Number of cylinders	4
Bore, mm	78
Stroke, mm	83.6
Displacement, cm^3	1598
Power, kW (min^{-1})	84 (6000)
Torque, Nm (min^{-1})	156 (4400)
Compression ratio	10.7
Number of valves in cylinder	4

Table 3. Measurement data of AVL DiCom 4000

Parameter	Measurement Range	Resolution
NO_x	0...5000 ppm Vol	1 ppm
HC	0...20000 ppm Vol	1 ppm
CO	0...10 % Vol	0.01 % Vol
CO_2	0...20 % Vol	0.1 % Vol
O_2	0…25 % Vol	0.01 % Vol

RESEARCH METHODOLOGY

Nissan Qashqai HR 16DE spark ignition (SI) engine, controlled with a programmable control unit *MoTeC M800*, was used for the experimental research. The technical specifications of the engine are provided in Table 2.

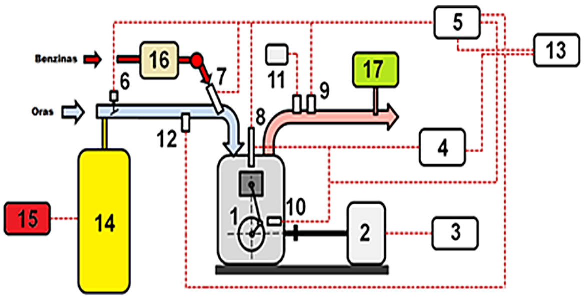

Fig. 1. Laboratory equipment scheme: 1 – SI engine Nissan HR 16DE; 2 – engine load stand AMX 200/100; 3 – engine load stand control unit; 4 – indicated pressure measurement equipment AVL DiTEST DPM 800; 5 – engine control unit ECU MoTeC M800; 6 – throttle control servomechanism; 7 – fuel injector; 8 – ignition spark plug with integrated pressure sensor AVL ZI31; 9 – oxygen sensor; 10 – engine crankshaft sensor; 11 – exhaust gas temperature sensor; 12 – air mass meter; 13 – PC computer; 14 – HHO gas equipment; 15 – electrical supply source; 16 – current clamps and multimeter; 17 – fuel tank and fuel consumption measurement equipment AMX 212F; 18 – exhaust gas analyser AVL DiSmoke 4000

Research was carried out using laboratory research equipment whose scheme is provided in Figure 1. Measurement data is transferred to the stand electronic control unit, where engine operating parameters are registered: brake torque (M_B) and crankshaft speed (n, min^{-1}). *AMX 212F* fuel meter is used to determine fuel consumption (B_f, kg/h). *BOSCH HFM 5* air mass flow meter was used to measure the intake air mass (B_{air}, kg/h). By using the *AVL DiTest DPM 800* device and *AVL ZI31-Y7S* piezo sensor, in-cylinder pressure was measured in the engine's cylinder (p, bar).

Exhaust gas emission (CO, CO_2, HC and NO_x concentration) was measured before the catalyst using the *AVL DiCom 4000* exhaust gas analyser. *AVL DiCom 4000* technical specifications are provided in Table 3.

HHO gas is produced through electrolysis by using a 70 V power source, and the generated gas volume (l/min) is controlled by changing the strength of the current. Hydrogen as a fuel additive in the HHO gas composition is supplied through the engine's air intake manifold, where it mixes with the gasoline and biobutanol mixture injected into the manifold, after entering the combustion chamber. Six different fuels (mixtures) were used: gasoline (G), gasoline + 3.6 l/min HHO gas (G+HHO), gasoline + 10% volume biobutanol (G+B10), gasoline + 10% volume biobutanol and HHO (G+B10+HHO), gasoline + 20% volume biobutanol (G+B20), gasoline + 20% volume biobutanol and HHO (G+B20+HHO). Lower calorific values (H_u) of fuel mixtures were calculated by applying the additivity principle (Fig. 2).

