Low calorific gas combustion in an SI engine under oxygen enrichment

Rolandas Paulauskas*, Adolfas Jančauskas*, Ernest Bykov*, Kęstutis Zakarauskas*

Rolandas.Paulauskas@lei.lt

*Lithuanian Energy Institute, Laboratory of Combustion Processes, Breslaujos g. 3, Kaunas, 44403, Lithuania

Abstract

Landfills are the third-largest source of anthropogenic methane emissions, a potent greenhouse gas contributing significantly to climate change. In response, the EU aims to phase out landfilling practices. Once organic waste is no longer deposited, methane generation declines, making Combined Heat and Power (CHP) production using conventional spark-ignited gas engines unfeasible due to insufficient gas quality and volume. Despite this, residual methane emissions to the atmosphere persist. To mitigate these emissions, landfills are typically sealed and equipped with "bio-windows"—engineered zones where methane-oxidizing microbes convert methane into carbon dioxide. However, these systems only partially reduce methane concentrations. Not all the gas generated within the landfill necessarily migrates through these bio-windows, meaning uncontrolled emissions can still escape into the atmosphere.

To mitigate this risk and recover the energy content of residual methane, this study focuses on the utilization of low-calorific gases—such as landfill gas with low methane concentrations—in a naturally aspirated spark ignition engine, operated under varying levels of oxygen enrichment. The experimental setup is based on a 100 kW, four-cylinder spark ignition engine originally designed for biogas applications, with a total efficiency of 91.7% and an electrical efficiency of 30.9%. Modifications were made to the engine's intake manifold to enable controlled air intake and pressurized pure oxygen supply. Additionally, the fuel line was adapted to include gas sensors for real-time methane concentration measurements and to facilitate adjustments to the oxidizer composition. The modified system was designed to combust low-methane gas mixtures (20 vol% CH_4 in CO_2) under stoichiometric conditions, with the oxygen concentration in the oxidizer varied between 25 and 40 vol%.

Introduction

To achieve the European Union's goal of combating climate change and reaching net-zero emissions by 2050, a transition from fossil fuels is essential. According to Eurostat data, renewable energy sources account for only 24.5% of the overall energy share. For this reason, it is critical to utilize all potential renewable energy sources, including those previously considered unfeasible. One such example is gases from exhausted landfills (LFG), which is a renewable energy source with considerable potential. Landfill gas is a product of the natural anaerobic decomposition process that occurs when biodegradable waste breaks down. It primarily consists of a mixture of methane and carbon dioxide. Established practices indicate landfill gas extracted from non-operational landfills typically contain 45–75% methane purity. However, as biodegradable material diminishes over time, the methane yield from landfills gradually decreases. Once a critical threshold is reached, the methane concentration becomes insufficient for energy production. As a result, the gases produced under such conditions remain unused and escape into the atmosphere, contributing to greenhouse gas (GHG) emissions. Therefore, using these gases for energy production prevents additional GHG emissions.

Energy is produced by combined heat and power systems, which typically use internal combustion engines (ICE). The minimum required methane concentration for ICE is 40vol%. If the methane content is lower, a significant CO_2 content lowers its calorific value becomes too low to sustain stable combustion and alters its combustion characteristic. Extremely low CH_4 content biogas presents technical challenges for ICE, leading to reduced in-cylinder peak pressure [1] and a lower heating value (LHV) of the air-fuel mixture [2]. Gas with low methane content has high self-ignition temperature directly results in high anti-knock index. Low antiknock quality leads to detonation, a phenomenon where uncontrolled combustion produces vibratory pressure waves that disrupt the normal pressure development in the engine. This results in overheating, reduced engines power and decreased overall performance and efficiency.

To answer these challenges, multiple technologies have been studied with the potential to increase the combustion stability and reduce emissions. To improve the combustion process and performance of the gases with low CH_4 content, enrichments such as propane or hydrogen can be introduced to raise its LHV [3]. However, propane is incompatible with the “Green Deal” ideology, and hydrogen technologies are still in development. Alternatively, enriching compositions with low hydrocarbon content with 1–2% additional oxygen can extend the lean ignition limit [4]. Also, these methods generally reduce CO and HC emissions [3–5]. For this reason, it is proposed that these problems could be solved using oxygen-enriched combustion technology.

