Strojnícky časopis – *Journal of* MECHANICAL ENGINEERING,
VOL 74 (2024), NO 3, 69 - 80

THE EFFECT OF COMPOSITION OF SYNTHESIS GAS ON THE PARAMETERS OF SUPERCHARGED COMBUSTION ENGINE

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Abstract: Synthesis gases produced from municipal waste or plastic waste pose a great alternative source of energy, as they are not only reducing dependency on the fossil fuels, but also diversify energy sector and reduce the amount of a landfilled waste. This is directly related to the recent initiatives and legislation related to the greening of transport. The presented contribution focuses on the influence of six selected synthesis gases on the internal parameters of an internal combustion engine intended for cogeneration. The investigated gases fall into the category of medium-energy gases (8 – 14 $MJ.kg^{-1}$). The experimental measurements have shown that mainly the proportion of hydrogen in the mixture has an effect on shortening the burning time and also on the maximum rate of pressure increase. A higher proportion of CO and H_2 increased the maximum combustion pressure with slightly reduced power. The concentration of CH_4 directly affected the volumetric value of the heating value of the mixture with a subsequent direct effect on the IMEP or engine torque. The engine operating at full load at speed of 1500 min^{-1}, when running on the selected mixtures in comparison with the operation on natural gas, decreased its engine torque in the range between 13 and 20% and increased its hourly fuel consumption from 2.31 $kg.h^{-1}$ for natural gas to the span of 7.90 - 12.30 $kg.h^{-1}$ for measured gases. During the measurement of the control characteristic all investigated synthesis gases have developed an abnormal (detonation) combustion near the optimum pre-ignition angle.

KEYWORDS: supercharged combustion engine, synthesis gases

1 Introduction

Currently, the world is facing many environmental challenges, among which are increasingly pronounced climate changes, environmental pollution and the associated growing volume of waste. Also for this reason, the concept of circular economy is increasingly coming afore, so it is important not only to separate and recycle, but also to look for ways to use waste either for the production of energy or for the production of fuels.

In 2022, 2,597,457 tons of municipal waste were produced in Slovakia, which represents a 4% decrease compared to the previous year.

On average, 478 kg of municipal waste was produced per inhabitant in 2022. In 2022, 50% of the total amount of municipal waste was recycled, approximately 39% of the waste ended up in landfills, and 9% of the total amount of municipal waste was used for energy. For comparison, 36% of municipal waste was evaluated in neighbouring Austria.

