Simulation of spark ignition engine performance working on biogas hydrogen mixture

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Abstract. Numerical simulations of *Nissan Qashqai HR16DE* engine with increased compression ratio from 10,7:1 to 13,5:1 was carried out using AVL BOOST software. Modelled engine work cycles while engine works with biogas (BG) and hydrogen (H₂) mixtures. For biogas used mixture of 35 % carbon dioxide (CO₂) and 65 % methane (CH₄). Three mixtures of biogas with added 5 %, 10 % and 15 % H₂ was made. The simulation of engine work cycles was performed at fully opened throttle and changing engine crankshaft rotation speeds: $n_{e1} = 1500$, $n_{e2} = 3000$, $n_{e3} = 4500$, $n_{e4} = 6000$ rpm. Simulation results demonstrated what adding hydrogen to biogas increase in-cylinder temperature and nitrogen oxides (NO_x) concentration because of higher mixtures lower heating values (LHV) and better combustion process. Other emissions of carbon monoxide (CO) and hydrocarbons (HC) decreased while adding hydrogen due to the fact that hydrogen is carbon-free fuel.

Keywords: spark ignition engine, biogas, hydrogen, performance

1 Introduction

Huge challenges for developed countries is to reduce usage of fossil fuels and greenhouse gas (GHG) emissions. The biggest constituent of greenhouse gas and largest contribution to global warming is carbon dioxide [1], [2]. After 2012 in Lithuania largest carbon dioxide equivalent source is transport sector Fig.1.

One way to reduce greenhouse gas emission and fossil fuel usage in this sector is to use small, high efficiency engines like 2018 FORD ECOBOOST 999 cm³ petrol engine with turbocharger which generates 100 HP and emits just 97 g/km of CO₂ or VAG Group 999 cm³ TFSI engine with 97 HP and 97 g/km of CO₂ [4]. The more efficient engine the less fuel they use and less greenhouse gas that have a harmful effect on the environment they produce. Other way is to increase usage of alternative fuels.

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Fig. 1. Total GHG emissions from the different subsectors within the Energy Sector (CRF 1) [3]

In Lithuanian transport sector is one of the largest energy consumers Fig. 2. In 2016 used 215 thousand tons of petrol which includes just 9.9 thousand tons of bioethanol. A similar situation is with diesel fuel, transport sector in 2016 used 1398 thousand tons of diesel fuel which includes just 54.9 thousand tons of biodiesel [5]. Transport sector use just about 4 percentages mainly first generation alternative fuel.

Fig. 2. Final energy consumption in Lithuania [3]

First way works in case of passenger vehicles and they also could use alternative fuel or just a part of it. Freight or public transport must have high engine torque and small engines aren't capable of producing it. So in heavy transport best way of reducing usage of fossil fuels and greenhouse gas emissions should be increased usage of second third or fourth generation alternative fuel. One of possibility is to use biogas. There is a large chose of raw

material from which biogas could be produced. Also depending on the raw material it could be second third or fourth generation alternative fuel.

Biogas is mixture of different gases made out of anaerobically digested organic matter from waste materials. Biogas consist mainly from combustible methane and inert CO₂, if CO₂ concentration increase fuel lower heating value decrease [6]. Depending on raw material and parameters of anaerobic digestion process, CO₂ and CH₄ concentration in biogas can variate. Typically, methane concentration is from 55 – 88 %, CO₂ concentration is from 20 to 45 % and hydrogen sulphide (H₂S) concentration is from 1 to 2 %. Also in biogas could be found traces of carbon monoxide (CO), hydrogen and oxygen (O₂) [7]. Properties comparison of biogas with low concentration of methane and other gaseous fuel used in transport sector shown in Table 1.

