

COMBUSTION OF SYNTHESIS GAS WITH THE CONSTANT AMOUNT OF INERT GASES IN THE MICROCOGENERATION UNIT ENGINE

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Abstract: In the scope of the green energy and climatic changes waste poses as a great resource as an alternative fuel or source for their production. This helps to decrease the need for fossil resources, as well as diversify energy production. This kind of waste utilization and mitigation therefore directly fits into latest legislation and green initiatives. This paper focuses on the influence of five synthesis gases with relatively high heating values on the internal parameters of the internal combustion engine intended for cogeneration. Measurements show that proportion of the hydrogen in the mixture has indirect influence on the combustion duration and also maximal pressure rise rate. Interestingly hydrogen proportion in fuel showed no direct influence on the maximal in-cylinder pressure. Higher CO to CH₄ ratio reduced burn time and increased maximal combustion pressure with slightly decreased performance. Concentration of CH₄ directly influenced volumetric LHV value of the mixture with subsequent influence on the IMEP and engine effective torque. Generally, operation of the engine at full load at 1500 min⁻¹ on chosen mixtures compared to the runs on methane showed decrease of engine torque output of up to 13.4% and increase of the hourly fuel consumption from 1.56 for pure methane to maximally 3.87 kg.h⁻¹ for measured gases. Lastly, for one of the fuels erratic engine operation was observed.

KEYWORDS: Synthesis gas, Combustion engine, Alternative fuel, Municipal waste, Waste to fuel

1 Introduction

Influenced by the latest scientific, political, but also popular opinions there is strong public and also legislative influence to decrease the amount of landfilled waste and to reduce waste generation in general. This goal has been subsequently included in OSN international agreements and documents such as “2030 Agenda”, or “The future we want” document [1, 2]. European action plans like: “A new Circular Economy Action Plan” from 2020, but also national legislation had been also greatly influenced [3, 4]. Despite all the governmental regulations the amount of generated municipal waste in central European region is increasing in both total and per capita production, as is shown on the Figure 1 bellow.