Experimental research was carried out by running the engine at different ignition advance angles (Θ), measured according to the crankshaft angle before the top dead centre (°CA

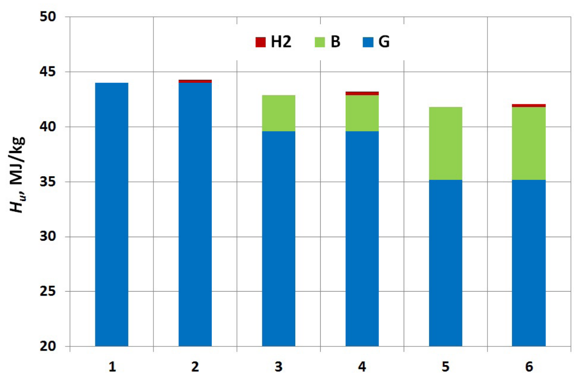

Fig. 2. Lower heating value of fuels: 1 – G; 2 – G+HHO; 3 – G+B10; 4 – G+B10+HHO, 5 – B+B20; 6 – B+B20+HHO

BTDC) when the throttle is opened at 20%, at n = 2000 min^{-1} and with excess air ratio λ = 1, which is ensured by the wideband oxygen sensor.

The combustion process analysis of the selected engine was carried out using the *AVL BOOST* program. A dual-zone combustion model was used in the program [13].

RESEARCH RESULTS AND THEIR ANALYSIS

When the engine is running on gasoline (G), with the throttle opened at 20 %, at n = 2000 min^{-1} and λ = 1, the highest brake torque (M_B = 95.3 Nm) can be reached at Θ = 20°CA BTDC (Fig. 3). By advancing the ignition to Θ = 30°CA BTDC, brake torque decreases to 91.9 Nm, by delaying to Θ = 12°CA BTDC it decreases to 91.1 Nm. When running the engine on G+HHO fuel, maximum 94.9 Nm brake torque can be reached at Θ = 18°CA BTDC. The brake torque decreases by ≈ 0.4%, as HHO gas has low density and this worsens the filling of cylinders [14], however hydrogen accelerates combustion, therefore it is necessary to delay the moment of ignition. When the engine is running on G+B10 and G+B20 fuel, due to lower butanol combustion speed, it is necessary to advance combustion to 22°CA BTDC in order to reach maximum M_B values (94.9 Nm and 95.3 Nm). The optimum ignition advance angle for G+B20+HHO fuel, as well as for gasoline, is Θ = 20°CA BTDC. Higher hydrogen combustion speed compensates slower biobutanol combustion, however the brake torque decreases from 95.3 Nm to 94.6 Nm (≈ 0.7 %) due to lower calorific value of the fuel mixture (Fig. 2) and poorer filling of cylinders, which was influenced by lower HHO density.

When the engine was running on G and when Θ = 22°CA BTDC, the lowest brake specific fuel consumption was obtained (*BSFC* = 238.1 g/kWh) (Fig. 4). When supplying HHO gas and when Θ = 22°CA BTDC, *BSFC* decreased to 237.5 g/kWh. In order to compensate the combustion speed increased by hydrogen, it is necessary to delay the ignition advance angle [15]. By using B+HHO, the thermal energy of fuel is transformed most efficiently into mechanical at Θ = 20°CA BTDC (*BSFC* = 236.8 g/kWh) and brake specific fuel consumption decreases by ≈0.5%. When the engine is running on G+B10%, *BSFC*, compared to G, increases from 238.8 g/kWh to 244.4 g/kWh (≈2.3%) at Θ = 20°CA BTDC. When increasing biobutanol concentration to 20% (B+B20), brake specific fuel consumption increases from 238.8 g/kWh to 250.0 g/kWh (≈4.5%). Higher *BSFC* are achieved due to lower calorific value of biobutanol [16]. When the fuel mixture contains 10% and 20% of biobutanol and when supplying HHO, a decrease in *BCFC* can be noticed accordingly from 244.4 g/kWh to 243 g/kWh (≈0.6% and from 250.0 g/kWh to 249.1 g/kWh (≈0.4%)).

The highest engine efficiency η_e can be reached when the engine is running on G+B20 fuel mixture and, compared to gasoline, increases from 0.343 to 0.345, at Θ = 22°CA BTDC (Fig. 5). When using HHO gas, a decrease in the coefficient of efficiency can be noticed due to higher calorific value of hydrogen. Highest engine efficiency, when using HHO, can be achieved by delaying spark timing to Θ = 18°CA BTDC and reaches 0.343.