Table 1. Comparison of hydrogen, LPG, natural gas and biogas properties [8], [9]

Property	Biogas	Methane	Natural gas	Hydrogen (H ₂)
Composition (% vol)	CH ₄ – 57 % CO ₂ – 41 % CO – 0,18 % H ₂ – 0,18 %	CH ₄ – 100 %	CH ₄ – 85 % C ₂ H ₆ – 7 % C ₃ H ₈ – 2 % N ₂ – 1 % CO ₂ – 5 %	H ₂ – 100 %
Lower heating value (LHV) at 1 atm and 15°C (MJ/kg)	17.0	50.0	50.0	120.0
Density at 1 atm and 15°C (kg/m ³)	1.20	0.717	0.79	0.0838
Flame speed (cm/s)	25	36.5	34	270-320
Stachiometric A/F (kg of air/ kg of fuel)	5.8	17.2	17.3	34.3
Flammability limits (vol% in air)				
Leaner	7.5	5.3	5.0	4.0
Richer	14.0	14.0	15.0	75.0
Octane number				
RON	130	125	120	130
MON	-	-	120	-
Autoignition temperature (°C)	650	595	540	858

Raw material for making biogas could be any organic material. But it would be best if raw materials wont includes sugarcane, food crops, animal fats anything what suitable for food and will produce first generation alternative fuel. For next generation biogas production commonly used raw materials includes industrial and commercial waste, municipal solid waste, by-products from farms or water treatment plants and many others. List of raw materials suitable for production of next generation biogas is shown in Fig. 3.

Biogas could be used in internal combustion engines, because large part of biogas composition is methane 55 – 88 % which could be burn in internal combustion engine. Using biogas in compression ignition engine is possible, but because of 15 – 25 % higher auto ignition temperature and low ignitability, comparing with diesel, engine can't operate on 100 % of biogas. Therefore compression ignition engines must have pilot injection of diesel fuel to ignite biogas. There is no such problem then biogas is used in spark ignition engine. The same spark plugs which ignites petrol – air mixture can ignite mixture with biogas. Also biogas has about 20 – 30 % higher octane number than petrol fuel and greater resistance to knock. But in biogas there is a part of non-combustible gas – CO₂ which

decrease lower heating value of the fuel. As an example then CO_2 concentration increase from 13 % to 49 % lower heating value decrease 41 % also maximum in cylinder pressure decreases and brake specific fuel consumption increase [6]. For better engine parameters biogas could be cleaned from CO_2 and burned just CH_4 , but it's not economical, so there is a need to find measures to improve ecological and energetic parameters of spark ignition engine using produced and untreated biogas.

Fig. 3. Raw materials for biogas production

Researchers tried to use different measures to increase engine effectiveness and performance. Porpatham et al. tried to increase oxygen concentration in the intake air 21 %, 22 % and 23 %. Higher oxygen concentration in the intake air improves mixture burning speed and increases power output. The maximum brake thermal efficiency with 22 % of oxygen is 27 % and with 23 % – 28 %, and occurs at an equivalence ratio of 0.95. While with the same equivalence ratio and engine working with biogas and air with 21 % of oxygen brake thermal efficiency was 26.2 %. The main cause of this is the increased combustion rate [10]. Other researchers tried to use biogas on engines with increased compression ratio. Kwon et al. conducted research on a small one-cylinder spark ignition engine and increased its compression ratio by 15 %. Increased compression ratio leads to 21.8 % higher engine power and 7.8 % higher thermal efficiency when engine working on CH_4 . While adding CO_2 , the engine performance degrades. When engine working with 40 % CO_2 and 60 % CH_4 engine generate same power as it was generating before modification and working with CH_4 [11]. There are also other means used to increase engine effectiveness while using biogas. One of possibility is to use dual fuel biogas – hydrogen blends to improve combustion properties [12]. Adding hydrogen increase fuel blend lower heating value, flame speed and reduce GHG emission, because of hydrogen burning emissions [13]. Leung and Wierzbina investigated burning characteristics of biogas – hydrogen mixture. Observed that 10 % of hydrogen in biogas has significantly improved flame stability and gave better results than further increasing part of hydrogen in biogas [14].

2 Materials and methods

For numerical simulation of spark ignition engine AVL BOOST model was made. Fig. 4 presents created AVL BOOST model. The basis of the model was *Nissan Qashqai HR16DE*

engine, with displacement of 1598 cm³, multiport fuel injection system and maximum engine power of 84 kW at 6000 rpm.