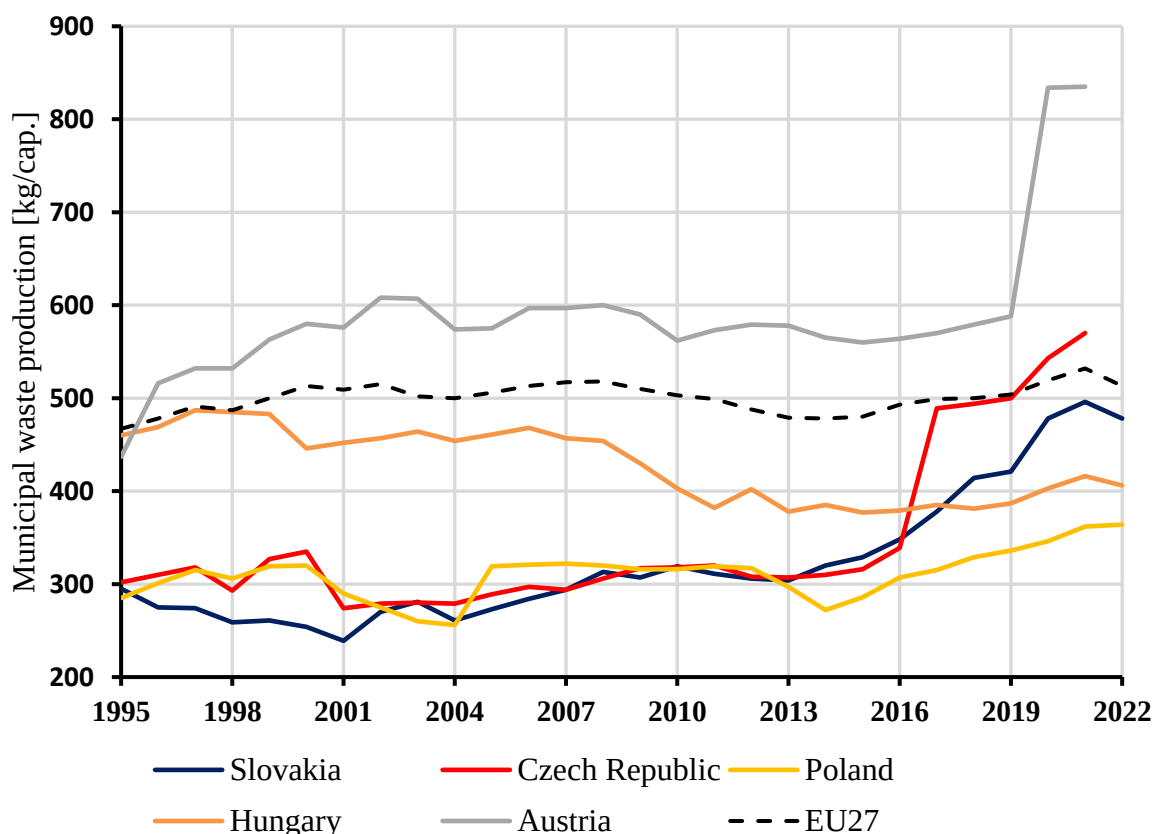


Fig. 1 Trend of per capita municipal waste production in the central European region [5].

One way to reduce the amount of landfilled waste is to separate to recycle and compost [6]. However, non-separated waste cannot be composted and not every part of the municipal waste can be recycled or is remunerative. Also recycling of materials such as plastics comes with its own negative implications and still not well understood ecological impacts [7, 8]. On the other hand, there are processes for extracting energy from the waste which are also capable of reducing the amount of the landfilled waste and therefor reduce negative impacts of landfilling while also providing alternative energy source. These processes can be divided into two groups: waste-to-fuel and waste-to-energy processes. Second mentioned include the methods of waste combustion with an electricity and heat generation. This means direct oxidation of the waste in the combustion chamber by utilizing external energy source or energy of the waste to sustain the reaction. Obtained energy is right away used to drive steam turbines. On the contrary, waste to fuel methods utilize methods of gasification and pyrolysis to chemically decompose complex organic molecules (of the municipal waste) into the simple molecules of mainly saturated hydrocarbons and carbon oxides. These methods has been studied and used for decades and are suitable for decomposing any organic substrate including waste, plastic, oil, wood chips, coal etc. Similarly to the waste energy processes, these reactions may also be sustained by external energy source or the energy in the substrate, which is than partially oxidized. Obtained gases are often referred to as synthesis gases or syngases. Their primary components are methane, hydrogen, and carbon monoxide and depending on the utilised method also ethane, or higher hydrocarbons and inert gases such as carbon dioxide and nitrogen. This gaseous mixture can be subsequently purified and used for chemical production (including synthetic fuel production) or direct use in cogeneration units [7]. Use of these fuels for engine propulsion has been researched, but due to the influences of

the boundary conditions such as chemical composition and physical properties of the substrate, method used for gasification/pyrolysis, type of the reactor, conditions inside the reactor (temperature, pressure) and subsequent chemical treatment large variety of syngas mixtures may be obtained [9]. This varying composition than influences parameters of the combustion engine as was demonstrated in previous research [10, 11]. This is why it is important to examine as many fuel combinations as possible in different scenarios to be able to identify best possible combination of gaseous components for the combustion engine in the effective working range of the gasification plant.

This article will examine the influence of the different gaseous fuels on the piston internal combustion engine operation. Used engine was intended for the utilization in the micro-cogeneration unit. Chosen fuels are meant to mimic syngases obtained from the municipal waste and plastic gasification. Results of measurements are meant to help in setting up right boundary conditions for the syngas production to achieve optimal syngas composition for the intended use. Properties of these fuel mixtures are shown in the table 1 and graphic representation of their composition is depicted in the Figure 2.

Parameter	Unit	CH ₄	G1	G2	G3	G4	G5
CH ₄	[% vol.]	100	20	20	40	30	35
H ₂	[% vol.]	0	40	30	10	30	20
CO	[% vol.]	0	25	35	35	25	30
CO ₂	[% vol.]	0	10	10	10	10	10
N ₂	[% vol.]	0	5	5	5	5	5
LHV	[MJ.kg⁻¹]	50.012	19.494	17.094	19.987	21.073	20.473
LHV	[MJ.m ⁻³]	33.353	13.630	13.798	18.466	15.963	17.212
A/F ratio	[kg.kg ⁻¹]	17.12	5.92	5.13	6.33	6.60	6.46
M	[g.mol ⁻¹]	16.04	16.82	19.42	22.22	18.22	20.22
fuel in air	[% vol.]	9.5	22.5	22.5	17.0	19.4	18.1
$\rho_{NTP\ fuel}$	[kg.m ⁻³]	0.667	0.699	0.807	0.924	0.758	0.841
$\rho_{NTPmixture}$	[kg.m ⁻³]	1.152	1.091	1.115	1.157	1.118	1.139
LHV _{mixture}	[MJ.kg ⁻¹]	2.761	2.817	2.788	2.726	2.773	2.743
LHV_{mixture}	[MJ.m⁻³]	3.172	3.064	3.100	3.145	3.090	3.115

