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INVESTIGATION OF THE INFLUENCE OF HYDROGEN ON THE ENERGY PERFORMANCE OF A SPARK IGNITION ENGINE USING GASOLINE AND BIOETHANOL FUEL MIXTURES

Summary. The results of experimental studies of gasoline mixed with 10% bioethanol (E10), bioethanol mixed with 15% gasoline (E85), and hydrogen– oxygen gas (HHO) supplied as an additional fuel are presented in this paper. Research was carried out to determine whether E85 with hydrogen– oxygen gas is feasible for use as a replacement fuel. During the test, a port injection HR16DE spark ignition engine was used. Experiments were carried out at a constant engine speed (*n* = 2000 rpm), throttle opened at 15°, using a stoichiometric mixture $\lambda = 1.0$ and a lean mixture $\lambda = 1.1$. After determining brake torque, fuel consumption data, and energy performance, the results of various fuels were determined. It was found that the highest engine brake torque was developed using E85, but at the same time, fuel consumption increased. E85 yielded the best energy efficiency for a lean mixture ($\lambda = 1.1$). A small amount of HHO gas (~ 0.95% energy) yielded a small positive effect only on using E10 fuel at $\lambda = 1.1$.

1. INTRODUCTION

The first European standard for emissions was set in 1993, and in 1997, the Kyoto Protocol was signed. The actual protocol to reduce pollution levels was signed in Paris in 2016 [1]. With the introduction of the new regulation and the signing of the protocol, the search for alternative, cheap, and less polluting fuels that could replace conventional petrol and diesel began in Europe. Over the last twenty years, use of unsustainable energy sources has been a concern not only in terms of climate change but also energy supply [2]. The production and use of non-polluting electric vehicles are increasingly being promoted, but from a broader ecological perspective, the production and delivery of electric vehicles to the end user still require fossil fuels [3]. Electric cars are still expensive, making them unaffordable for middle-class consumers and those with lower-than-average incomes, most of whom live in the developing world, and it is unlikely that electric cars will become the dominant mode of transport in the world in the next five years [4]. One of the alternatives to improve cars with internal combustion engines could be use of less polluting fuel blends, which are sought after both in Europe and in other parts of the world. The best-known alternative is fuel produced from biomass. The production of fuels from biomass raises certain ethical and economic dilemmas [5]. Crops and their land that could be used for food are used to produce biofuels. The decline in crops and land used for food and the production of biofuels itself can lead to higher food prices [6]. This is especially relevant for third-world countries. Diverse alternative fuel sources must be sought. One of the most promising elements to use as fuel alone or mixed with other fuels could be hydrogen [7]. Hydrogen is good for storage of energy, which can be easily extracted from water, for which resources are practically inexhaustible. The final product of hydrogen oxidation becomes water [8].

The aim of this research was to investigate changes in engine energy performance after gasoline and bioethanol were enriched with hydrogen to evaluate the feasibility and practical application of bioethanol enriched with a hydrogen– oxygen mixture. There was little or none study papers found on bioethanol enriched with hydrogen.

2. PUBLISHED RESEARCH REVIEW

The search for alternative fuels to existing conventional fuels is constantly being pursued to meet the increasingly stringent requirements for vehicle pollution [9] and in search of fuels that can be produced from local raw materials [10]. These key aspects are reflected both in national and in European Union (EU) law and in EU-wide mobility policies, which focus on the rational use of resources without reducing the scale of the mobility process in the territories of the Member States [11, 12]. The use of fuel mixtures, in which fuel mixtures are partially or completely replaced by fuels derived from locally sourced feedstocks, is in line with these declaratory principles [13–15]. It can be used for a variety of biofuels (produced from feedstocks of biological origin) as well as hydrogen from the hydrolysis process [16]. Different combinations of alternative fuels with conventional petroleum-derived fuels yield both energy and ecological benefits, with lower air pollution, and are close to the energy performance of conventional fuels [17].