When the engine is running on G+B20+HHO mixture, η_e reaches 0.344 and is similar to the efficiency of gasoline when Θ = 20°CA BTDC

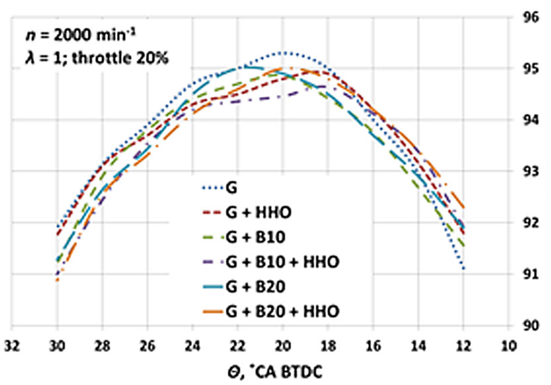

Fig. 3. Engine's brake torque M_B dependence on ignition advance angle Θ and fuel composition

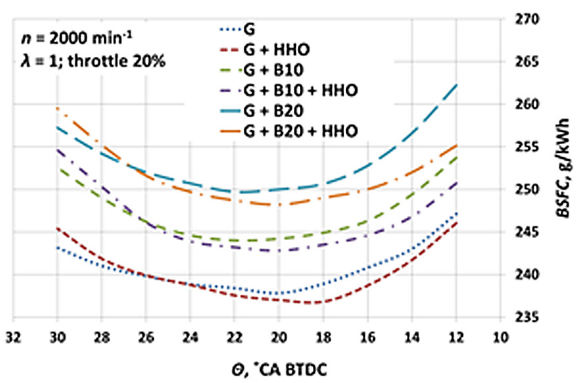

Fig. 4. Brake specific fuel consumption (BSFC) dependence on ignition advance angle Θ and fuel composition

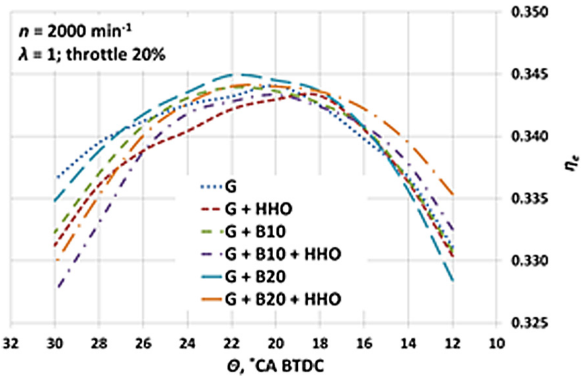

Fig. 5. Engine efficiency η_e dependence on ignition advance angle Θ and fuel composition

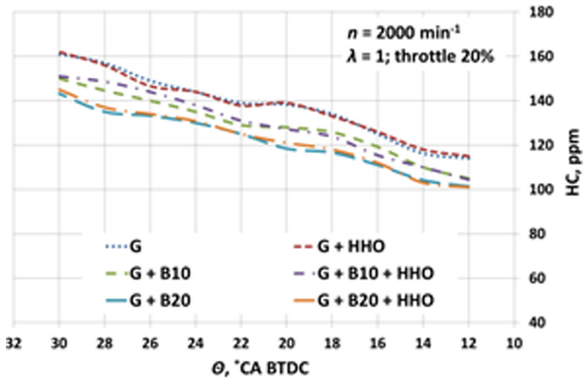

Fig. 7. Dependence of hydrocarbon (HC) concentration in exhaust gas on ignition advance angle Θ and fuel composition

(Fig. 5). HHO gas helps achieve better coefficient of efficiency, as it compensates slower biobutanol combustion. However, when comparing the engine's energy indicators, and when additionally using biobutanol and HHO gas, we can see that changes in the indicators are smaller than variations in measurements, therefore we can only state the change tendencies of these indicators.