An oxy-fuel combustion system, originally designed for solid fuel combustion, showed significant improvements in energy production [6]. However, the use of pure oxygen resulted in issues such as flame instability and locally high temperature gradients. To mitigate these problems and control the flame, recycled flue gas, mainly composed of CO_2, is mixed with the oxy-fuel mixture [7]. Numerical simulations have found that methane combustion with a CO_2/O_2 oxidizer mixture is most effective and stable when oxygen concentrations range from 28 to 32 vol.% [8]. Experimental studies, however, indicated slightly higher limits (31-35 vol.%) for stable combustion [9]. In both cases, lower oxygen concentrations in the CO_2/O_2 mixture led to reduced stability, and stable flames could not be sustained with oxygen levels below 23 vol.%.

Also, oxygen-enriched combustion has been extensively studied for spark ignition (SI) engines, showing potential for reducing emissions while enhancing engine performance. Investigations using oxygen-enriched air with 23–25% O_2 (v/v) have reported power increases ranging from 5% to 17%, along with a 25–32% reduction in CO emissions and a 30–40% decrease in HC emissions when combined with three-way catalysts [10]. Bench tests demonstrated that higher oxygen enrichment ratios (OERs) lead to increased combustion temperatures, improved power output, and significant reductions in HC and CO emissions. At OER = 25%, HC emissions decreased to 58–87 ppm and CO emissions dropped to 5.71–8.60% of baseline levels. However, NOx emissions increased substantially. Particulate number emissions initially rose with OER but declined at higher manifold absolute pressure and OER = 25%. For biogas-fueled SI engines, increasing oxygen concentration in the intake air extends the lean combustion limit, enhances combustion rates, and improves thermal efficiency and power output. Oxygen concentrations above 23% reduce HC and CO emissions significantly but cause a sharp rise in NOx emissions. At an equivalence ratio of 0.95, increasing oxygen from 21% to 23% at full throttle raises brake thermal efficiency from 26.2% to 28%, increases power output from 5 kW to 5.35 kW, and reduces HC and CO emissions by 41% each. Additionally, peak heat release rate improves from 63.6 J/°CA to 76.3 J/°CA, and combustion duration shortens from 36° to 31° [4]. However, NOx emissions increase by 45.6%, rising from 3440 ppm to 5010 ppm and shows a need of controlled combustion temperature to detain thermal NO reaction rate.

These findings underscore the potential of oxygen-enriched combustion technology to enhance combustion stability and extend the operational limits of ultra-low-calorific landfill gas (below 40vol% of CH_4), where high heat capacity of CO_2 cause reduction of the combustion temperature which then affects the NO formation extinguishing the technology drawbacks.

To mitigate this risk and recover the energy content of residual methane, this study focuses on the utilization of low-calorific gases—such as landfill gas with low methane concentrations—in a naturally aspirated spark ignition engine, operated under varying levels of oxygen enrichment. The experimental setup is based on a 100 kW, four-cylinder spark ignition engine originally designed for biogas applications, with a total efficiency of 91.7% and an electrical efficiency of 30.9%. Modifications were made to the engine’s intake manifold to enable controlled air intake and pressurized pure oxygen supply. Additionally, the fuel line was adapted to include gas sensors for real-time methane concentration measurements and to facilitate adjustments to the oxidizer composition. The modified system was designed to combust low-methane gas mixtures (20 vol% CH_4 in CO_2) under stoichiometric conditions, with the oxygen concentration in the oxidizer varied between 25 and 40 vol%.

Experimental methodology

The CHP unit consisting of the spark ignition engine, generator and controlling unit was purchased from company TEDOM. The system title is MICRO 30 designed for biogas fuel with minimal methane content of 50 vol%. The unit was mounted into the container of 6 m length and 2.5 m wide (see Fig. 1).