Tab. 1 Physical and chemical properties of methane (CH₄) and synthesis gases (G), (*LHV* – lower heating value of fuel, *A/F ratio* – air to fuel ratio, *M* – molar mass, $\rho_{NTP\ fuel}$ – density of fuel at NTP, *LHV_{mixture}* - volumetric heating value of stoichiometric mixture, NTP = 20 °C, 101 325 Pa)

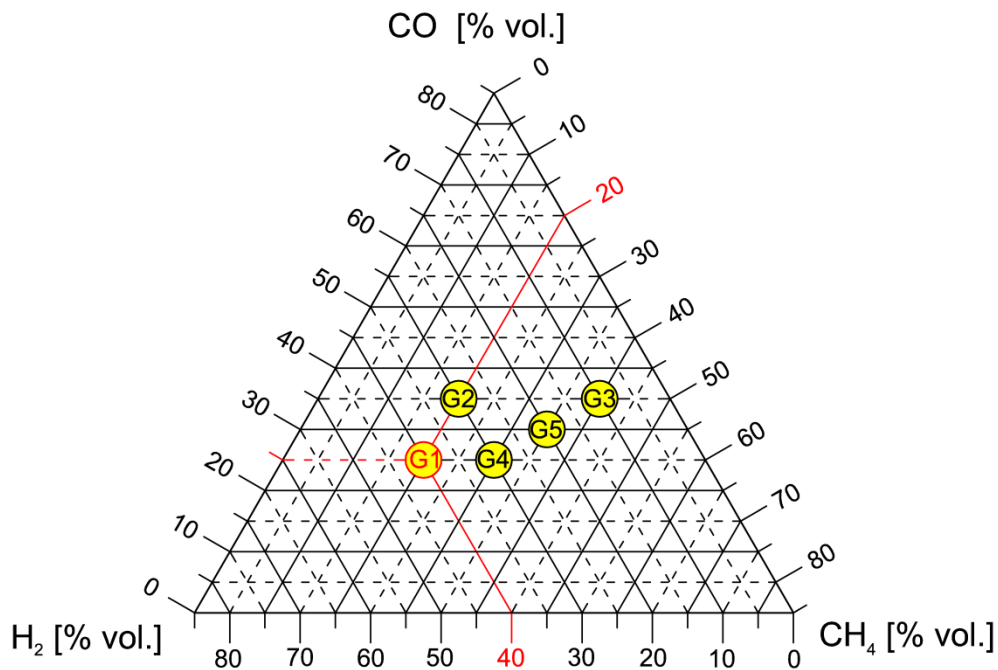


Fig. 2 Ternary diagram of chosen syngas composition with constant amount of the inert gases (10 % vol. CO_2 , 5 % vol. N_2), with highlighted example of syngas G1 composition (20 %vol. CH_4 , 40 %vol. H_2 , 25 %vol. CO).

2 Research methods

Influence of above mentioned gases on the combustion was examined on the naturally aspirated 4-stroke spark ignition combustion engine Lombardini LGW 702. Basic scheme of this research engine is shown in the Figure 3.

