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INFLUENCE OF SYNTHESIS GAS COMPOSITION ON INTERNAL COMBUSTION ENGINE PARAMETERS

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Abstract: The presented article deals with the possibility of using synthesis gas produced from municipal waste in a spark-ignition combustion engine intended for a micro-cogeneration unit. The subject of investigation is the effect of fuel composition on the internal parameters of the internal combustion engine analysed from the course of pressure in the cylinder. The analysis shows that, in general, increasing the proportion of hydrogen increases the pressure rise rate as well as the rate of heat release in the cylinder. The presented results will serve to understand the processes taking place in the combustion engine as well as the importance of the composition of synthesis gas produced from renewable energy sources in order to achieve the highest possible energy and economic evaluation in the cogeneration unit.

KEYWORDS: internal combustion engine, synthesis gases, analysis of pressure

1 Introduction

The current energy crisis in Europe, caused by the problematic supply of traditional energy sources such as oil and natural gas, leads to the increased support and use of alternative energy sources that both contribute to the diversification of energy sources and, last but not least, to the reduction of the carbon footprint by using renewable energy sources. The directive of the European Union [1] requires its members to landfill as little waste as possible or to increase the share of energy obtained from renewable energy sources and to follow the waste-to-energy (WtE) line as much as possible. The combined production of electricity CHP (Combined Heat and Power) in a cogeneration unit using synthesis gas combustion is also coming to the fore.

In addition to energy self-sufficiency, it is also important to reduce the environmental burden by improved waste management. The protection of the environment also means reasonable disposal of waste. A total of 13,164,742 tons of waste was generated in the Slovak Republic in 2020. In 2020 2,611,556 tons of municipal waste were produced. Most often, the municipal waste was deposited in landfills (1,189,239 tons), which represents up to 45.5% of the total amount. In the 2030 Environmental Strategy Framework, the Slovak government has committed to reduce the rate of landfilling to 25% by 2035 [2]. A possible solution to reducing the proportion of waste landfilling is also the waste gasification, producing synthesis gases (SG). The gas produced in this way, after being purified, can be efficiently used in a cogeneration unit. A certain disadvantage of this system is that the cogeneration unit must be built at the place of synthesis gas production due to the high consumption and storability of

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the gases. However, and at the same time, the extraction of electricity and especially waste heat from the combustion engine must be ensured. The advantage of municipal waste incineration compared to its direct burning means mainly a lower production of gaseous and solid emissions [3, 4, and 5]. In the case of landfilling, in addition to the environmental burden, there is also a risk of gradual release of landfill gas (a high proportion of methane). Ecological recovery is also advantageous when dealing with used tires [6]. The composition of synthesis gases from waste management depends mainly on the input raw material, as well as on the method of its processing. The main components of such gases are mainly methane, carbon dioxide, carbon monoxide, hydrogen and nitrogen. Before application of synthesis gases it is necessary to clean them mainly from tars and water vapour. Tars cause clogging of narrow openings as well as filters in the combustion engine [7, 8]. The amount of tar in the fuel should not exceed the value of 0.01% vol., which corresponds to the value of 10 mg.Nm^{-3} for combustion engines. At the values above 30 mg.Nm^{-3}, the operation of the combustion engine starts to be problematic [9].

In the following figure (Fig. 1) a ternary diagram is shown, in which the area of the possible composition of the synthesis gas using the gasification process is marked together with the selected composition of the synthesis gas, so as to cover the entire area. The amount of inert gases is constant for each synthesis gas (CO_2 20% vol., N_2 25% vol.).

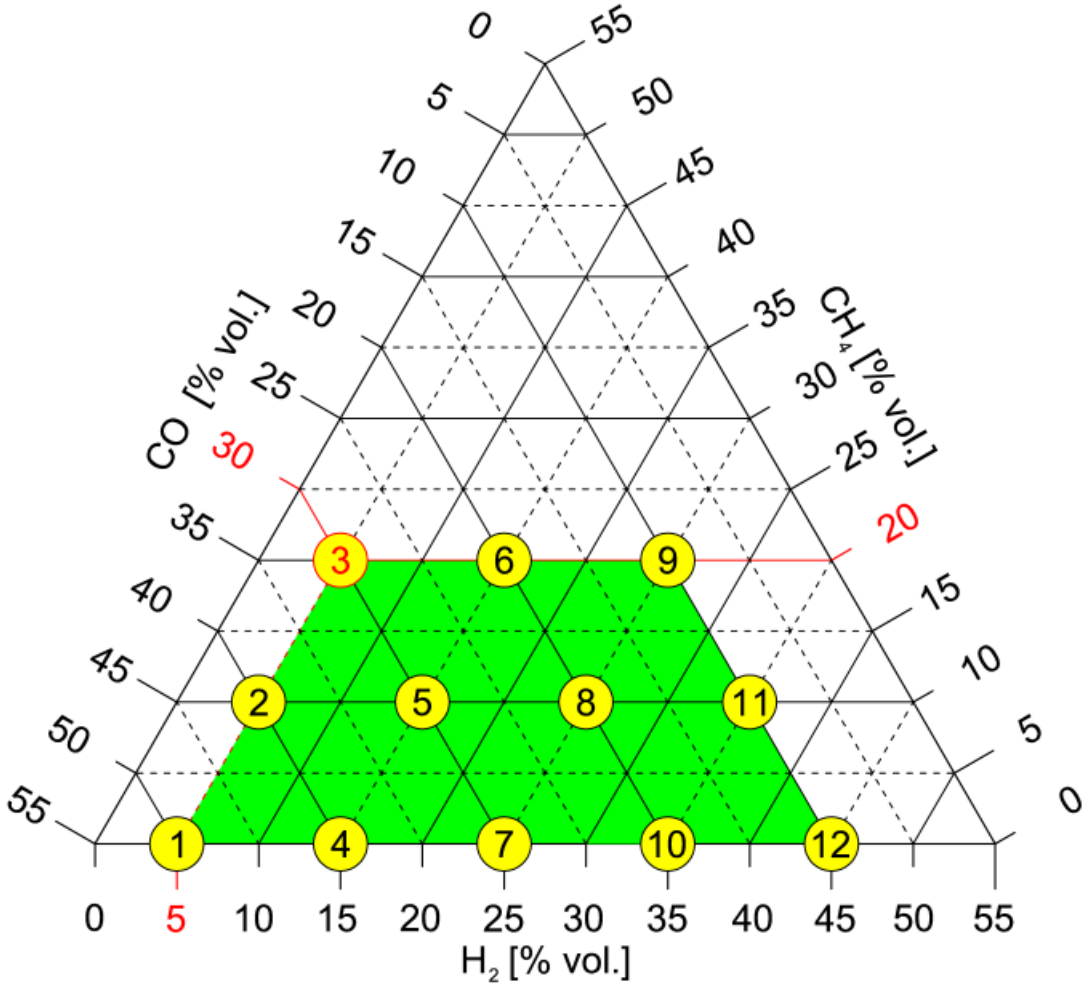


Fig. 1 Ternary diagram of the composition of synthesis gas with a constant composition of inert gases (20% vol. CO_2, 25% vol. N_2), together with an example of the composition of synthesis gas SG3 (30% vol. CO, 20% vol. CH_4, 5% vol. H_2)

