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Impact of biomethane gas on energy and emission characteristics of a spark ignition engine fuelled with a stoichiometric mixture at various ignition advance angles

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HIGHLIGHTS

- Biogas is an environmentally friendly fuel for Otto engines.
- The impact of supplying additional biomethane gas to a spark ignition engine is evaluated.
- Engine and environmental characteristics were studied.
- Using biogas requires operational modifications.

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ABSTRACT

The impact of supplying additional biomethane gas with composition of 65% methane (CH_4) and 35% carbon dioxide (CO_2) to a spark ignition engine on energy and emission characteristics was studied. The tests were performed on a Nissan Qashqai HR 16DE engine, with the engine throttle 15% open, a constant stoichiometric fuel mixture and various ignition advance angles. It was found that an increase in added biomethane gas results the drop in engine power output. This effect had two primary causes. First, the cylinders were refilled less effectively. Second, biogas, by impacting the efficiency and speed of the combustion process, reduces the thermal efficiency of the engine. The second effect can be partially improved by accelerating the combustible ignition mixture. It was also observed that CO_2 gas, which is in biogas composition, suppress combustion process which increases the content of carbon monoxide (CO) in exhaust gas, but reduces emissions of nitrous oxide (NO_x). Increased carbon dioxide amount in fuel mixture has small influence on CO_2 increase in exhaust gas because the methane in biogases reduces C/H ratio of the fuel mixture. Hydrocarbons which are in methane composition has smaller molecular mass, evaporates and combust easier which has influence on reduced concentration of unburnt hydrocarbons (HC).

1. Introduction

Global warming has forced humankind to focus on the reduction of greenhouse gas emissions and, consequently, on the production and consumption of ecological and environmentally friendly fuel [1–4]. In 2009, the European Commission approved a directive encouraging all vehicles fuels to include 10% biofuel by 2020. The most popular biofuel is biodiesel mixed with mineral diesel and bioethanol or bio methanol, which is added to petrol [5]. Vehicles also use gas fuel, e.g., liquefied petroleum gas (LPG), compressed natural gas (CNG), biogas, hydrogen and hydromethane. Liquefied petroleum gas is used in Otto engines, where its adoption is easy and cost-efficient [6,7]. Natural gas is used in its liquefied or compressed form. The use of CNG in light vehicles is more efficient, compared with petrol engines. CNG can also be used in Otto diesel engines, and engines designed for natural gas use. However, both LPG and CNG are fossil fuels. These gases could replace biogas [8]. The raw materials available for biogas production are abundant (from agriculture, municipal waste, industrial waste and green

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biomass) and underutilised [9–12]. Key components in biogas include methane (CH_4) and carbon dioxide (CO_2). Biogas contains far less hydrogen sulphide (H_2S), ammonia (NH_3), hydrogen (H_2), nitrogen (N_2), carbon monoxide (CO) and oxygen (O_2) than petrol. As a fuel, biogas has an extremely low energy density on the volume basis on account of its high CO_2 content and the flame speed is just 25 cm/s as against 34 cm/s for natural gas [13]. The energy value in biogas depends on the methane content, which should be as high as possible for vehicle use. For example, the methane content in the biogas used in Sweden is at least 96%, the hydrogen sulphide content is limited to 23 mg m^{-3}, and the moisture content must not exceed 32 mg m^{-3} [14]. The large quantity of CO_2 present in biogas lowers its calorific value, flame velocity and flammability range. On the other hand, the auto ignition temperature of biogas is high (Table 1) and it resists knocking which is positive property for SI engines [13].

Scientists have been studying the opportunities for biogas use for marine and road transport [13,15]. The energy utilization of biogas is maximized when it is converted into electricity via a biogas generator and gas engine, which makes the process eco-friendly and energy efficient [16]. The use of purified (at least 90% methane) biogas in diesel engines has been widely analysed. The use of biogas with the carbon dioxide partially eliminated, i.e., the content of carbon dioxide varied from 5% to 35%, has been studied [17]. It was found that the use of biogas with a low methane content resulted in an increased CO_2 content in the exhaust gas because, according to V.B. Kovacs and A. Torok, this phenomenon depends on the CO_2 content in the biogas [18]. That is, if the carbon dioxide content in the biogas is high, the CO_2 content is also high in the engine combustion products. However, the research results demonstrated that additional use of biogas in a diesel engine can reduce NO_x emissions [17,19]. The added mass of non-reacting gas absorbs heat and lowers the combustion temperature which has influence for NO_x formation. The effect of CO_2 variation in fuel composition is similar to that of exhaust gas recirculation, which is known as the dilution effect [20]. Biogas use in Otto engines has been studied by analysing the biogas operating properties and the engine operating mode. As a result, biogas is recommended as a fuel for Otto engines. However, the impact of the methane/carbon dioxide ratio in biogas on engine operation is still unclear. If this impact is insignificant, it is probable, reasonable and cost-efficient to use biogas, with the CO_2 either partially removed or not removed.