First-generation biofuels are currently the most popular in the world. This is due to several reasons: developed fuel production technology, well-established supply and sales markets, and positive consumer evaluation. Spark-ignition internal combustion engines are commercialized and have their own brand of fuel, which is a mixture of 85% ethanol and 15% petrol: E85 fuel [18]. They are well known and approved by car manufacturers; they have adapted their cars to this fuel with the special marking Flexible Fuel Vehicles [19]. The 85% ethanol limit is set by car manufacturers to reduce ethanol emissions at low temperatures and to avoid starting problems in cold weather (below 11°C) [20]. It is important to mention that the physical-chemical properties of iso-octane and ethanol differ significantly. Ethanol has a significantly lower calorific value (26.9 MJ/kg) compared to Iso-octane (44.3 MJ/kg), and the enthalpy of evaporation differs significantly (272 kJ/kg of isooctane, 840 kJ/kg of ethanol) [21]; this results in higher fuel consumption on increasing the amount of ethanol in the fuel blends [22]. Therefore, to optimize engine performance, it is important to choose ignition timing that ensures good performance and fewer emissions. For a carburetor 4-stroke, 4-cylinder SI engine, this value would be +4 CAD [23]. The use of ethanol-fueled SI engines results in an increase in the *BTE* parameter due to the higher flame rate and lower heat loss in the cylinders [24]. However, there is a relatively high loss of exergy (the maximum or minimum energy value that can be optimally used (obtained or released) in a thermodynamic process, subject to the limitations of thermodynamic laws), which is proposed to be reduced by exhaust reuse, engine cover, and waste heat recovery methods [25]. It has been observed that reducing the temperature of the supplied fuel increases the overall exergy [26]. It is very important to ensure the homogeneity of the fuel mixture using the E85 fuel and to apply the optimal number of spark plugs, which would lead to a better ignition process of ethanol-containing fuels [27]. The flame rate of the E85 fuel increases with increasing engine speed and compression ratio, as well as a decrease in standard deviation and uncertainty values [28]. An exhaust gas regulation (EGR) system results in better Otto cycle efficiency, which increases the product ratio of specific heat during combustion [29].

This type of fuel can also be used in diesel engines as dual fuel, which improves the combustion process in the engine [30] and leads to a high level of fuel substitutability (up to 89%) [31].

COV_{IMEP}, a reduction in *BSFC* under particularly lean combustion conditions, is observed with the addition of hydrogen to ethanol-containing fuels [32]. In an SI engine operating under stoichiometric conditions, there is a general tendency toward a decrease in volumetric efficiency due to hydrogen displacing part of the intake air. In this context, enrichment with hydrogen would increase the flammability limit of ethanol and allow it to operate on very lean mixtures [33]. With the use of a three-component mixture consisting of petrol-ethanol (E22) and hydrogen, the stability of the SI engine was achieved with the use of a lean mixture, hydrogen, and a reduction in fuel consumption of up to 13.1% [34]. With the use of an ethanol–hydrogen fuel mixture in CI engines, the specific ignition timing of the brake, the mean effective pressure, and the thermal efficiency of the brake increase with increasing hydrogen fraction in ethanol [35].

3. EXPERIMENTAL EQUIPMENT, METHODS USED, AND FUEL

The test equipment shown in Fig. 1. consists of a spark-ignition engine (Nissan HR 16DE), loaded with an electromagnetic braking system, equipment for measuring fuel consumption, and combustion products. The engine is controlled and programmed by the electronic control unit MoTeC m800. The MoTeC m800 control unit is connected via a personal computer. The engine is connected to an AMX 200/100 kW eddy current braking system (load stand). The load stand is controlled by the AMX 210 control unit. A fuel consumption meter is connected to the AMX 210 control unit. Fuel consumption is determined by weighting in grams per second (the measuring container holds 800 g of fuel). A mixture of hydrogen and oxygen gas is produced by a HHO gas generator. The gas mixture is supplied to the engine through the intake manifold. Combustion gas in the exhaust manifold is measured using an AVL DiCom 4000 gas analyzer. The experimental equipment parameters are shown in Tab. 1.

Table 1

Experimental equipment

Engine

Indicators of engine Nissan HR 16DE	
Number of cylinders	4
Working volume, dm^3	1.598
Maximum power, kW (rpm)	84 (6000)
Maximum torque, Nm (rpm)	156 (4400)
Degree of compression, ε	10.7

Fuel consumption meter

AMX210	
Fuel state	Liquid
Measuring type	Gravitational weight
Measuring range	-
Accuracy	±0.10%
Repeatability	-

Load stand

AUTOMEX AMX200/100	
Load mechanism	Eddy Current brake
Working speed	0 – 6000 rpm
Max load torque	480 Nm
Max load power	200 kW
Accuracy	±0.9 Nm

Gas analyzer

AVL DiCom 4000	
Gases	Limits and accuracy
(NO_x)	0....5000 ppm (±1)
(CH)	0....20000 ppm (±1)
(CO)	0....10 % (±0.01 %)
(CO_2)	0....20 % (±0.1 %)
(O_2)	0....25 % (±0.01 %)

To measure the pressure in the cylinder, a special spark plug with an integrated piezo crystal sensor ZI31 was installed instead of the standard spark plug. The measuring range of the sensor is 0 – 200 bar; the operating temperature range is -40º – +350 º C; the sensitivity is 12 pC/bar; and thermal shock error $\Delta p \leq \pm 0.5$ bar. Pressure data recording was performed using AVL DiTEST DPM 800 and LabView Real Time equipment.