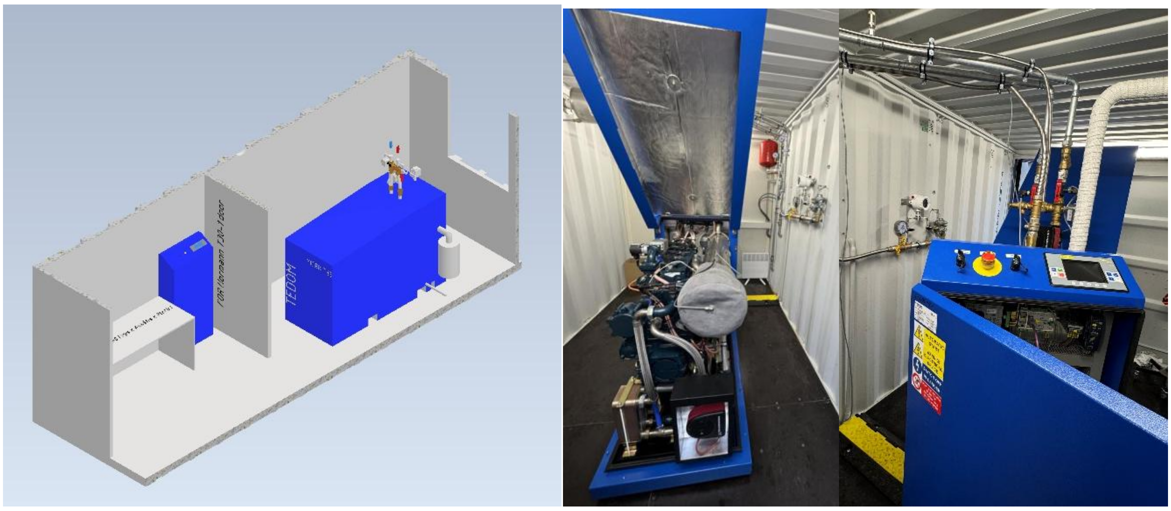

Figure 1. 3D drawing and photos of the prepared CHP unit.

The unit was connected to the secondary heating line which consisted of 100 kW heat exchanger to ensure sufficient cooling for the engine. During the engine work, the load was controlled from 4.5 kW to 27 kW. Main technical parameters of the engine are presented in Table 1.

Table 1. Technical parameters of CHP unit Tedom Micro 30

Parameter	***Value***	***Parameter***	***Value***
Electrical output	30 kW	**Secondary cooling circuit**	
Heat output	59 kW	Heat output total	59 kW
Fuel input	97,1 kW	Inlet/outlet temperature	65-85 °C
Fuel efficiency	97,1%	Max/min inlet temperature	70/40 °C
Engine	TB 40 G5V NX88	Volume/flow	50 dm^3/0.7 kg/s
No of cylinders	4	**Exhaust**	
Arrangement	inline	Flow	131 kg/h
Bore x stroke	100 x 120 mm	$T_{max/min}$	210/180 °C
Displacement	3769 cm^3	**Fuel**	
Compression ratio	13:1	Biogas (CH_4 concentration	Min: 50%, Nom: 65 %
Speed	1500 min^{-1}	T_{max}	35 °C
Primary cooling circuit		**Air**	
Inlet/outlet temperature	65-85 °C	$T_{min/max}$	10/35°C
Max allowed pressure	130 kPa	Quantity	114 kg/h
Coolant volume	13 dm^3		
Coolant type	ethylene glycol (35%)		

To simulate biogas composition, natural gas was mixed with CO_2 supplied from the cylinders and the CO_2 content in the mixture was increased from 35 vol% to 80 vol% during the work of the engine. The methane concentration in the stream was measured using the hydrocarbon sensor XDIWinF1-D/A-Flammable THE300A, range 0-100 vol%. For oxygen-enriched experiments, the oxidizer supply line was upgraded. An additional electronically controlled flap and mas flow meter were installed on the air suction line and in that case the air suction was limited by the flap according to going mass flow to the engine. The surplus of air required for combustion was replaced with pure oxygen and supplied to the engine above the installed flap. The oxygen concentration in air was increased regarding to CO_2 in the mixture and O_2 level in air changed from 21 vol% to 40 vol%. The oxygen concentration in air was measured using an installed sensor ZD22 Basic, range 0-96 vol%. The schematic layout is provided in Figure 2.