Table 1
Fuel properties.

Parameter	Fuel	
	Petrol	Methane
Chemical formula	C_4–C_{12}	CH_4
Molecular mass (μ)	100–105	16.04
Elemental composition (%)		
Carbon	85–88	75
Hydrogen	12–15	25
Oxygen	~0.025	
Density (20 °C) ρ (kg/m^3)	740***	0.717**
Boiling temperature (°C)	25–215*	−162*
Freezing point (°C)	−40*	−182*
Specific heat of vaporization (kJ/kg)	350*	557*
Stoichiometric ratio A/F (kg of air/kg of fuel) (kg)	14.9	17.2
Octane number	98	~120
Lower heating value H_u (MJ/kg)	43.5	50
Auto ignition temperature (°C)	~400	~650
Adiabatic flame temperature (°C)	~2104	~1950

* At 101.3 kPa pressure.
** At 0 °C temperature and 101.3 kPa pressure.
*** At 20° C temperature.

The objective of this research was to evaluate the impact of the carbon dioxide contained in biogas on the operating characteristics of an Otto engine and evaluate benefits of biogas additive in fuel mixture.

2. Materials and methods

Petrol (P) and biomethane gas (M65%), containing 65% (according to molar mass) of methane (CH_4) and 35% (according to molar mass) of carbon dioxide (CO_2), were used in this study. The lower calorific value of methane (H_{u_M} = 50 MJ/kg) exceeds the lower calorific value of petrol (H_{u_P} = 43.5 MJ/kg) by ~15%; therefore, increasing the amount of additionally supplied biogas increases the total calorific value of the fuel mixture compared with petrol by ~2.6%, ~3.3% and ~3.9% (Fig. 1), because the methane energy also increases in the fuel by ~19.3%, ~24.9% and ~29%, respectively (Fig. 3).

Petrol and biomethane were injected separately via the internal combustion engine air intake manifold. The engine working parameters and petrol injection was controlled with a MoTeC M800 programmable electronic engine control unit. The biomethane was injected by additional injectors using an electronically controlled OSCAR-N gas injection system. The studies were performed with the engine fuelled with only pure petrol (P) and petrol with additional feeds of 20 l/min (P + M65% 20 l/min), 25 l/min (P + M65% 25 l/min) and 30 l/min (P + M65% 30 l/min) of biomethane. The fuel properties are provided in Table 1.

A schematic diagram of the experiment is provided in Fig. 2. The HR 16DE spark ignition internal combustion engine from the Nissan Qashqai was used as the test engine. The technical data for the engine are provided in Table 2. The engine was controlled by using a MoTeC M800 programmable electronic control unit. During the experiments, the following engine parameters were maintained electronically: shaft rotation speed n = 2000 min^{-1}, 15% open engine throttle and stoichiometric mixture λ = 1. The advance ignition angle Θ was changed during the test from 14 °CA BTDC to 30 °CA BTDC. The engine load was generated by eddy current load stand AMX 200/100 over which engine effective torque M_e was measured. In-cylinder pressure was traced by integrated pressure sensor AVL ZI31_Y7S in spark plug (sensor nominal sensitivity 12 pCul/bar) and recorded using AVL DiTEST DPM 800 equipment. Petrol (P) hourly consumptions (B_{d_P}) were measured using electronical fuel consumption meter AMX 212F. Biomethane gas (M65%) consumptions were measured using gas meter KG-0095-G06-94-10. Exhaust emissions were measured with an AVL DiCom 4000 exhaust gas analyser.

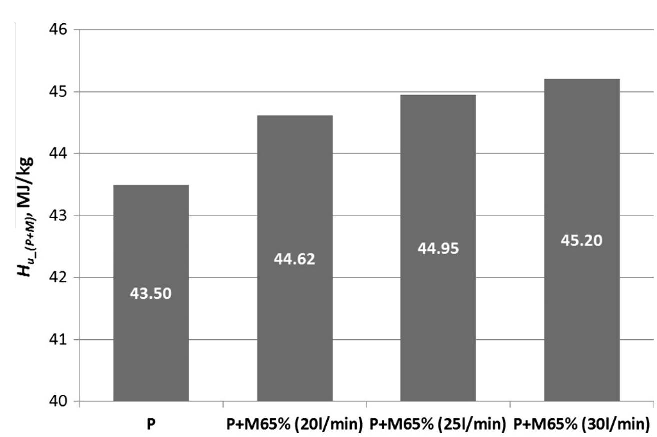

Fig. 1. Dependence of the fuel mixture lower calorific value (H_u) on the additional amount of biomethane gas supplied.