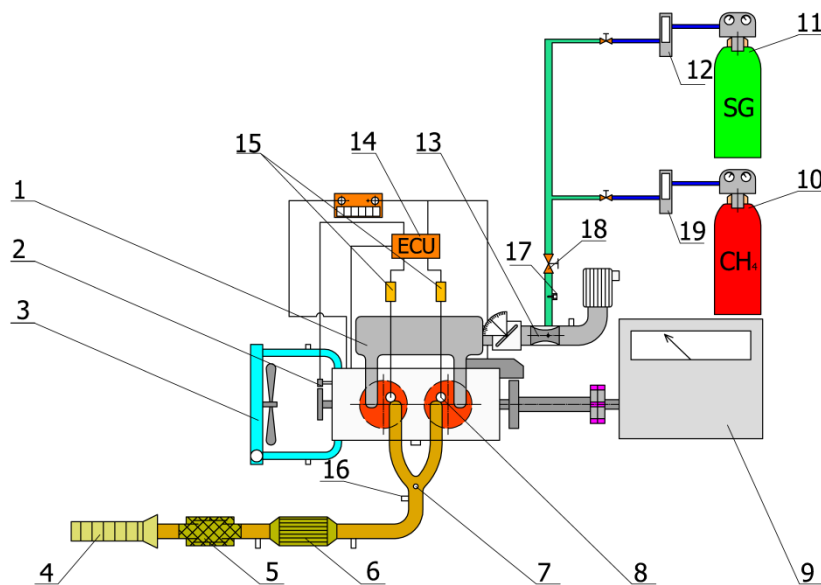


Fig. 3 The basic scheme of the internal combustion engine Lombardini LGW 702 (1 - intake manifold, 2 - crankshaft position sensor, 3 - water cooler, 4 - exhaust system, 5 - silencer, 6 – catalytic converter, 7 - exhaust temperature and pressure sensor, 8 - spark plug with integrated pressure sensor, 9 - dynamometer, 10 – methane pressure bottle, 11 - pressure bottle with syngas, 12,19 – gas mass flow meters, 13 - mixer with diffuser, 14 - engine control unit, 15 - ignition coils, 16 - broadband lambda probe, 17 - stepper motor, 18 - mixture richness regulation).

This research engine was chosen as a power-unit for a small cogeneration unit. Therefore, our results will be focused on its nominal RPM which is 1500 min^{-1} where we will gradually change the spark ignition angle to determine its optimal value for stoichiometric mixture and full load for each gas (based on the maximal average indicated mean effective pressure). Our focus will be mainly on the internal combustion parameters such as course of the pressure in the cylinder, indicated mean effective pressure (IMEP) and fuel burnout curve. These will be obtained mainly by spark plug with integrated pressure sensor and subsequent post processing in the in-house developed Matlab program. This utilizes single-zone-zero-dimensional thermodynamic model based on law of conservation of energy when the system is closed. Heat release will be determined based on the Rassweiler-Withrow method.

3 Results and discussion

As was mentioned before, our combustion investigation was based on the course of the pressure inside of the cylinder. This is depicted on the Figure 4, which lines represent the average value of the 195 consecutive cycles for stoichiometric mixture, optimal ignition angle at full load and 1500 min^{-1} for each gas.