Fig. 4. Nissan *Qashqai* HR16DE engine AVL BOOST model: SB – system boundaries; MP – measuring points; J – junctions; I – port fuel injectors; PL – plenum; R – restriction; CAT – catalytic converter; El – engine parameters

Compression ratio was increased from 10.7:1 to 13.5:1, for spark ignition engine (SIE), fuelled with biogas for better power output and thermal efficiency while using biogas [15]. Rest engine specification shown in Tab.2.

Table 2. Engine specification

Items	Specification	Items	Specification
Engine Capacity, cm ³	1598	Stroke, mm	83.6
Rated engine power, kW	84	Compression ratio	10.7:1 → 13.5 :1
At engine speed, min ⁻¹	6000	Number of valves per cylinder	4
Rated engine torque, Nm	156	Intake valves open	336° bTDC
At engine speed, min ⁻¹	4000	Intake valves close	108° bTDC
Fuel system	Multipoint injection	Exhaust valves open	156° aTDC
Bore, mm	78.0	Exhaust valves close	308° bTDC

In AVL BOOST software for biogas was used mixture of 35 % carbon dioxide and 65 % methane. Also for increase of SIE, working with biogas, performance hydrogen was added

and produced three fuel mixtures with 5 %, 10 % and 15 % of H₂. All compounds were mixed by mass. All mixtures have different *LHV* witch could be calculated according to the formula:

$$LHV_{fuelmix} = \frac{LHV_1 \times \%_{fuelcomp.1}}{100} + \frac{LHV_2 \times \%_{fuelcomp.2}}{100} \tag{1}$$

where:
*LHV*₁, *LHV*₂ – lower heating values of the fuel components, MJ/kg;
%_{fuelcomp.1}, %_{fuelcomp.2} – percentage of a certain fuel component in a fuel mixture, % (by mass).
Lower heating values of methane, hydrogen and calculated biogas/hydrogen mixtures showed in Fig. 5. Highest *LHV* of 120 MJ/kg has hydrogen which increase all biogas mixtures lower heating values.

Fig. 5. LHV of methane, hydrogen, biogas and biogas/hydrogen mixtures

The simulation of engine work cycles was performed at fully opened throttle and changing engine crankshaft rotation speeds: *n*_{e1} = 1500, *n*_{e2} = 3000, *n*_{e3} = 4500, *n*_{e4} = 6000 rpm, engine working on biogas and biogas/hydrogen mixture where hydrogen mass fraction was 5 %, 10 % and 15 %. For engine crankshaft rotation speed 1500 rpm start of combustion was set to be 17.8 °CA before top dead center (BTDC) and air excess ratio (AER) – 0.950. Increased engine crankshaft rotation speed to 3000 rpm start of combustion was set to be 18.8 °CA BTDC and AER – 0,950. For engine crankshaft rotation speed of 4500 rpm start of combustion was set to be 20.0 °CA BTDC and AER – 0.900. Engine working at 6000 rpm start of combustion was set to be 20.0 °CA BTDC and AER – 0.866. For all mixtures ignition timing and AER was set respectively.

3 Results and discussions

Modelling engine work cycles for biogas all four crankshaft rotation speeds have set angle of combustion start. While adding hydrogen same angle is maintained. As showed in Fig.6 indicated pressure in cylinder reach maximum value of 9.857 MPa when engine working on biogas, while adding hydrogen indicated pressure drops in all measured point. The higher

concentration of hydrogen, the lower indicated pressure. Comparing maximum pressure of BG and mixture with 15 % H₂ its decrease by 1,88 %. Pressure drop could be caused by constant angle of combustion start, because mixtures with hydrogen have faster diffusion velocity, a lower ignition and a faster flame speed [16].

Adding hydrogen with LHV of 120 MJ/kg increase all mixtures lower heating value. Biogas and 5 % hydrogen mixture LHV increased by 4.38 MJ/kg, with 10 % H₂ – 8.75 MJ/kg and with 15 % H₂ by 13.13 MJ/kg comparing with BG. Because of higher mixture LHV maximum burning temperature increased (Fig.7). While engine working with biogas reach maximum temperature of 2611.21 K adding 5 %, 10 % and 15 % of hydrogen increased maximum temperature by 44.03 K, 81.04 K and 110,75 K compering with biogas.