The two following tables (Tab. 1 and 2) show the basic physical-chemical properties of the above-selected synthesis gases compared to the reference fuel, which was methane. The selected synthesis gases have a lower heating value in the range from 5.1 $MJ.kg^{-1}$ to 11.2 $MJ.kg^{-1}$. From the preliminary analysis, the expected performance parameters can be determined in advance, based on the volumetric heating value of the stoichiometric mixture of fuel and air. In addition to this parameter, the output performance parameters are influenced by filling the cylinder with a fresh mixture, as well as by the rate of heat release and the volumetric formation of burned gases.

Tab. 1: Physical and chemical properties of methane (CH_4) and synthesis gases (SG), (LHV – lower heating value of fuel, A/F – 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)

Parameter	***Unit***	***CH_4***	***SG1***	***SG2***	***SG3***	***SG4***	***SG5***	***SG6***
CH_4	[% vol.]	100	0	10	20	0	10	20
H_2	[% vol.]	0	5	5	5	15	15	15
CO	[% vol.]	0	50	40	30	40	30	20
CO_2	[% vol.]	0	20	20	20	20	20	20
N_2	[% vol.]	0	25	25	25	25	25	25
LHV	[$MJ.kg^{-1}$]	50.012	5.138	7.158	9.361	5.476	7.714	10.164
LHV	[$MJ.Nm^{-3}$]	33.353	6.389	8.544	10.708	6.217	8.374	10.529
A/F ratio	[$kg.kg^{-1}$]	17.12	1.26	2.04	2.88	1.38	2.24	3.17
M	[$g.mol^{-1}$]	16.04	29.91	28.71	27.52	27.31	26.11	24.92
fuel in air	[% vol.]	9.5	43.4	33.0	26.7	43.4	33.0	26.8
$\rho_{NTP\ fuel}$	[$kg.m^{-3}$]	0.667	1.243	1.194	1.144	1.135	1.086	1.036
$\rho_{NTP mixture}$	[$kg.m^{-3}$]	1.152	1.221	1.201	1.188	1.174	1.165	1.159
$LHV_{mixture}$	[$MJ.m^{-3}$]	**3.172**	**2.771**	**2.820**	**2.859**	**2.696**	**2.767**	**2.818**

Tab. 2: Physical and chemical properties of methane (CH_4) and synthesis gases (SG), (LHV – lower heating value of fuel, A/F – 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)

Parameter	***Unit***	***CH_4***	***SG7***	***SG8***	***SG9***	***SG10***	***SG11***	***SG12***
CH_4	[% vol.]	100	0	10	20	0	10	0
H_2	[% vol.]	0	25	25	25	35	35	45
CO	[% vol.]	0	30	20	10	20	10	10
CO_2	[% vol.]	0	20	20	20	20	20	20
N_2	[% vol.]	0	25	25	25	25	25	25
LHV	[$MJ.kg^{-1}$]	50.012	5.882	8.385	11.171	6.386	9.231	7.028
LHV	[$MJ.Nm^{-3}$]	33.353	6.043	8.197	10.364	5.871	8.027	5.701
A/F ratio	[$kg.kg^{-1}$]	17.12	1.53	2.49	3.55	1.71	2.79	1.94
M	[$g.mol^{-1}$]	16.04	24.71	23.52	22.32	22.11	20.92	19.51
fuel in air	[% vol.]	9.5	43.3	33.0	26.7	43.3	33.1	43.3
$\rho_{NTP\ fuel}$	[$kg.m^{-3}$]	0.667	1.027	0.978	0.928	0.919	0.870	0.811
$\rho_{NTP mixture}$	[$kg.m^{-3}$]	1.152	1.128	1.130	1.131	1.081	1.094	1.034
$LHV_{mixture}$	[$MJ.m^{-3}$]	**3.172**	**2.616**	**2.707**	**2.767**	**2.542**	**2.657**	**2.466**

Note: The methane numbers of synthesis gases were not measured or calculated. So the specific values for the measured gases are not known. But all gasses in Tab. 1 and Tab. 2 did not show signs of detonation or abnormal combustion. These gases are with a sufficient representation of inert gases, which together with methane, prevented abnormal combustion even with a higher percentage of hydrogen in the gas.

2 Experimental methods

Experimental measurements were carried out on a Lombardini LGW 702 spark-ignition combustion engine, with compression ratio 12.5:1, designed to drive a micro-cogeneration unit [10, 11]. A two-cylinder naturally aspirated engine with a displacement of 686 cm^3 was used to reduce operating costs for experimental measurements (Fig. 2). The synthesis gases (provided by the supplier) were mixed in pressure bottles and with the help of a two-stage regulator, the gases were supplied to the mixer (nozzle with a diffuser).