When analysing CO concentration in exhaust gas, a negative effect can be observed when additionally using biobutanol and supplying HHO gas (Fig. 6). The highest CO concentration in exhaust gas was recorded during early ignition. CO concentration, when the engine is running on gasoline, is lowest when Θ = 20°CA BTDC and reaches 0.55%, when additionally supplying HHO gas, it increases in the entire advance angle change range and is lowest (0.57%) when Θ = 18°CA BTDC.

After using 10% and 20% biobutanol additive in gasoline, CO emission increases accordingly by 0.6% and 0.7% (up to 1,3 times) Θ = 20°CA BTDC. An increase in CO concentration is determined by lower combustion temperature. In order for the CO to be able to connect the missing oxygen molecule, temperature must be higher than 1000°C [9]. When using a butanol additive, there is a decrease in the lower calorific value of the fuel mixture and combustion temperature, and this increases CO concentration when using biobutanol as a fuel additive. When using HHO gas, there is little change in the CO concentration, because on one hand HHO worsens the filling of cylinders, and on the other hand it improves (catalyses) the combustion process.

In the entire Θ range, when adding biobutanol to gasoline (10% and 20% volume), HC concentration decreases in exhaust gas accordingly by ≈10 ppm (≈8%) and ≈20 ppm (≈14%) (Fig. 7). This can be explained by a simpler molecular structure of biobutanol [9]. HHO gas has little impact on HC concentration, even though hydrogen

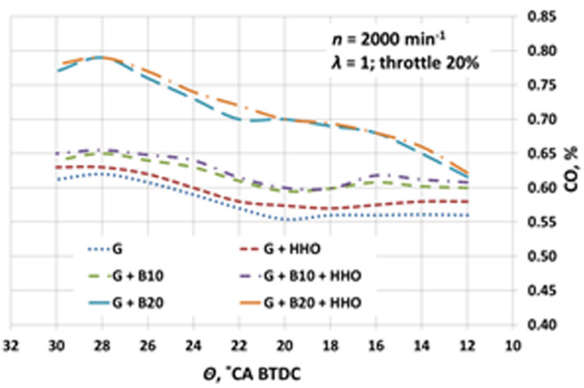

Fig. 6. Dependence of carbon monoxide (CO) concentration in exhaust gas on ignition advance angle Θ and fuel composition

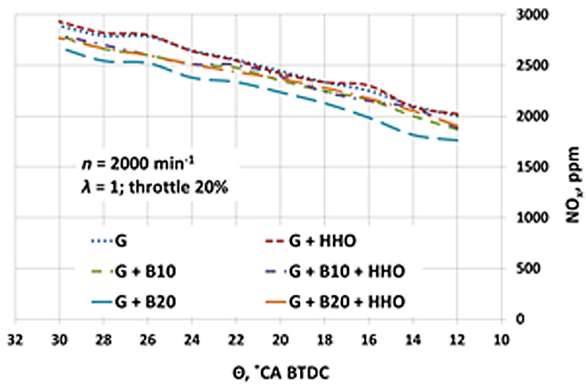

Fig. 8. Dependence of nitrogen oxide (NO_x) concentration in exhaust gas on ignition advance angle Θ and fuel composition

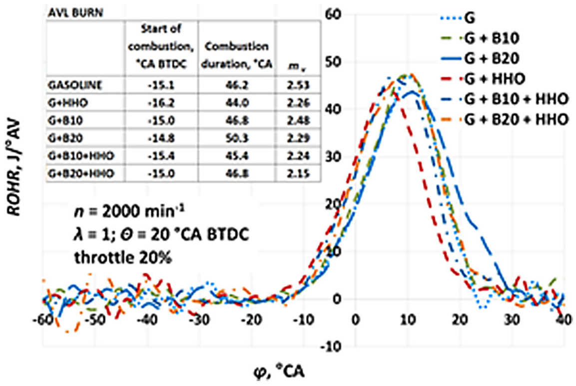

Fig. 9. Dependence of the Rate of Heat Release (ROHR) on different fuel

improves the oxidation of HC compounds, however, due to worse filling of cylinders, combustion temperature decreases.