Modelling engine work cycles, while engine working with biogas, best brake specific fuel consumption (BSFC) achieved when engine crankshaft rotation speed was 3000 rpm, then BSFC was 334.7 g/kWh (Fig. 8). Adding hydrogen to BG increase mixtures LHV and in all measured points BSFC decrease. Highest difference noticeable with BG and 15 % of hydrogen. Then BSFC decreased by 90.21 g/kWh (26.9 %) at engine crankshaft rotation speed 3000 rpm, at the same conditions 5 % and 10 % of hydrogen lowered BSFC respectively 10.9 % and 19.7 %.

Fig. 6. Indicated pressure in cylinder

Fig. 7. Maximum temperature in cylinder

Fig. 8. Brake specific fuel consumption

Fig. 9. Nitrogen oxides emission

Fig. 9 presents NO_x concentration in the exhaust gas. Minimum concentration established when engine working with biogas. Adding hydrogen increases NO_x concentration, which depends on maximum in cylinder temperature [17]. As shown in Fig. 6 H₂ raised temperature in cylinder at all measured points. Highest NO_x concentration when engine working with BG (1175.42 ppm) achieved at 3000 rpm. Increasing H₂ concentration leads to increase of NO_x emission, adding 5 %, 10 % and 15 % of hydrogen respectively increased nitrogen oxides by 2.65 % 3.34 % and 9.89 % comparing to BG.

Fig. 10. Carbon monoxide emission

Fig. 11. Hydrocarbons emission

Fig. 10 shown CO emission dependence on engine speed with and without addition of H_2 . It can be noted that CO emissions have decreased at all engine speeds adding 5 %, 10 % and 15 % of hydrogen. Biggest influence in CO emission could be seen when engine working with BG and 15 % H_2 mixture. At engine speed of 1500 rpm CO concentration decreased by 0.707 %, 3000 rpm by 0.301 %, 4500 rpm by 0.483 %, and at 6000 rpm by 0.852 % comparing when engine works with biogas. Emission reductions are due to the fact that hydrogen is carbon-free fuel and reduces fuel mixture C/H ratio, furthermore H_2 have high flame rate, increases in-cylinder temperature and combustion efficiency [18], [19].

The assessment of biogas and hydrogen mixtures revealed what increased amount of hydrogen decrease HC emission as can be seen in Fig. 11. While adding H_2 , concentration of hydrocarbons decreased in all measured point. Engine working with biogas at 3000 rpm HC concentration in exhaust gasses was 522.48 ppm, added 5 % of hydrogen reduced hydrocarbons concentration by 9.51 %, 10 % of H_2 reduced by 17.28 % and 15 % of H_2 reduced by 24.78 % comparing at same engine speed with emission when engine working with biogas. HC reduction causes by increased in-cylinder temperature and more complete combustion because of added hydrogen and reduced carbon content of the fuel [20].

4 Conclusions

Numerical simulations of *Nissan Qashqai HRI6DE* engine with increased compression ratio and working with biogas/hydrogen mixtures analysis lead to conclusions:

1. Engine working with biogas (65 % CH_4 / 35 % CO_2) and additionally supplied hydrogen has lower indicated pressure, because hydrogen have faster diffusion velocity, a lower ignition and a faster flame speed. To maintain indicated pressure angle of combustion start and air excess ratio should be adjusted.
2. Adding hydrogen with LHV of 120 MJ/kg increase in-cylinder temperature in all measuring points. Bigger part of biogas replaced with hydrogen increases LHV of the mixture and in-cylinder temperature. Maximum recorder temperature of 2721.96 K fixated with 15 % of hydrogen.
3. In all measuring points BSFC decreased while adding hydrogen, because of increased mixtures LHV and more efficient combustion process. Engine working with BG and 15 % H_2 BSFC was 279,52 g/kWh, 244,53 g/kWh, 252,48 g/kWh, and 281,71 g/kWh while increasing engine speed from 1500 rpm to 6000 rpm.
4. Adding hydrogen to biogas improved CO and HC emissions in all measured points, because of increased in-cylinder temperature, more complete combustion and reduced

carbon content of the fuel. However, adding hydrogen increased NO_x concentration because of increased in-cylinder temperature.

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