Hydrogen gas (HHO) is extracted in a gas generator using electrolysis. HHO gas is a mixture of hydrogen and oxygen that is extracted from water. It is not necessary to accumulate the extracted gas mixture, as the gas is consumed immediately. This makes the measurement process easier and simpler, as additional equipment is not required to store hydrogen. Therefore, the process is both simplified and becomes cheaper. For the generator to produce hydrogen and oxygen, the tank capacity must be filled with an electrolyte consisting of 97% distilled water and a 3% potassium hydroxide (KOH) solution. The HHO gas generator is connected to a $U = 70$ V voltage source.

The properties of the fuel are shown in Tab. 2, were presented in [25] study. Were different blends created with different fuels? Various energy parameters were examined by looking at these blends. It is believed that biofuels obtained from different biomass could potentially be used as renewable energy because they meet ~ 10% of the global demand.

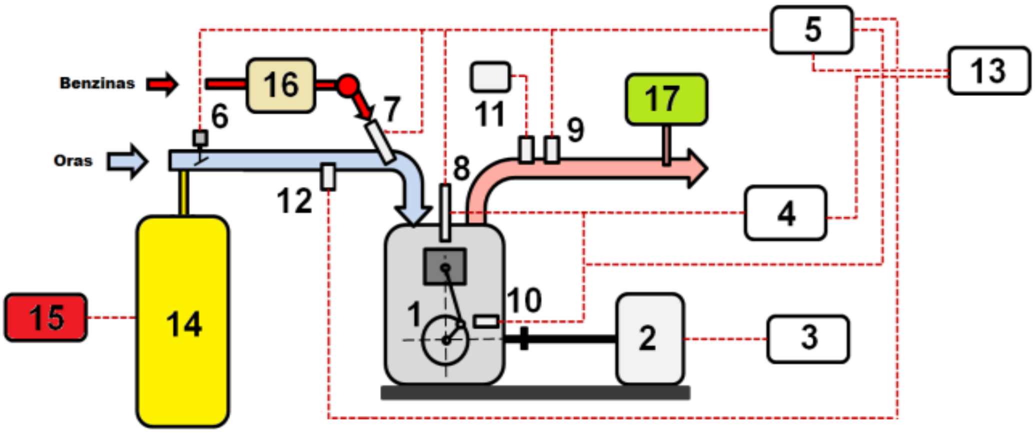

Fig. 1. Schematic of the test equipment: 1 - Engine; 2 - Eddy current braking stand; 3 - Eddy current braking stand ECU; 4 - AVL DiTEST DPM 800 cylinder pressure monitoring system; 5 - Engine ECU MoTeC M800; 6 - Throttle body; 7 - Injector; 8 - Spark plug with an internal pressure sensor; 9 - Oxygen sensor; 10 - Crankshaft sensor; 11 - Exhaust gas temperature sensor; 12 - Mass air flow sensor; 13 - Control center; 14 - HHO gas generator; 15 - External power supply unit; 16 – Petrol-measuring container; and 17 - Exhaust gas analyzer AVL DiCom 4000

Table 2

Comparison of fuel properties

Indicator	Fuel		
	Gasoline (E10)	Hydrogen	Bioethanol (E85)
1	2	3	4
Chemical formula	C4…C12	H_2	C2H5OH
Molecular weight μ	100..105	2	46.07
Elemental composition %			
Carbon	85…88	0	52.2
Hydrogen	15…12	100	13.1
Oxygen	~ 0.025	0	34.7
Density (20˚C) ρ, kg/m^3	738.2	0,09	782.9
Boiling point, t_s, °C	27…225	-253	78
Freezing point, °C	-40	-260	-114
Stoichiometric air to fuel ratio l_0, kg air/ 1 kg fuel	14.7	34.5	10.5
Cetane number	8…14	5-10	8
Octane number	95	130	108
Lower heating value (LHV), MJ/kg	41.30	120	29.16

On analyzing fuel properties, we find that the net calorific value of E85 is 29% less and H_2 ~ 3 times higher compared to E10. The octane number of E85 is 13% higher and H_2 is 36% higher compared to E10. A kilogram of E85 requires ~ 28% less air to burn than E10, and a kilogram of H_2 requires 1.3x more air than petrol. The E10 ratio of C/H = 6.2 and the E85 ratio is C/H = 4. This suggests that bioethanol will lead to lower CO_2 emission and make the fuel more resistant to detonation, but will have to be used at higher quantities.