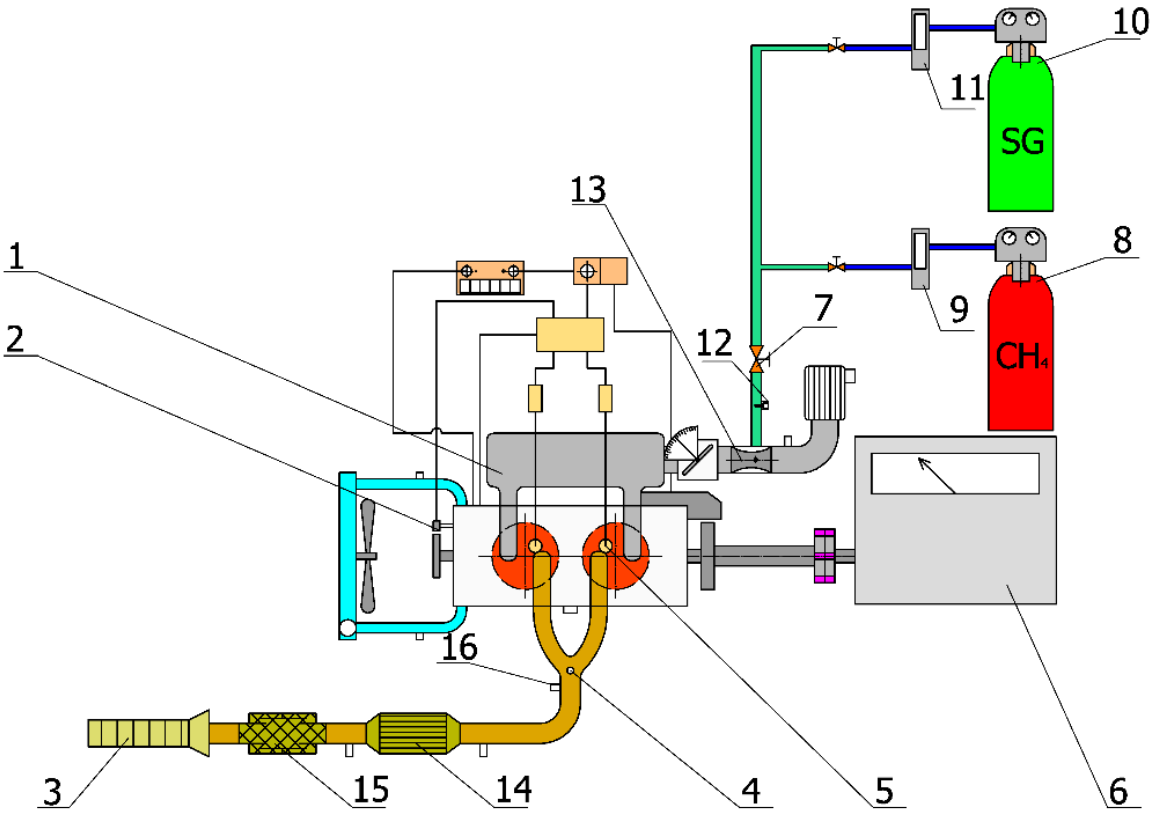


Fig. 2 The basic scheme of the internal combustion engine LGW 702 (1 - intake manifold, 2 - position sensor of the crankshaft, 3 - exhaust system, 4 - exhaust temperature sensor, 5 - spark plug with integrated pressure sensor, 6 – dynamometer, 7 – mixture richness regulation, 8 – pressure bottle of methane, 9,11 - mass flowmeter of gas, 10 - pressure bottle of syngas, 12 – stepper motor, 13 - mixer (nozzle with diffuser), 14 – catalyst, 15 – silencer, 16 – broadband lambda probe)

The load modes were performed on the MEZ Vsetín electric induction dynamometer (1DS 736V). The stoichiometric composition of the mixture has been controlled by the control unit, which by feedback regulation based on information from a wide-band lambda probe located before of the catalyst, controls the flow of fuel through a stepper motor located in the fuel

branch and regulates the amount of fuel into the mixer with the diffuser. The course of pressure in the cylinder was recorded with a piezoelectric pressure sensor located in the Kistler 6118CC-4CQ02-4-1 spark plug. The correction of the dynamic course of the pressure in the cylinder was realized by sensing the course of the absolute pressure in the intake manifold with the Kistler 4075A10 piezoresistive pressure sensor. Calibration of zero pressure level was based on assumption of reaching inlet manifold pressure just at BDC. In this situation it is presumed that there exists the same pressure in the cylinder and in the intake manifold. The Kistler 2613B1 encoder was installed on the crankshaft, which provided information about the current position of the crankshaft. In addition to the pressure curves and crankshaft position, the current value of the start of ignition angle was also recorded in the bus module with the help of a sensor with an optocoupler, which was connected in parallel with the combined BOSCH P65-T ignition coil, which can give a spark energy up to 65 mJ. The program for processing and evaluating the measured data was created in the Matlab programming environment.

The analysis was based on a one-zone dimensionless thermodynamic model [12]. The model was designed for a closed system (when zero enthalpy flow across the system boundaries is assumed) at the time of compression and expansion, assuming the validity of the law of conservation of energy. The Rassweiler-Withrow method was used to analyse the course of fuel combustion (directly proportional to the release of heat) based on the knowledge that the total pressure in the cylinder is a combination of a partial increase in pressure from the movement of the piston and a partial increase in pressure from the combustion itself. The calculation is based on the following relationship:

$$dU = dQ - dW + \sum_i h_i . dm_i \tag{1}$$

Where:

- dU - differential of internal energy of matter in the system
- dQ - differential of heat delivered to the system
- dW - differential of the work produced by the system
- $h_i.dm_i$ - i-th component of enthalpy of mass flow across system boundaries (during combustion, this term is assumed to be zero)

The beginning and end of combustion is determined by means of entropy change in a closed system, and these values are then verified using the logarithmic p-V diagram (the deviation of the combustion curve from the compression or expansion straight line). During each operating mode (start of ignition angle change, fuel change) 197 consecutive cycles were recorded at the internal combustion engine operating speed of 1500 rpm.

The most important indicator of performance parameters that can be obtained by indicating the pressure in the cylinder is the mean indicated pressure (IMEP). The following graphs (Fig. 3 and Fig. 4) show IMEP curves depending on the angle at which 50% of the fuel is burned. The individual IMEP values are plotted in the graphs as a set of 197 consecutive cycles for each mode of operation, in which the start of ignition angle has been gradually reduced from 40 °CA BTDC to the value when the internal combustion engine is still capable of continuous operation without misfiring. The graphs also show dispersion of individual values, which represents the coefficient of variation (COV). The comparison fuel has always been pure methane. The highest values of IMEP (0.845 MPa) have been achieved when operating on synthesis gas SG2. In this optimum operating mode (φ_{ign} = 30 °CA BTDC), the value of COV_{IMEP} is 2.55%, which can also be seen in the dispersion of individual values. To the

contrary, the lowest performance parameters are achieved when the combustion engine is operated on synthesis gases, which have a high content of hydrogen (35 or 45% vol.). Specifically these are gases marked SG10 or SG12. As can be seen from the graph (Fig. 4), with the decreasing start of ignition angle, the angle $\alpha_{50\%MFB}$ moves after TDC, but taking into account the problems with the uniformity of running of the combustion engine (misfiring), the maximum possible values of IMEP have not been reached. The smallest achieved start of ignition angle was for SG12 16 °CA BTDC, when the value of IMEP was 0.678 MPa at the position $\alpha_{50\%MFB}$ 2.9 °CA ATDC. For the other synthesis gases, the angle $\alpha_{50\%MFB}$, at which the highest performance parameters were achieved, varied in the interval from 2.7 °CA ATDC (SG2) to 11.3 °CA ATDC (SG6). The decrease in the performance parameters compared to operation on methane was from 12% to 30%.