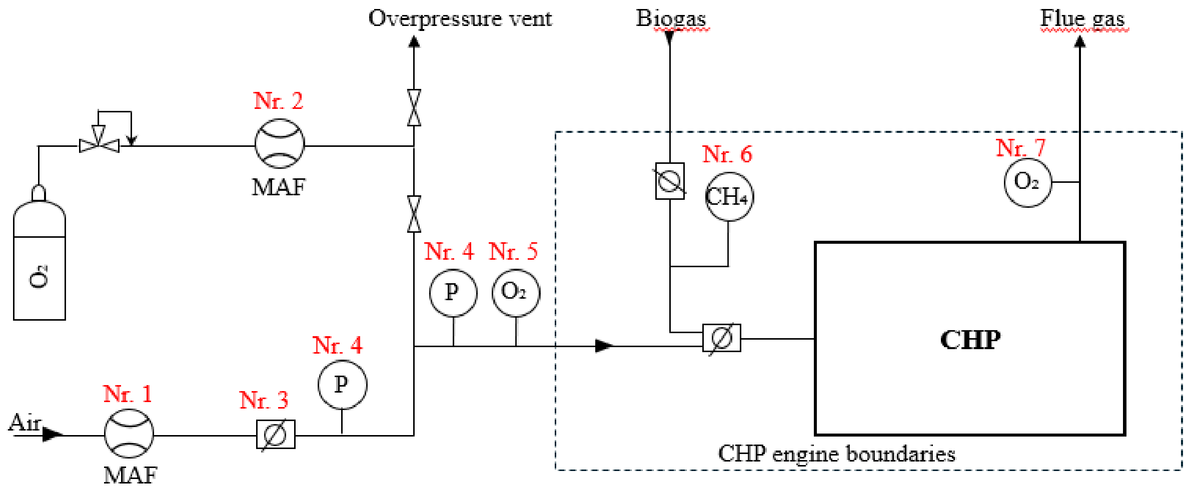

Figure 2. Scheme of fuel and oxidizer supply system to CHP: 1 – mass flow meter of sucked air, 2 – mass flow controller for pure oxygen, 3 – flap to control air suction, 4 – pressure meter, 5 – oxygen sensor, 6 – methane sensor, 7 – oxygen in flue gas sensor.

Results and Discussion

The first runs of CHP unit were performed with natural gas and main parameters were determined by changing the electrical load from 25 to 100%. Working with natural gas, the gas consumption varied from 4.7 to 15 m^3/h. With low load, the engine efficiency decreased by 5%. Figure 3 present the determined parameters at different loads.

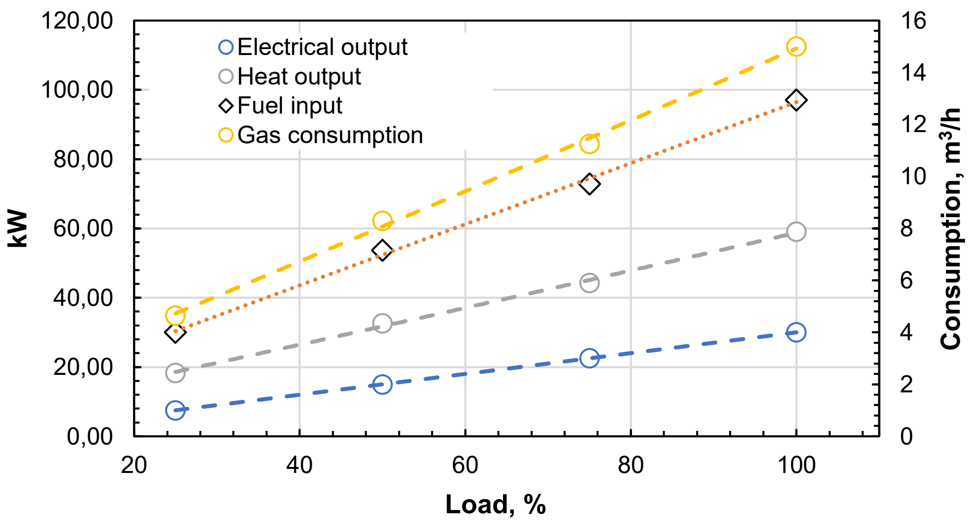

Figure 3. Main CHP parameters at different load combusting natural gas.