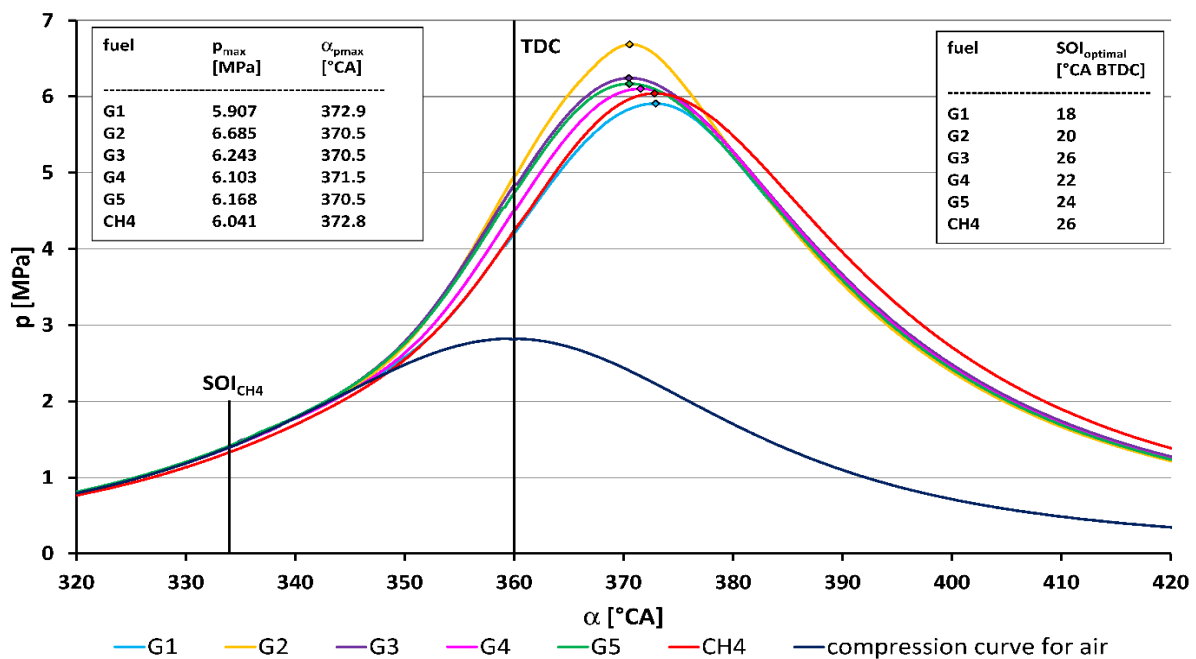


Fig. 4 Course of pressure in the cylinder of an internal combustion engine when operating on methane and synthesis gases, Conditions: speed 1500 min^{-1} , full load, the stoichiometric ratio of mixture, the optimal start of ignition angle for each fuel

As can be seen on the figure above syngas labelled G2 reached highest pressures during combustion (appx. 6.7 MPa) close to the TDC 10.5°CA aTDC. This is largely influenced by the shortest combustion duration ($\alpha_{10-90\text{MFB}}$) for this gas out of all the gases, which is visible on the Figure 5 bellow. On the contrary lowest maximal pressure was achieved on the G1 gas runs (appx. 5.9 MPa) 12.9°CA aTDC. However, this cannot be explained by the combustion duration as this syngas has had the shortest combustion duration, equal to the G2 gas (Figure 5). Moreover, this result is also interesting in the scope of fast burning hydrogen share in the gas composition (40% vol.) which was the greatest out of all the researched syngases. However, highest IMEP value was achieved for SOI 16°CA and 18°CA bTDC, which is closest to the TDC of any researched syngas and its influence on the low maximal pressure and its position is therefore most likely. Other gases achieved only slightly higher maximal

combustion pressures compared to the methane ($6.10 \div 6.24$ MPa vs. 6.04 MPa), marginally closer to the TDC ($10.5^\circ\text{CA} \div 11.5^\circ\text{CA}$ aTDC vs. 12.8°CA aTDC).

Maximal pressure rise rates were almost all slightly higher than the reference methane fuel (0.225 MPa/ 1°CA) in the range of 0.229 MPa/ 1°CA for G2, up to 0.240 MPa/ 1°CA for syngas G3. The only exception was gas labelled G1 with maximal pressure rise rate value of 0.195 MPa/ 1°CA . These values are unforeseen as the gas with highest hydrogen proportion had lowest pressure rise rate and on the other hand gas with the lowest amount of hydrogen had the highest pressure rise rate.

Bellow depicted courses of the combustion (Figure 5) show that all the researched gaseous mixtures were burning faster compared to the stoichiometric mixture of the methane (24.4°CA) with the longest $\alpha_{10-90\text{MFB}}$ angle of 23.4°CA for gas labelled G3 and the shortest $\alpha_{10-90\text{MFB}}$ angle of 19.5°CA for already mentioned gases G1 and G2. Slow burn of the syngas G3 was expected as it contains the lowest amount of the hydrogen (10% vol.) and highest amount of methane (40% vol.) and carbon monoxide (35% vol.). Also, as expected the G1 gas with the highest proportion of hydrogen (40% vol.) had the shortest burn time observed.