When increasing the ignition advance angle *Θ*, combustion temperature rises and there is an increase in NO_x emission [16] (Fig. 8). When the engine is running on gasoline and after starting to additionally supply HHO, there is an increase in the NO_x concentration (≈1.5%). This is caused by hydrogen contained in HHO gas, which actively participates in the combustion reactions and increases combustion temperature and pressure (Fig. 9). Largest decrease of NO_x concentration (from 2444 ppm to 2234 ppm (≈8%)) was achieved using G+B20 fuel mixture (*Θ* = 20°CA BTDC), as the specific evaporation heat of biobutanol is higher than gasoline's (biobutanol – 430.3 kJ/l, gasoline – 223.3 kJ/l) [11], whereas the calorific value is lower. HHO gas once again increases NO_x concentration to 2300 ppm.

After carrying out a combustion process analysis with the *AVL BOOST* program, it was found that 20% of biobutanol delays the start of combustion from 15.1°CA BTDC to 14.8°CA BTDC, however HHO gas shortens the fuel combustion delay and combustion starts at 16.2°CA BTDC (Fig. 9). 20% of biobutanol extends the combustion duration from 46.2°CA (G) to 50.3°CA (G + B20), and changes the combustion intensity [17] coefficient *m* from 2.53 to 2.29. This influences slower Rate of Heat Release (*ROHR*) during combustion, lower combustion temperature and maximum pressure. When using HHO additive, the combustion duration of gasoline is shortened to 44°CA, and combustion intensity-coefficient *m* changes to 2.26 – the intensity of combustion increases. When using both biobutanol and HHO additive, hydrogen compensates the change in the combustion indicators influenced by biobutanol, and the fuel mixture's *ROHR* is similar to pure gasoline.

CONCLUSIONS

After carrying out experimental research on a spark ignition engine operating at n = 2000 min^{-1} speed, with the throttle opened at 20%, at λ = 1 and using gasoline, biobutanol (10% and 20% volume) and HHO gas (3,6 l/min) mixtures, and carrying out numerical modeling using the *AVL BOOST* program, it was found that:

1. Due to low density, HHO gas influences the filling of engine cylinders, and the decrease in torque M_B and engine efficiency η_e, however the recorded changes do not exceed the measurement tolerance limits. Hydrogen in the HHO gas increases the combustion speed of the fuel mixture, but not its rate of heat release and, in order to achieve the highest engine efficiency, ignition must be delayed by ≈2°CA (from *Θ* = 20°CA BTDC to *Θ* = 18°CA BTDC).
2. 20% of biobutanol in gasoline slows the fuel mixture's combustion speed and *ROHR*, and ignition must be advanced by ≈2°CA. Compared to gasoline, butanol has lower calorific value and this slightly increases η_e (from 0.344 to 0.343). When using G+B20+HHO fuel mixture, it is not necessary to adjust the ignition advance angle, as slower combustion of the gasoline–biobutanol mixture is accelerated by hydrogen and, in this case, engine efficiency does not change.
3. When increasing biobutanol concentration in the fuel mixture by 20%, CO concentration increases in the exhaust gas by 1.3 times, as the fuel mixture's calorific value and combustion temperature decrease and this worsens the combustion processes. HHO gas additive has little influence on the CO concentration, because on one hand HHO worsens the filling of cylinders, and on the other hand it improves (catalyses) the combustion process.
4. After increasing biobutanol concentration to 20%, HC concentration decreased in exhaust gas accordingly by ≈14% in the entire ignition advance angle change range due to simpler molecular structure of biobutanol. HHO gas has little impact on HC concentration, even though hydrogen improves the oxidation of

HC compounds, however, due to worse filling of cylinders, combustion temperature decreases and combustion becomes worse.

5. The largest decrease (≈8%) of NO_x concentration in exhaust gas was achieved by using G+B20 fuel mixture, as lower calorific value of biobutanol and higher specific evaporation heat decreases the maximum combustion temperature. HHO gas has little influence on NO_x concentration when the engine is running on gasoline, however, when increasing biobutanol concentration in the fuel mixture, hydrogen increases NO_x concentration more intensively, as it improves the combustion process which was worsened by biobutanol and increases *ROHR*.

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