4. RESULTS AND ANALISIS

Experiments were performed with the engine running at different ignition timings (Θ), with 15% open throttle, when $n = 2000$ rpm, and excess air coefficient $\lambda = 1.0$ and $\lambda = 1.1$. To ensure HHO gas supply of 3.8 l/min., a voltage of 70 V and a current of 10 amps (700 W) were used. After estimating the density of hydrogen in HHO gas, it was estimated that the hydrogen supply was ~0.0137 kg/h. This accounted for ~ 0.35% of the total mass of fuel; hydrogen energy in the fuel accounted for ~ 0.95%.

Different fuels burn at different speeds; thus, different angles of ignition timing (16° CA bTDC – 30° CA bTDC) were tested and data were collected within that range. The combustible mixture is ignited at a certain point, and thermal energy is converted into mechanical energy. When engine load is applied, a strain gauge is pressed, which calculates the engine brake torque, and the data are transmitted to the main control unit. The results of the experiment at different ignition timing angles are shown in Figs. 2 - 5. The engine reaches its maximum brake torque when $\lambda = 1.0$ at 22° CA bTDC with both E10 and E85, and 26° CA bTDC when $\lambda = 1.1$. This indicates a slower burning rate of the lean mixture and it is likely that the addition of HHO gas may accelerate it.

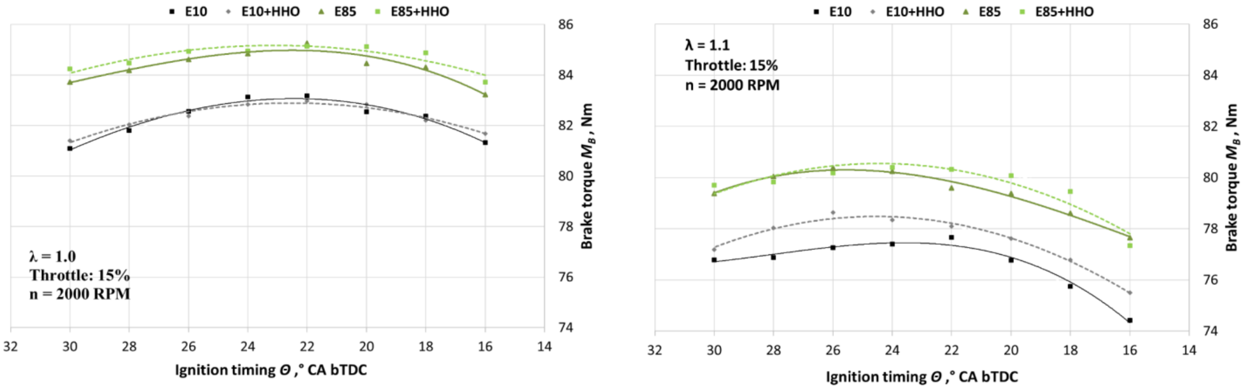

Fig. 2. Engine brake torque M_B

Fig. 2 shows that E85 has a higher torque (~ 2.5%) due to the higher fuel consumption compared to petrol with both $\lambda = 1.0$ and $\lambda = 1.1$. Burning 1 kg of petrol requires 14.7 kg of air, but burning 1 kg of bioethanol requires 10.5 kg of air. This is because E85 has oxygen-containing molecules and the engines ECU is trying to maintain the correct excess air by injecting more E85. Engine brake torque is directly influenced by the amount of fuel that is sprayed into the cylinder and its lower heat value. Adding HHO to the mixed fuel had no significant effect on brake torque, when $\lambda = 1.0$. When $\lambda = 1.1$ and E10 is used, HHO aids faster burning of the flame and increases M_B up to1%.