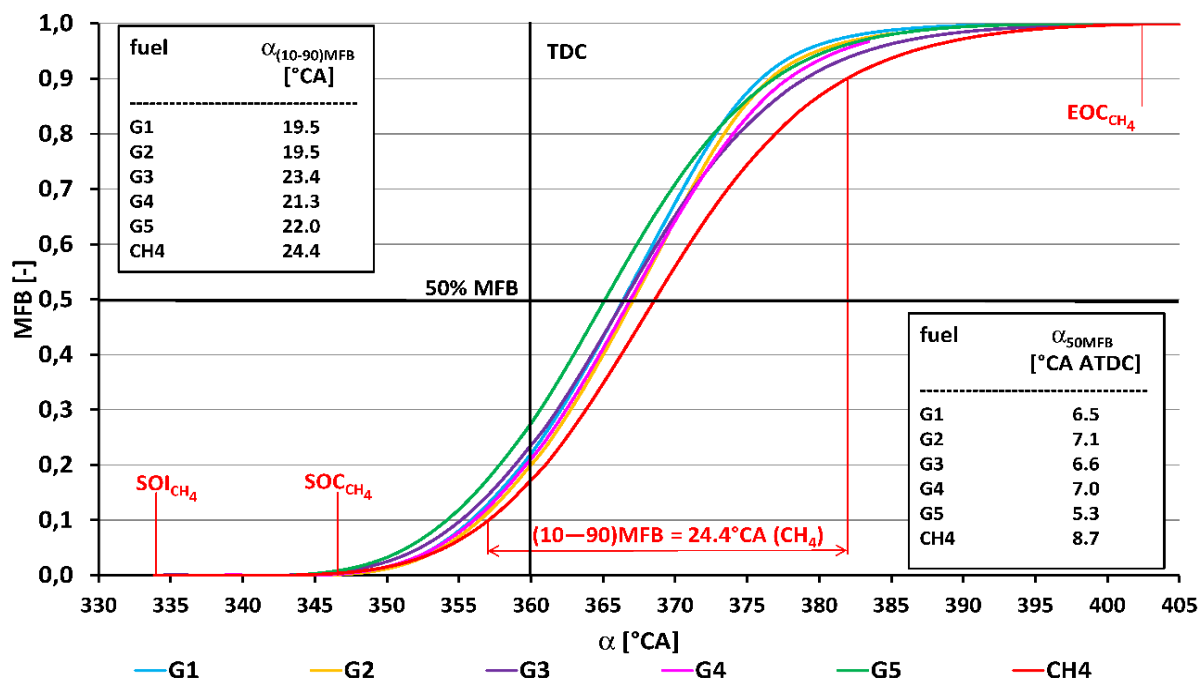


Fig. 5 Course of burning of fuel as dependent on the crankshaft angle for methane and synthesis gases (G1-G5) (MFB - Mass Fraction Burned, α - Crankshaft Rotation Angle, TDC – Top Dead Centre, SOI – Start of Ignition, SOC – Start of Combustion, EOC – End of Combustion) Conditions: 1500 min^{-1} , full load, stoichiometric mixture, optimal SOI angle for each fuel

Maximal combustion pressure and fuel burnout can illustrate some influence of the fuel on the engine output power and torque. However, superior parameter for this evaluation is Indicated Mean Effective Pressure (*IMEP*). Values of *IMEP* for all the researched gases and ignition angles are depicted by dots in the Figure 6.