The following graphs (Fig. 5 and Fig. 6) show average pressure curves in the area of compression and expansion for optimum start of ignition angles for the given synthesis gas compared to the reference fuel, which was methane. The highest values of maximum pressure (6.28 MPa) have been achieved by the synthesis gas from the first group SG2. However, considering the large negative area before TDC and a rapid drop in the pressure curve in the expansion stroke, the synthesis gas SG2 has lower performance parameters compared to methane. The lowest values of maximum pressure (4.84 MPa) have been achieved when burning SG6.

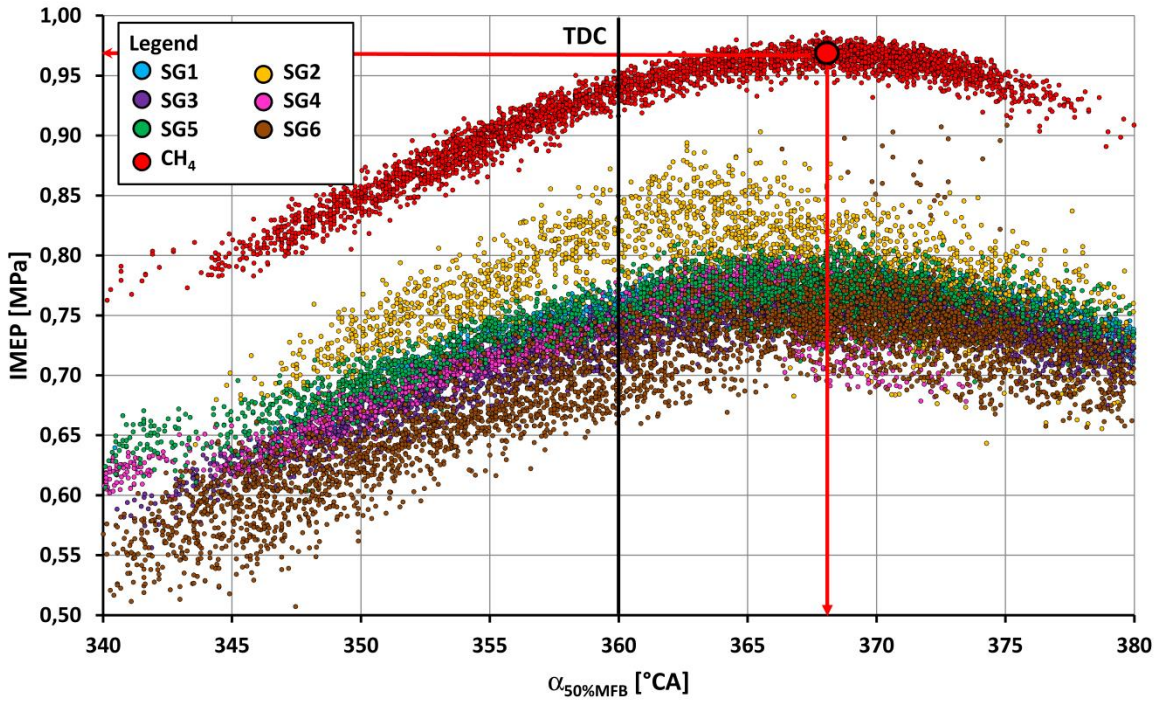


Fig. 3 Course of the mean indicated pressure (IMEP) depending on the angle of rotation of the crankshaft α50% MFB, when 50% of the mass of the fuel is burned during the combustion of methane and synthesis gases (SG1-SG6). Conditions: 1500 rpm, full load, stoichiometric mixture

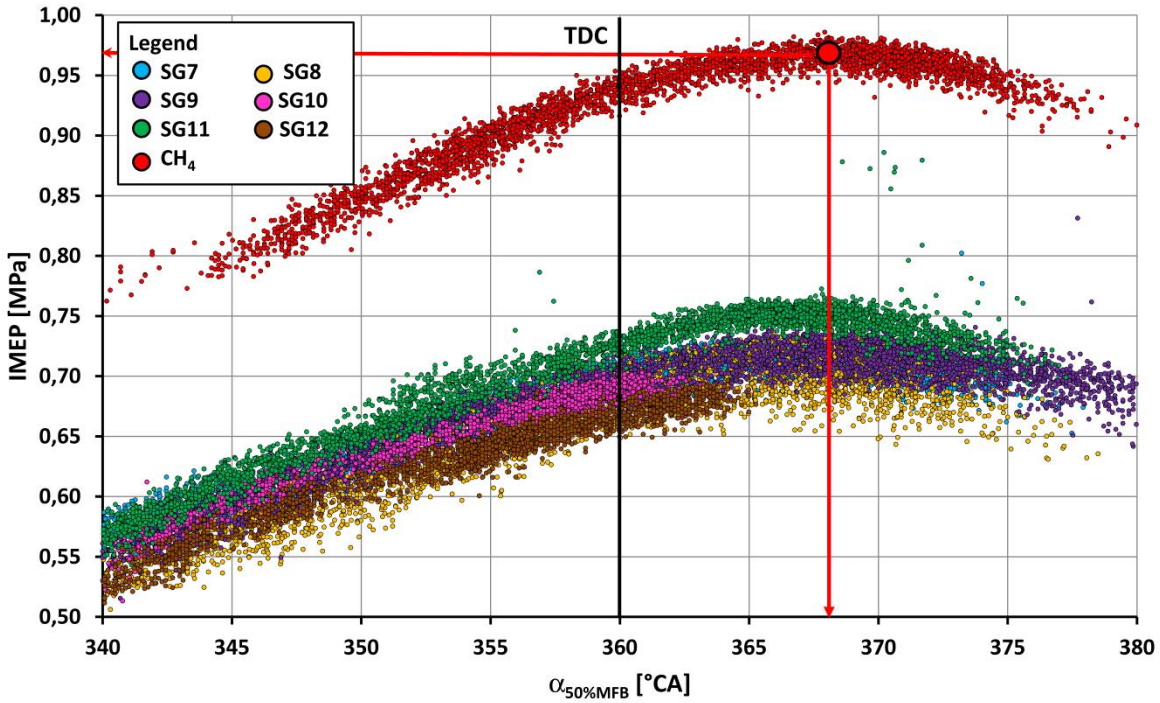


Fig. 4 Course of the mean indicated pressure (IMEP) depending on the crank angle of the crankshaft α50% MFB, when 50% of the mass fraction of the fuel is burned during the combustion of methane and synthesis gases (SG7-SG12). Conditions: 1500 rpm, full load, stoichiometric mixture