Hourly fuel mass and volume consumption (Fig. 4), when using E85, increased by ~ 30% compared to E10. More E85 must be injected to maintain the set λ. At $\lambda = 1.1$, the same trends are maintained as $\lambda = 1.0$ using the same fuels. Only consumption decreases by 7% because less fuel is injected.

The experiment showed that the comparative fuel consumption with hydrogen gas did not change significantly. This is likely to be due to the fact that HHO gas energy accounted for less than 1% of the total energy in the fuel mixture.

The highest brake-specific fuel mass consumption $BSFC_{\_m}$ (Fig. 4) was achieved on using E85 and the lowest brake-specific fuel mass consumption $BSFC_{\_m}$ was achieved on using E10. This is because when the E85 mixture is burning, more fuel needs to be injected as the control unit tries to maintain the set λ value because E85 fuel has a smaller LHV. $BSFC_{\_m}$ was influenced by changes in the ignition timing and λ. With a stoichiometric mixture (λ = 1), the lowest fuel mass consumption is achieved when Θ = 22° CA bTDC.

A leaner mixture (λ = 1.1) can reduce fuel consumption by 0.4%, but the ignition must be brought forward to Θ ≈ 26° CA bTDC because a leaner mixture burns more slowly (Fig. 5). HHO gas accelerates combustion, in which case it is not necessary to change the ignition timing for E10 and leave it at Θ = 22° CA bTDC. This is more noticeable when the engine is running on E10 + HHO fuel compared to E10 with no HHO gas; when the mixture is set to λ = 1.1, the fuel mass consumption is reduced by 4%.

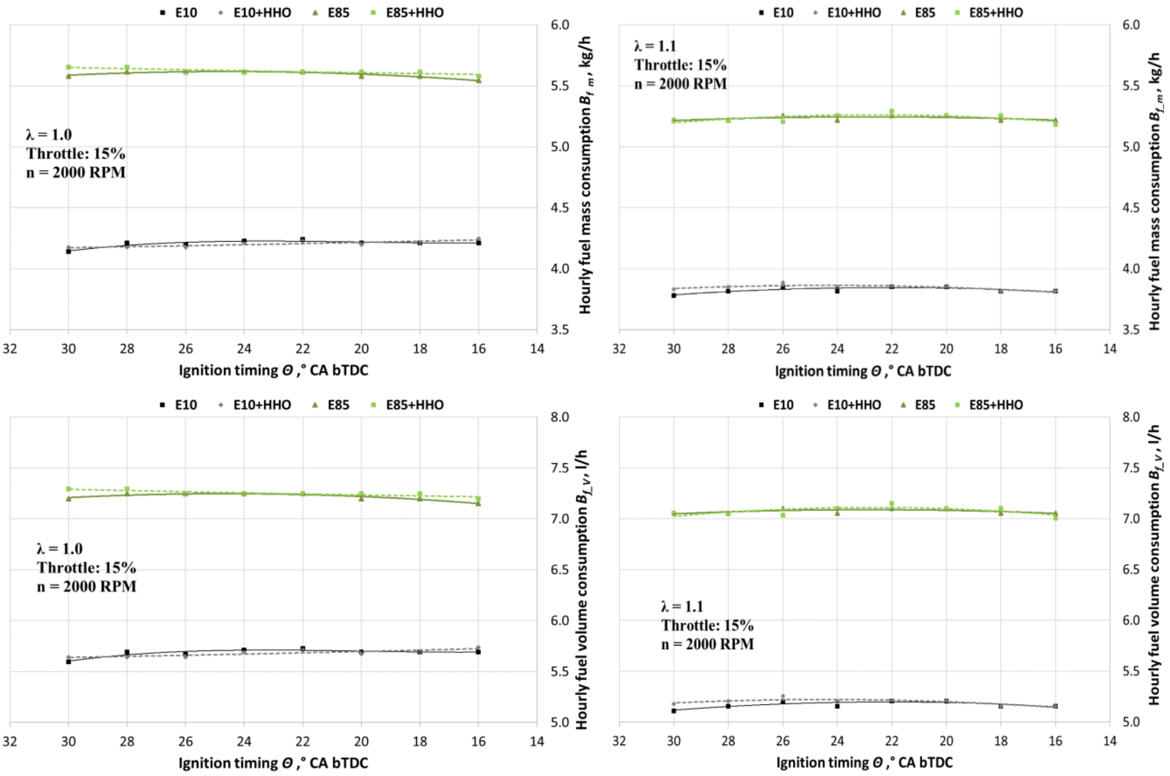

Fig. 3. Hourly fuel mass and volume consumption

Brake-specific fuel volume consumption $BSFC\_V$ (Fig. 4) gives an opportunity to estimate consumption and price of fuel for the consumer. After estimating the price of fuel at the time the experiment was conducted, it was estimated that 1 kWh of E85 was 37 ct and 1 kWh of E10 was 39 ct. Using E85, the amount of fuel needed to produce 1 kWh of energy cost ~ 2 ct (~ 5%) less than when using E10. HHO gas slightly reduced the volume consumption of E10 fuel at λ = 1.1, but the cost-effectiveness is not positive because of the cost of HHO equipment and its operation.