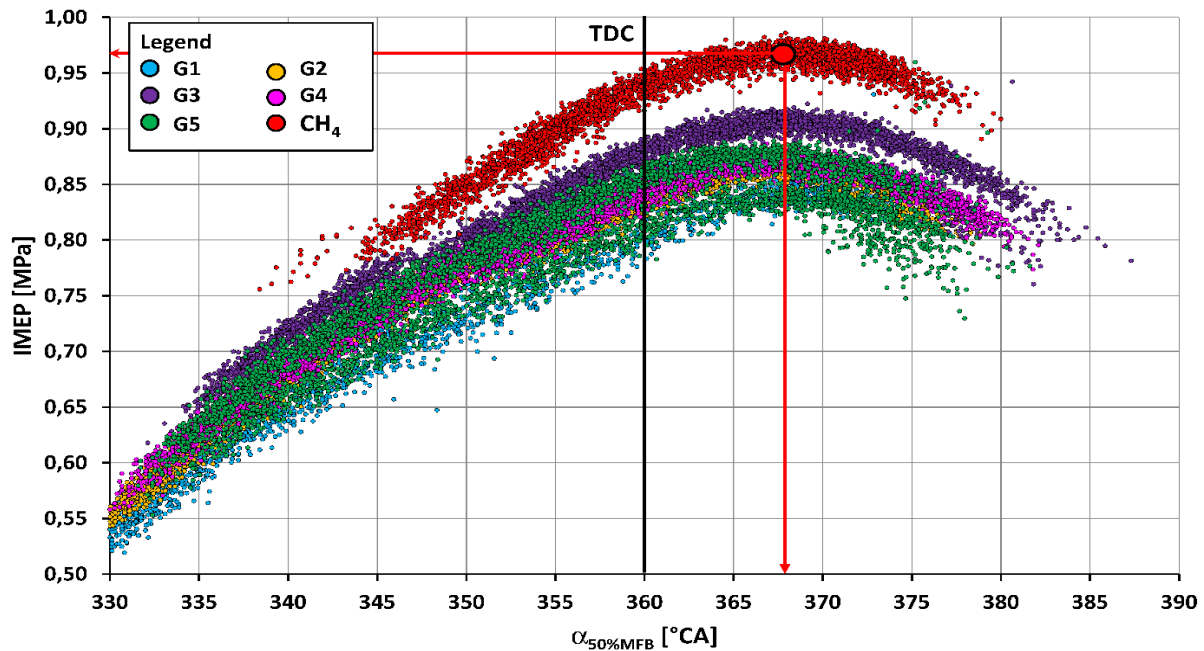


Fig. 6 Course of the indicated mean effective pressure (IMEP) depending on the angle when 50% of the fuel mass is burned for methane and synthesis gases, with a marking of max. IMEP values for methane (optimal star of ignition (SOI) angle 26°CA BTDC). Conditions: speed 1500 min⁻¹, full load, the stoichiometric ratio of the mixture

Average *IMEP* values for the ideal ignition angle were achieved while burning pure methane with the value of 0.965 MPa. This value was followed by the syngas G3 with the *IMEP* value of 0.903 MPa. It is evident from the mentioned graph that while burning gas labelled as G5 there was a large fluctuation in the *IMEP* values which may result in instable engine operation. Coefficient of variation for the G5 gas *IMEP* during combustion at the ideal ignition angle was 2.91% which is almost 6 times the value of *COV* for the G2 gas (0.55%) and almost double of the second highest *COV* value of the G1 gas (1.71%). Third highest *IMEP* value was recorded for the G4 gas (0.868 MPa), followed by the G2 (0.865 MPa), G1 (0.8605 MPa) and G5 (0.860 MPa) gases. It is important to add that despite lowest average *IMEP* for the syngas G5, output torque of an engine during its run was the third highest after methane and the G3 gas. However, its fluctuations were also high. Moreover, the output torque of the engine was decreased from the run on methane by 6% (G3) to 13.4% (G1). It is important to add that gas labelled G4 achieved higher performance parameters in the terms of *IMEP* (0.868 MPa vs 0.865 MPa) and also output torque (39.5 N.m vs. 38.7 N.m) compared to the G2 gas which had slightly higher volumetric lower heating value (*LHV*) for stoichiometric mixture compared to the G4 (3.10 MJ.m⁻³ vs. 3.09 MJ.m⁻³). This is possibly caused by different methane and carbon monoxide representations in each mixture. From the above-mentioned values and the table 1 is also visible expected direct correlation between the lower volumetric heating value of the stoichiometric mixtures and the *IMEP*/torque output values of the engine.

Due to the 15% proportion of the inert gases and low air to fuel ratio, increase in hourly fuel consumption was observed. This raised from 1.56 kg.h⁻¹ for methane to 3.23 kg.h⁻¹ for gas G4 and up to 3.87 kg.h⁻¹ for gas labelled as G2. This increase indirectly correlated to the air to fuel ratio, as was expected.