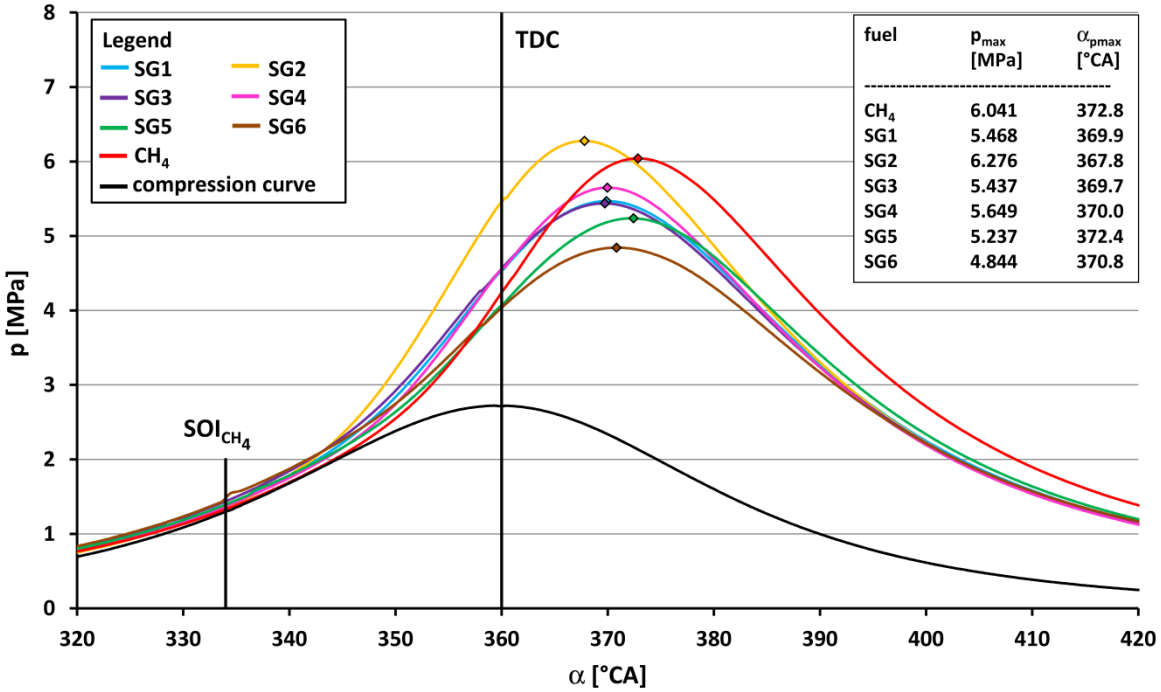


Fig. 5 Pressure profile **p** in the cylinder of internal combustion engine during operation on methane and synthesis gases (SG1-SG6). Conditions: 1500 rpm, full load, stoichiometric mixture, optimal start of ignition (SOI) angle for each fuel, compression curve is for air

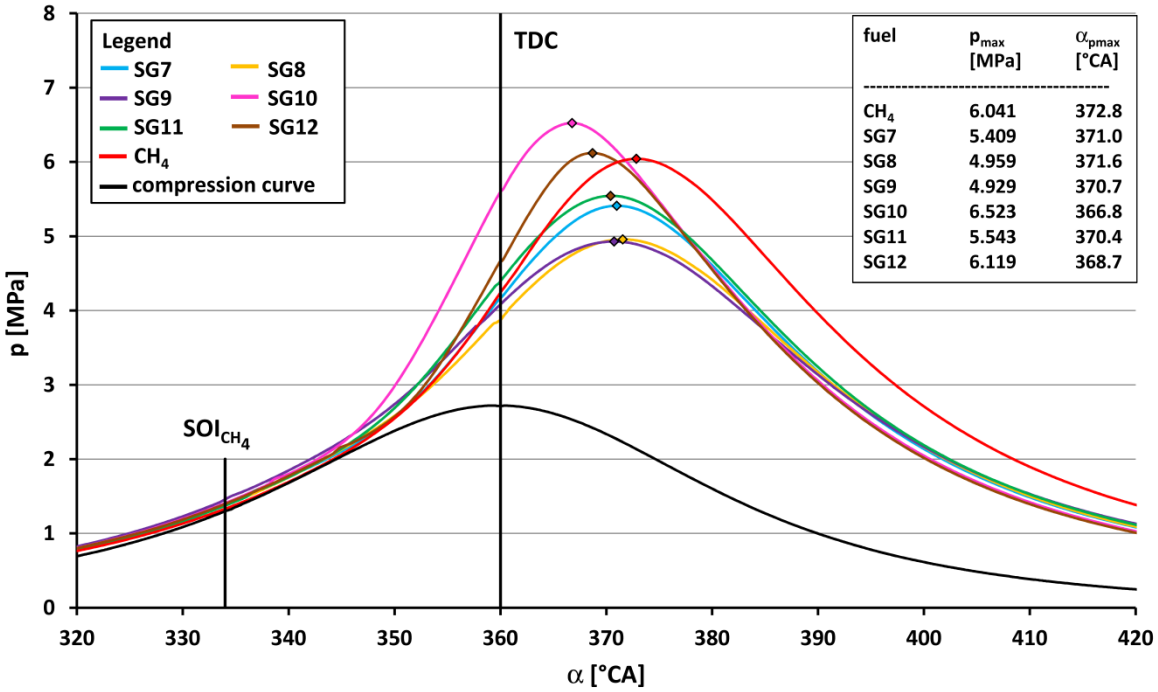


Fig. 6 Pressure profile **p** in the cylinder of an internal combustion engine during operation on methane and synthesis gases (SG7-SG12). Conditions: 1500 rpm, full load, stoichiometric mixture, optimal start of ignition (SOI) angle for each fuel, compression curve is for air.

From the other half of synthesis gases (Fig. 6) the highest maximum pressures were measured for SG10. However, it should be added that this synthesis gas did not have the optimum start of ignition angle set, due to the fact that at a start of ignition angle lower than 22°CA BTDC, the combustion engine exhibited a highly running instability in operation. Also the synthesis gas SG12 exhibited instability of the engine operation, when the start of ignition angle was less than 16°CA BTDC. Therefore, these two gases could not be correctly compared and evaluated with the other measured gases, since the instability of operation was encountered when searching for the optimum start of ignition angle. The maximum pressure ranged from 7.8 °CA ATDC for SG2 to 12.4 °CA ATDC for SG5.