One of the key parameters that characterizes engine performance is brake thermal efficiency (*BTE*) (Fig. 5). Engine energy efficiency mostly depends on the fuel properties, the excess air coefficient λ, the angle of ignition timing, and other factors. Replacement of E10 with E85, when λ = 1.0, increases the *BTE* by approximately ~ 5% because the engine develops more useful power and less energy is lost to mechanical losses. In addition, ethanol burns better because there is more oxygen and it has a simpler molecular structure. By leaning the mixture to λ = 1.1 and using E85, the *BTE* can be increased by ~ 7% compared to E10 when λ = 1.0.

Despite attempting to find the best ignition timing for this engine and increase its effective thermal efficiency, addition of HHO gas reduces it. Small portions of the HHO mixture act as an additive, slightly increasing the combustion rate and improving the combustion process, but at the same time reducing the thermal efficiency of the engine. This is because the net calorific value of hydrogen is about three times that of gasoline; however, the reduction of fuel consumption was very small, almost none. With HHO gas, the efficiency decreased by about 1.5%, except when λ = 1.1 and E10 + HHO fuel is used.

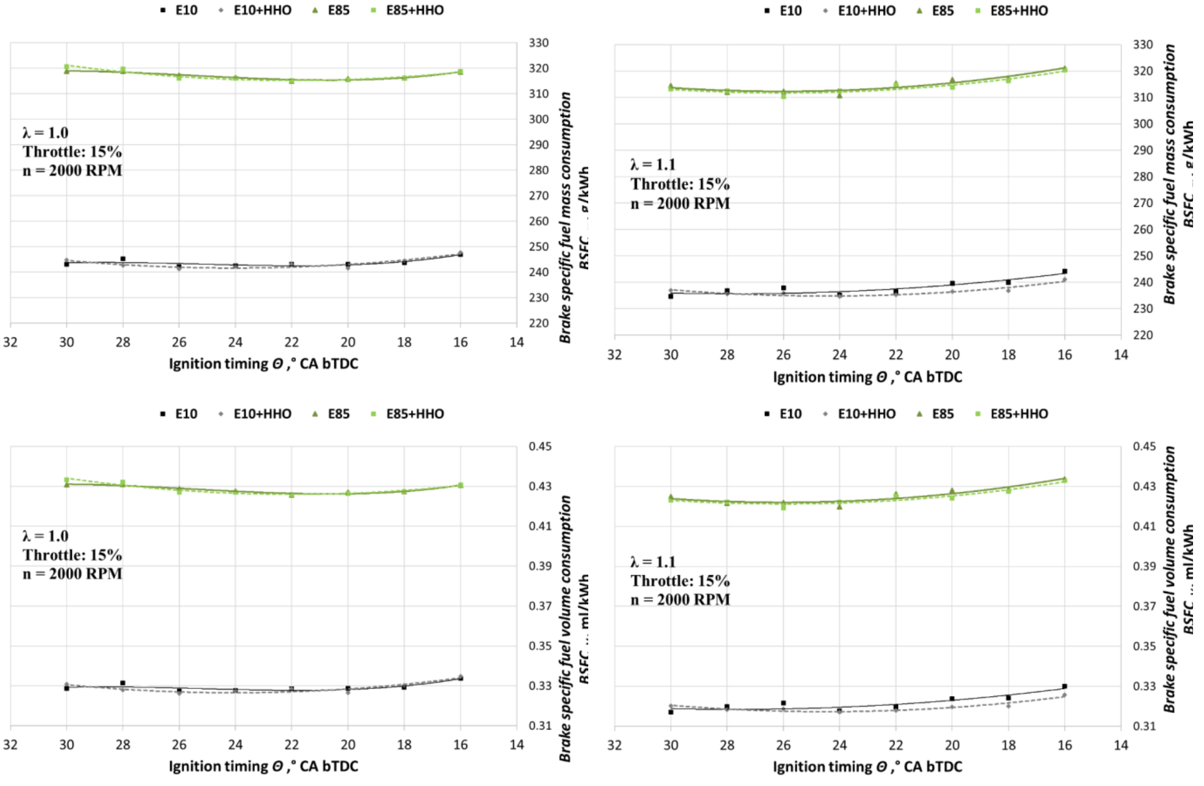

Fig. 4. Brake-specific fuel mass and volume consumption

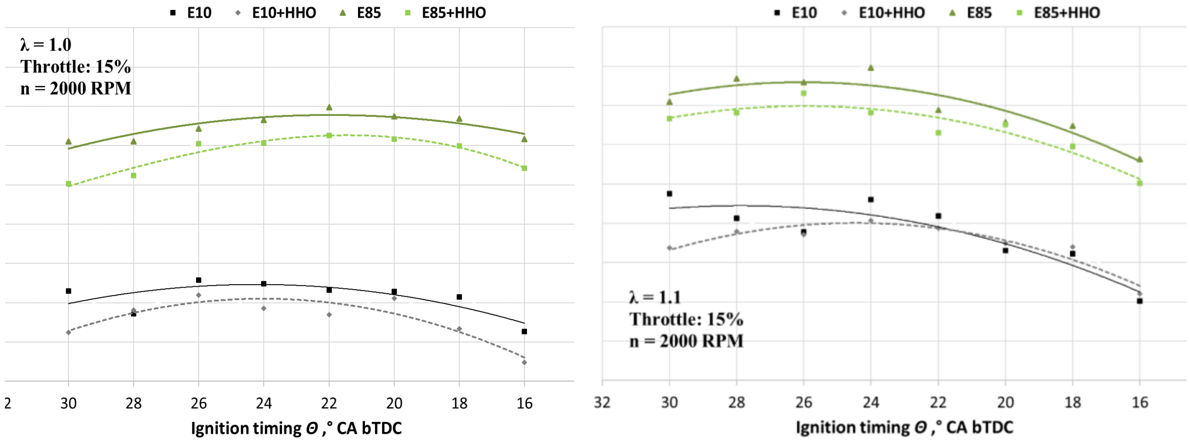

Fig. 5. Brake thermal efficiency

The rate of heat release (ROHR) diagram shows that when the engine is running on E85 fuel (7 ° CA ATDC), the maximum heat release is 2.1% higher compared to E10 (Fig. 6). This confirms the fact that when using E85 and with a stoichiometric mixture, the fuel provides more energy to the cylinder and thus creates more torque. The E85 ROHR peak is reached slightly later due to slower ethanol combustion. The HHO gas additive accelerates combustion and slightly increases combustion pressure and torque by ~ 1%. When the engine is run on lean mixture λ = 1.1, the ROHR intensity is reduced due to the lower fuel content and slower combustion. However, E85 fuel, as in the case of the stoichiometric mixture, emits more heat. In the case of lean fuel mixtures, the effect of HHO gas is recorded to be higher because the lean mixture burns more slowly and the addition of hydrogen increases the combustion rate, which also increases the maximum ROHR. This has a positive effect on engine brake torque.