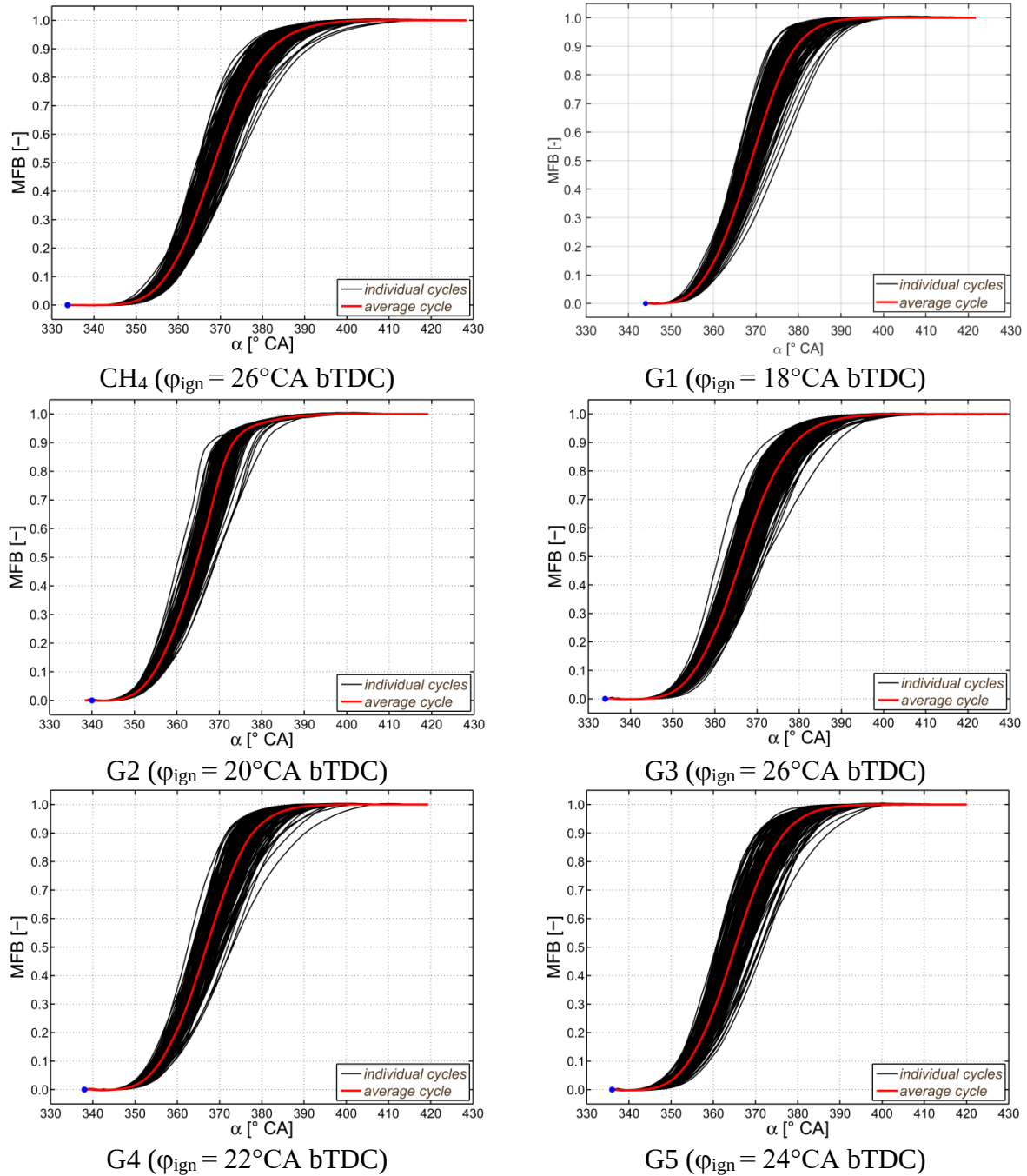


Fig 7: Mass fraction burnt (MFB) dependent on the crankshaft angle (α) (Conditions: optimum ignition angle, full load, stoichiometric ratio, speed 1500 min^{-1})

CONCLUSION

The use of waste generated gases in the cogenerating units poses a viable alternative to the fossil fuels on the way to the reduction of landfilling as well as to a more diverse and sustainable energy. While combusting these, similar internal engine parameters to the runs on the mixture of a methane or natural gas may be achieved. Selected parameters such as maximal combustion pressure, its location and maximal pressure rise rate were mostly comparable to the methane combustion. Only differentiating factors were combustion duration, *IMEP* and hourly fuel consumption. Where hydrogen addition to the mixture decreased the combustion duration and the lower volumetric LHVs of the syngases mixtures

caused decrease in the *IMEP* values which will result in the direct decrease to the torque output. However, this decrease was only 6÷13.4 %. All the observed influences of the different gaseous components were as follows:

- Maximal combustion pressure is not directly influenced by the proportion of the hydrogen in the mixture, but by the optimal *SOI* angle which are generally closer to the TDC for a hydrogen-rich mixtures and therefore may result in a decrease of a maximal in-cylinder pressures.
- Higher proportion of hydrogen in the mixture resulted in the expected decrease in the burn time.
- Higher proportion of hydrogen resulted in the decrease of the maximal pressure rise rate.
- Proportion of the methane in the mixture had a direct influence (except G2 and G4 gases) on the volumetric *LHV* of the stoichiometric mixture and subsequently on the *IMEP* and output torque of the engine.
- Hourly fuel consumption was as expected increased with a decreasing air to fuel ratio of each fuel.
- Erratic engine operation was observed while burning any, but gas labelled as G5 with high *COV* values for *IMEP*.
- By comparing gases labelled G2 and G3 it seems that higher CO to CH₄ ratio results in the faster burning of the mixture, higher maximal in-cylinder pressure, but slightly lower performance parameters.

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