The coefficient of variation for maximum pressure is 6.8% when the engine is operating on the reference fuel (methane). Out of the synthesis gases (except for gases SG10 and SG12), the highest value COV_{pmax} (8.92 %) was exhibited by the gas labelled SG9 and, on the contrary the lowest value (4.77 %) was observed with SG4. An important parameter that is manifested by increasing noise during combustion and also a shorter lifetime of the individual engine components is the pressure rise rate of the operation. When operating on methane, the maximum value of pressure rise rate was 0.225 MPa/1°CA. When operating on synthesis gases, the highest maximum value of pressure rise rate was (0.247 MPa/1°CA) measured for the gas SG2. Conversely, the lowest value (0.144 MPa/1°CA) was recorded when operating on the synthesis gas SG6. A good correlation can be found between the time span of the main combustion (10-90% MFB) and the value of pressure rise rate. The shorter the main combustion period, the increasing the pressure rise rate of the operation. In general, it can be stated that increasing proportion of hydrogen in the mixture increases the value of pressure rise rate.

The following graphs (Fig. 7 and Fig. 8) plot the dependence of the maximum pressure on the value of the angle, when 50 wt. % of the fuel has been burned. The plot was produced by gradually varying the start of ignition angle from 40 °CA BTDC to the start of ignition angle value when the engine was observed to be still running steadily. The step change was 1 °CA. Over the course of one measurement 197 consecutive cycles were recorded. Analysis of the maximum pressure values for the reference fuel shows that the maximum pressure value has settled at approximately 8.5 MPa, and when increasing the start of ignition angle this value does not change. This is due to the fact that the main combustion takes place before TDC, i.e. in the time of the compression stroke, however, at the same time the piston has not yet reached TDC and thus the stroke volume reduction is still in progress. The course of this dependence has an inverted S-shape. The location of the inflection point is approximately 6.1 MPa and 8.5 °CA ATDC. This region of the inflection point represents the operation of the internal combustion engine on methane with the optimum start of ignition angle (26 °CA BTDC). As can also be seen from the following graph (Fig. 8), the 50%MFB value (8.6 °CA ATDC) for optimum start of ignition angle is approximately the same as for SG10 and SG12 gases, where the values around the inflection point are not reached due to the inability to optimize the start of ignition angle. The dispersion of the maximum pressure values can also be seen from the plots that are numerically expressed by the coefficient of variation.

In general, it can be stated that the inflection point of the curves corresponds to the optimal operation of the combustion engine, when the highest performance parameters are achieved.

The last two graphs (Fig. 9 and Fig. 10) show the fuel mass fraction burnout curves (MFB) as a function of the crankshaft rotation angle for different synthesis gas mixtures compared to methane. The ignition delay (time between spark jump (SOI) and moment of visible combustion (SOC)) is approximately 12.5 °CA at the optimum start of ignition angle for methane. The main combustion (10-90% MFB) takes 24.4 °CA. The total burning period for methane (the period between SOC and EOC) is approximately 56 °CA.

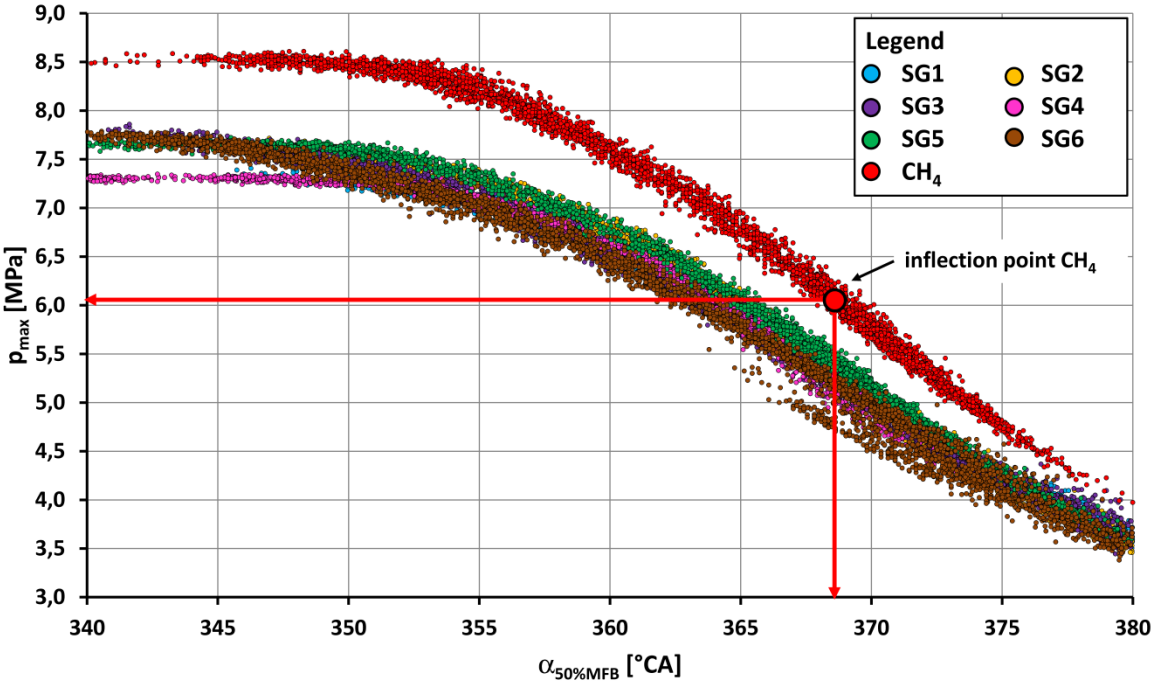


Fig. 7: The course of the maximum pressure depending on the angle at which 50 % of the fuel methane and synthesis gases (SG1-SG6) is burned. Conditions: 1500 rpm, full load, stoichiometric mixture.