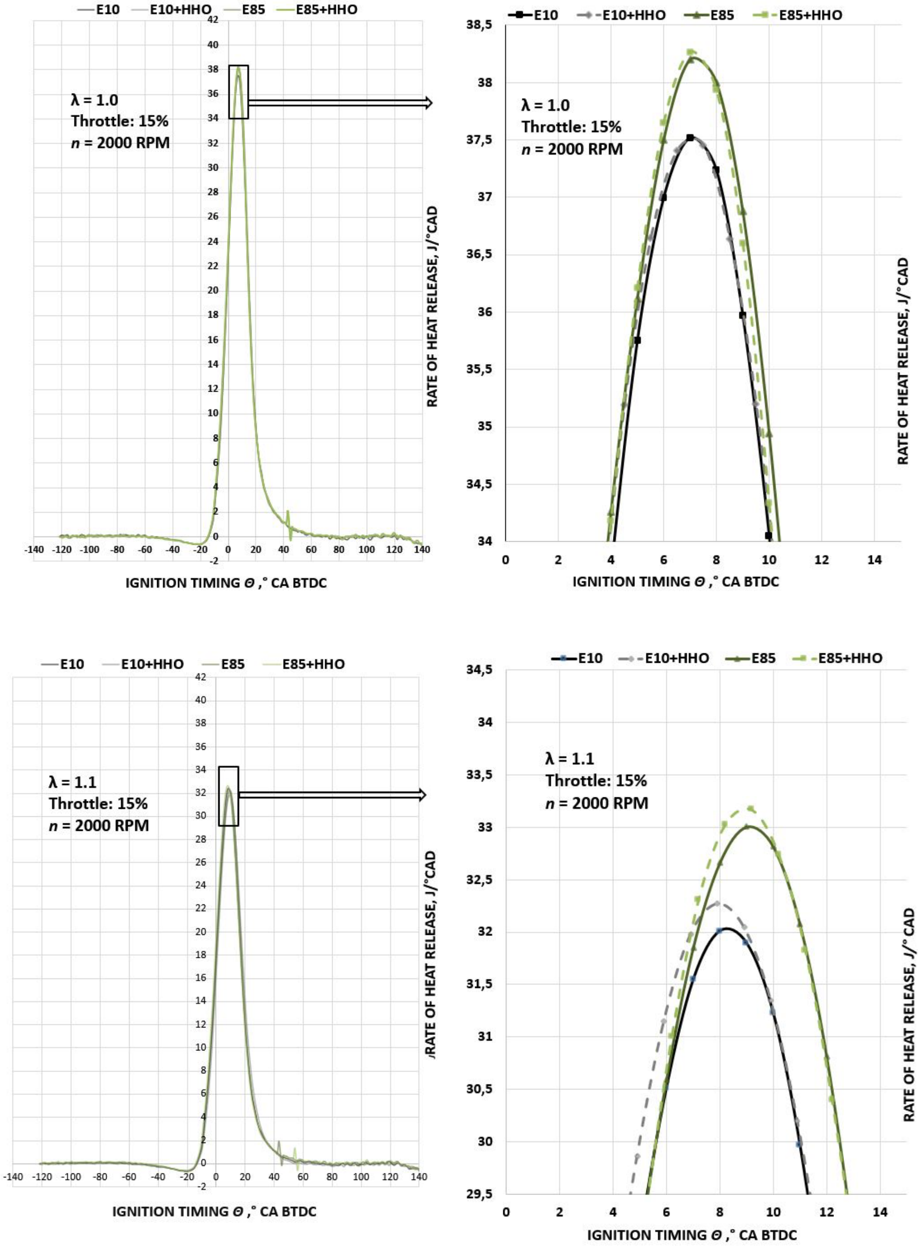

Fig. 6. Rate of heat release

5. CONCLUSIONS

On conducting experiments with the spark-ignition engine at $n = 2000$ rpm with 15% open throttle using E10 and E85 fuels with HHO gas and an excess air between $\lambda = 1.0$ and $\lambda = 1.1$, the following results were obtained:

1. The properties of E10, E85, and their blends with HHO were determined. E85, compared to E10, has a 35% lower C/H ratio, ~ 6% higher density, and ~ 29% lower *LHV*, and to achieve a stoichiometric blend with E85, ~ 28% less air is required.

2. Maximum brake torque is achieved using the E85 mixture at λ = 1.0 and increased by ~ 2.4% compared to E10. The use of fuels containing 85% bioethanol increased M_B because E85 requires ~ 28% more fuel to ensure a stoichiometric mixture. HHO gas, with an energy content of ~ 0.95% inside the fuel, creates an ~ 1% positive M_B effect when the engine is running on E10 at λ = 1.1, as it accelerates the slower combustion of the lean mixture.
3. The brake thermal efficiency of E85 is ~ 5% higher compared to E10 when λ = 1.0 due to the lower *LHV* and better combustion of this fuel. Using a lean mixture, λ = 1.1, the *BTE* of the E85 fuel increased further and was ~ 7% higher compared to E10 when λ = 1.0. HHO gas does not have a positive *BTE* effect as it has a high *LHV*.
4. E85 fuel hourly mass consumption is ~ 30% higher compared to E10 because, by maintaining λ = 1.0, ~ 28% more fuel can be injected for the same amount of air. Leaning the mixture to λ = 1.1 reduced fuel consumption for both E85 and E10 by 7%, while HHO gas accelerated the combustion of lean E10, but *BSFC* reduced it by an additional 1%.
5. It is more practical to use E85. E85 needed to produce 1 kWh of energy cost ~2 ct (~ 5%) less than using E10.

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