Further tests were acquired working on lowest methane content suitable for the CHP unit. The mixture of CH_4-50vol% in CO_2 was prepared and outputs of heat and electricity tested at 98% load. The values were similar to obtained ones under natural gas testing, but the exhaust temperature was lower. The oxygen enrichment was performed according to calculations of the adiabatic combustion temperature. The aim was not to exceed 1931 °C. If normal biogas mixture is supplied, increasing the oxygen content in the air up to 25%, the adiabatic combustion temperature increases up to 2022 °C. Due to this, the CO_2 content was increased in the mixture and engine parameters were modified for work with higher CO_2 concentration. The engine design ensured the possibility to combust mixtures with 40vol% of CH_4 in CO_2, but due to higher incombustible gas amount, the load was decreased to 92% leading to decreased electrical output to 27.5 kW. Seeking to achieve combustion of CH_4-30% in CO_2, oxygen content in the air was increased to 30vol%. This led to increased combustion temperature according to adiabatic combustion temperature calculations and exhaust temperature readings. The exhaust temperature increased by 20 °C, but the electrical output was only 24 kW due to decreased efficiency. The highest CO_2 concentrations in natural gas were set to 20 vol% and at this point the oxygen enrichment level was increased to 40 vol% of O_2 in nitrogen. Despite the increased level of oxygen enrichment, the engine efficiency has dropped and the electrical output at max load was only 21 kW. At this point of oxygen enrichment, the exhaust temperature increased and reached 450 °C while in the catalytic converter the temperature was 570 °C. Due to control program, which stops the engine when exceeding the catalytic converter temperature of 600 °C, the higher oxygen enrichment level was not tested. The heat and electricity outputs changing the engine load are presented in Figure 4.

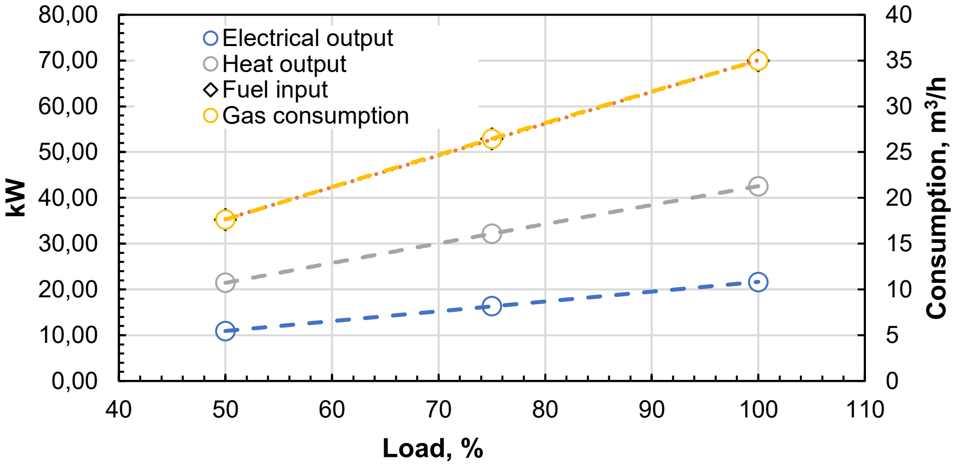

Figure 4. Main CHP parameters at different load combusting CH_4-20vol% under oxygen enrichment.

Conclusions

The initial results indicate that low-calorific value (LCV) gas mixtures can be successfully combusted in a spark ignition engine. However, due to the high CO_2 content, engine load must be reduced to maintain stable operation, resulting in a 27% decrease in both heat and electrical power output compared to operation with standard biogas (65 vol% CH_4 / 35 vol% CO_2). Despite this reduction in output, oxygen enrichment significantly enhances combustion quality and supports low pollutant emissions. As the oxygen concentration in the oxidizer increases from 25 to 40 vol%, the adiabatic flame temperature rises from 1650 °C to 1950 °C. This temperature increase, however, leads to a corresponding rise in NO_x emissions due to thermal formation mechanisms. During testing, the exhaust gas temperature remained around 450 °C, and no cylinder wall overheating was observed due to the heat absorption properties of CO_2.

Overall, the findings demonstrate that this technology has potential for deployment in closed landfills, enabling effective methane utilization and power generation from low-quality landfill gas.

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