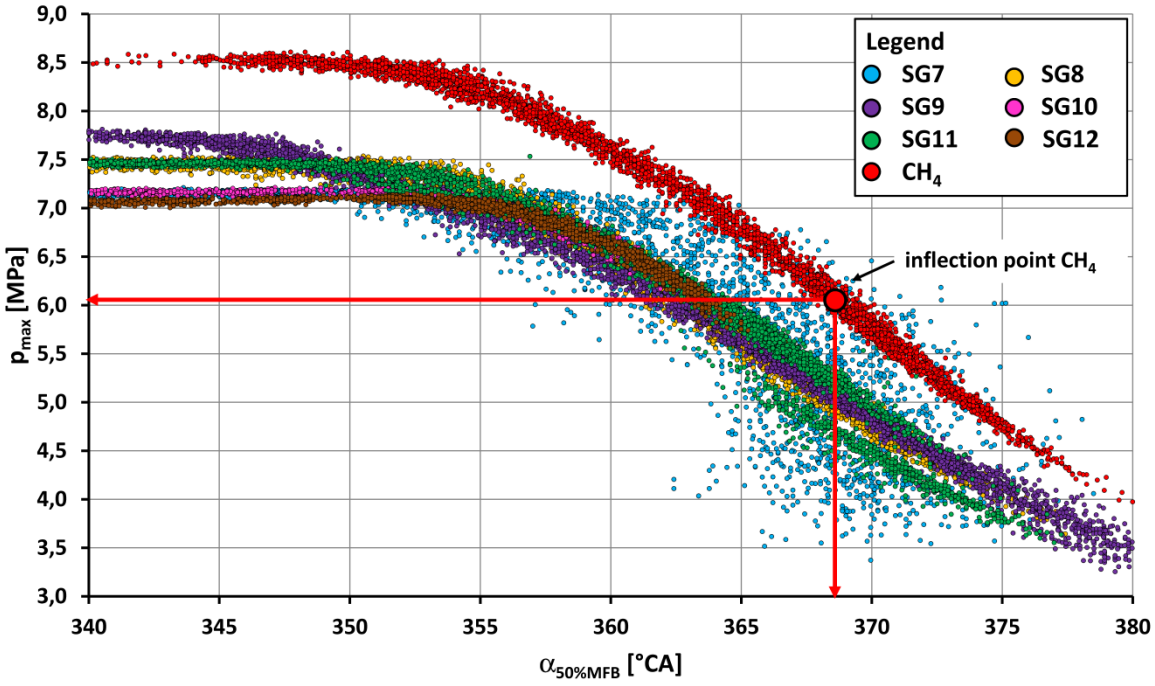


Fig. 8 The course of the maximum pressure depending on the angle at which 50 % of the fuel methane and synthesis gases (SG7-SG12) is burned. Conditions: 1500 rpm, full load, stoichiometric mixture.

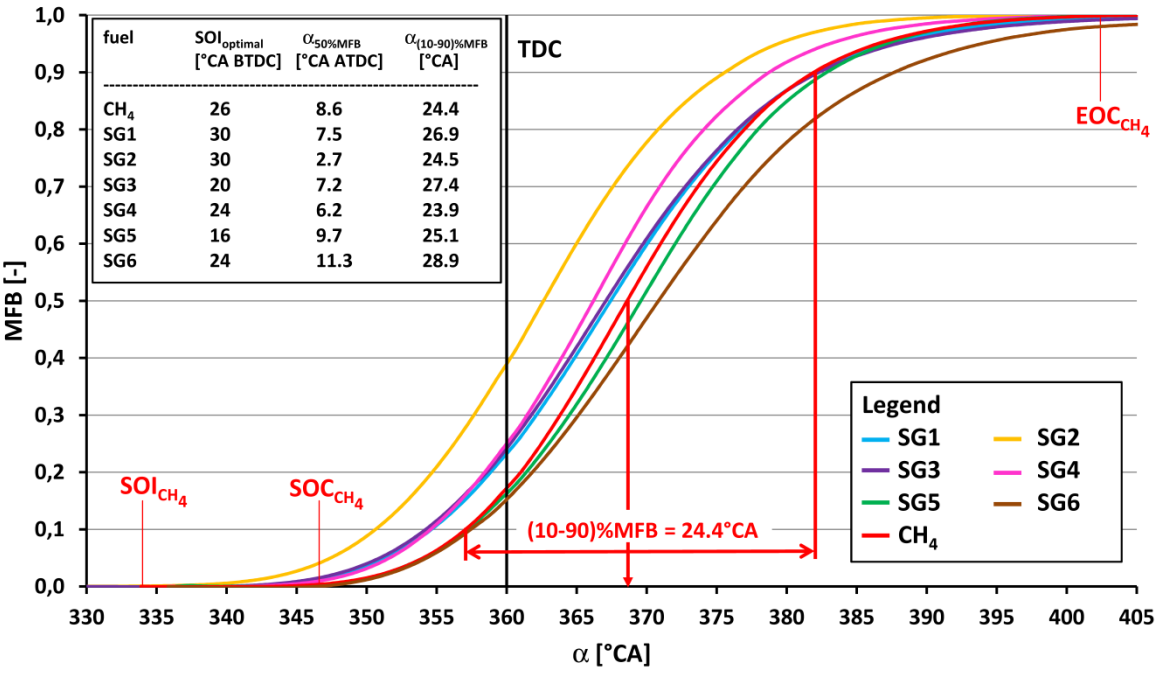


Fig.9 Course of burning of fuel as dependent on the crankshaft angle for methane and synthesis gases (SG1-SG6)(MFB - Mass Fraction Burned, α - Crankshaft Rotation Angle, TDC – Top Dead Centre, SOI – Start of Ignition, SOC – Start of Combustion, EOC – End of Combustion) Conditions:1500 rpm, full load, stoichiometric mixture, optimum SOI angle for each fuel

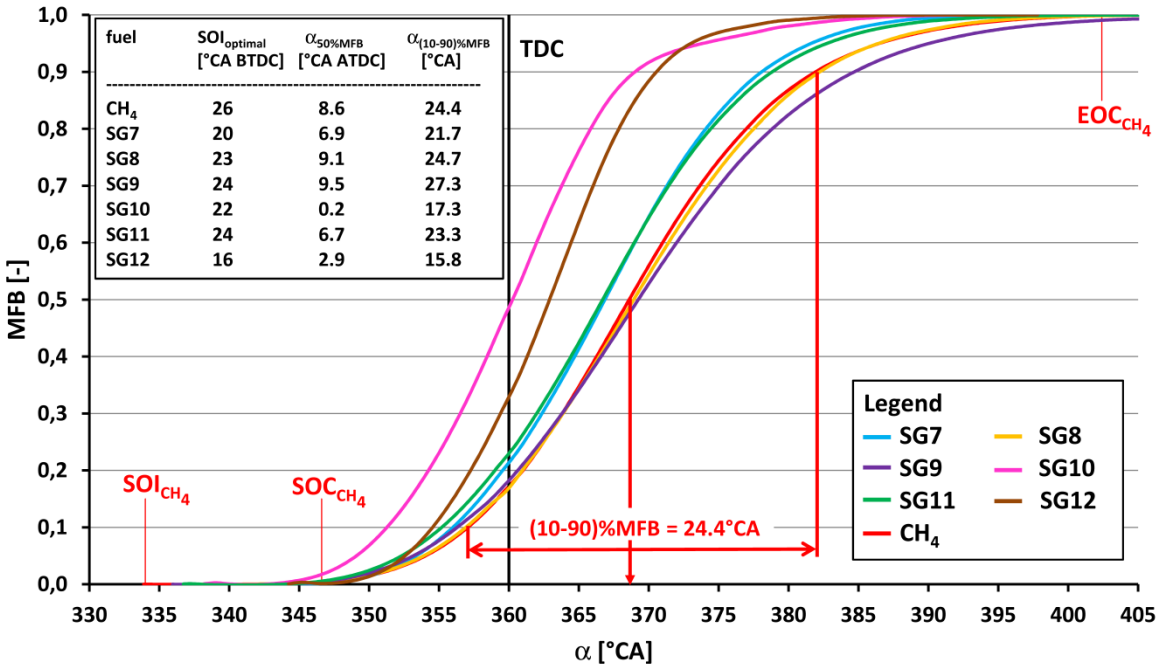


Fig. 10 Course of burning of fuel as dependent on the crankshaft angle for methane and synthesis gases (SG7-SG12)(MFB - Mass Fraction Burned, α - Crankshaft Rotation Angle, TDC – Top Dead Centre, SOI – Start of Ignition, SOC – Start of Combustion, EOC – End of Combustion) Conditions:1500 rpm, full load, stoichiometric mixture, optimum SOI angle for each fuel

Comparing the combustion histories of the synthesis gases at the optimum start of ignition (SOI) angles, the fastest fuel burn-out is for the gases with the highest hydrogen content (SG10 and SG12), in which case the main combustion periods are at 17.3 and 15.8 °CA, respectively. However, it should be noted that these gases do not have optimised start of ignition angles, therefore their results can only be tentatively compared with the other gases. On the other hand, SG6, SG3 and SG9 gases have the longest fuel burn-up periods (28.9 °CA and 27.4 °CA, respectively). All these gases have a constant amount of methane (20 % vol.) and different CO/H_2 ratios (20/15, 10/25, 30/5). The shortest periods between the moment of spark jump (SOI) and the angle (SOC) at which 5% of the fuel is burned (11.1 and 8.4 °CA, respectively) have the gases that have the highest hydrogen content (SG10 and SG12, respectively). In contrast, the gases (SG1, SG2, and SG3) with a constant hydrogen content (5% by volume) have the longest initial combustion period (about 21.5 °CA).

The coefficient of variation of the angle of position (COV_α), when a given mass fraction of fuel is burned, generally increases with increasing mass fraction of the fuel burned. For methane, these values are as follows: $COV_{\alpha 10\%MFB}$ = 0.36 %, $COV_{\alpha 50\%MFB}$ = 0.53 %, $COV_{\alpha 90\%MFB}$ = 0.71 %. When burning synthesis gases, the highest COV_α values in the whole range have the synthesis gases marked SG9 ($COV_{\alpha 10\%MFB}$ = 0.50 %, $COV_{\alpha 50\%MFB}$ = 0.91 %, $COV_{\alpha 90\%MFB}$ = 1.24 %). In general, the synthesis gases SG3, SG6 and SG9 show the highest COV_α values, having a constant methane content (20% by volume). On the contrary, gases with high hydrogen content (SG12, SG10, and SG7) have the lowest COV_α values. The synthesis gas with the designation SG12 has the lowest COV_α values ($COV_{\alpha 10\%MFB}$ = 0.14 %, $COV_{\alpha 50\%MFB}$ = 0.24 %, $COV_{\alpha 90\%MFB}$ = 0.31 %).

CONCLUSIONS

The application of synthesis gases produced from renewable energy sources in stationary internal combustion engines contributes to the reduction of the carbon footprint in the environment and achieves a diversification of energy sources. In the use of synthesis gases, the volumetric heating value of the stoichiometric mixture is the determining parameter that largely determines the output power. In addition to this parameter, the filling of the cylinder with fresh mixture, which is characterised by the volumetric efficiency, is also important. Last but not least, the heat release rate (the mixture burns out in the shortest possible period in the TDC region) has an influence on the resulting performance parameters. The following points summarise the basic knowledge about the effects of synthesis gases on the internal parameters of an internal combustion engine at an operating speed of 1500 rpm:

- The start of ignition (SOI) angle for maximum power parameters ranges from approximately 16 °CA BTDC for synthesis gases with high hydrogen content to approximately 30 °CA BTDC for gases with low hydrogen content;

- The largest decrease in mean indicated pressure (0.678 MPa and 0.686 MPa, respectively) compared to methane (0.965 MPa) has been observed for synthesis gases SG12 and SG10 with the lowest mixture volumetric heating values (2.466 $MJ.m^{-3}$ and 2.542 $MJ.m^{-3}$, respectively). The synthesis gases SG12 and SG10 have the highest hydrogen content among the mixtures studied. The lowest decrease in IMEP (0.845 MPa) has been observed for the synthesis gas labelled SG2, with the mixture heating value of 2.820 $MJ.m^{-3}$;

- The highest values of the maximum pressure (6.28 MPa) have been measured for the synthesis gas SG2, and for the high hydrogen content gases SG10 and SG12, with values of 6.52 MPa and 6.12 MPa, respectively. The coefficient of variation of maximum pressure has been the lowest (approximately 2.4%) for mixtures of gases with high hydrogen content (SG10, SG12); on the contrary, the highest value of this coefficient (8.9%) has been measured for SG9.

- It can be stated that when the hydrogen content in the mixture increases, the value of pressure rise rate also increases. The highest value (0.402 MPa/1°CA) has been found for operation on gas SG12 that also has the highest hydrogen content (45 % by volume). Conversely, the lowest value (0.142 MPa/1°CA) has been measured for the gas SG3. The pressure rise rate correlates with the length of main burn and there is a directly proportional relationship between the two, i.e. the shorter is the burn period, the more the pressure rise rate value increases.

- The main combustion commonly shortens as hydrogen is added to the mixture and, conversely, it gets longer as the proportion of methane increases. Specifically, the shortest burning period (15.8 °CA, Fig. 10) has been observed for SG12 and, conversely, the longest burning period (28.9 °CA, Fig. 9) is for gas SG6 that contains 15% H2, 20% CH4, and 20% CO. The moment of burning half of the fuel was generally in the range of the interval from 2.7 °CA ATDC (SG2) to 11.3 °CA ATDC (SG6), except SG10 and SG12 gasses.

The present results indicate a high potential for the use of synthesis gases produced from municipal waste in stationary internal combustion engines as alternative energy sources for power cogeneration units. The use of synthesis gases will lead to reduced load of carbon footprint in the environment and through energy recovery to the reduction of municipal waste.

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