DOI: 10.2478/scjme-2024-0034, Print ISSN 0039-2472, On-line ISSN 2450-5471

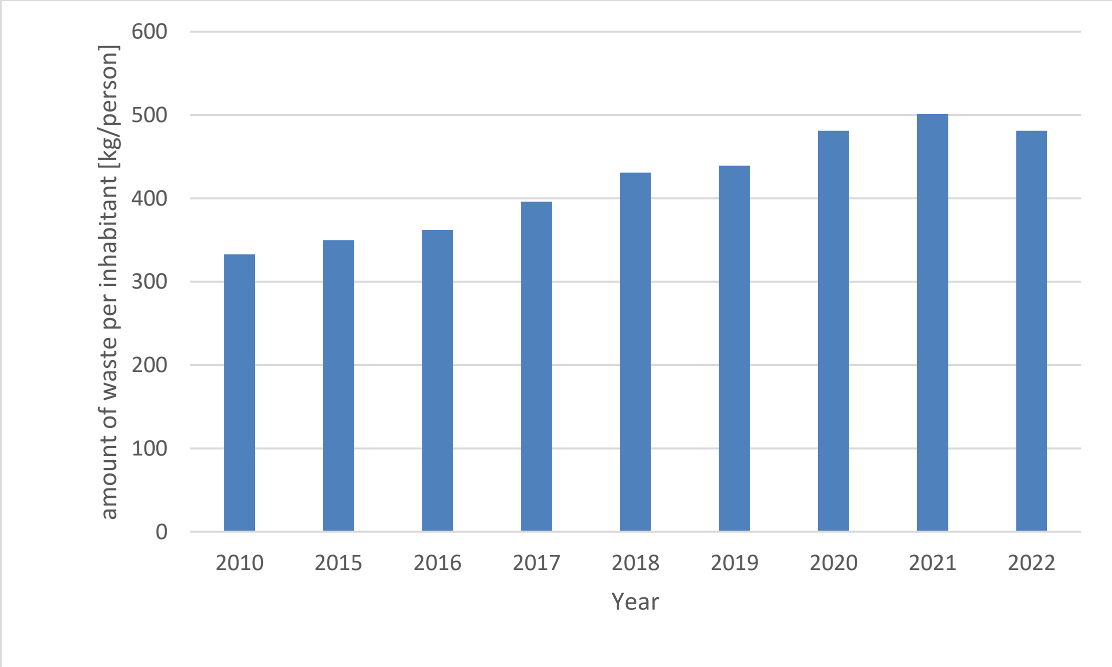

Fig. 1 Development in the amount of municipal waste per inhabitant [1]

From the energy point of view, we can evaluate the waste according to several parameters, such as cellulose content, humidity or geographical location. One of the most frequently used parameters is heating value expressing the amount of heat released during the processing or burning of a unit amount of waste. The average heating value of a mixed municipal waste is about 10-15 MJ.kg^{-1}, depending on the proportion of biological components and humidity [3]. The lower the relative humidity w_r of the waste, the higher the heating value; on the contrary, as the ash content increases, the heating value decreases.

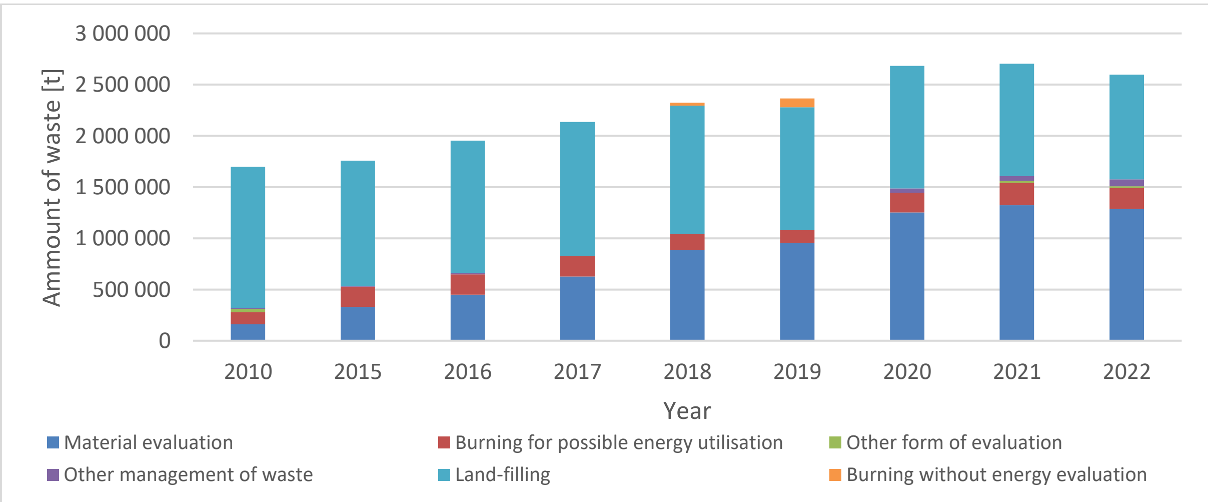

Fig. 2 Development of the amount of municipal waste according to the method of handling [2]

In terms of heating value, the value of the lower heating value of the fuel plays a key role, which can be determined according to relation (1):

$$H_{inf} = H_{awf} \,.\, B - 2445 \,.\, W \; [kJ.kg^{-1}] \tag{1}$$

$H_{inf} - lower\ heating\ value\ of\ fuel\ [kJ.kg^{-1}]$

$H_{awf} - expresses\ the\ heating\ value\ of\ the\ dry\ sample\ and\ is\ defined\ as\ the\ lower\ limit\ of\ the\ heating\ value$

$B - expresses\ the\ content\ of\ the\ combustible\ component$

$W - expresses\ the\ water\ content\ in\ the\ sample$ [%]

The efficiency of the process of converting fuel into energy is assessed by the indicator of the degree of energy utilization. The following formula is used for its calculation:

$$\eta_e = \frac{Q_{prod} - (E_f + I_{imp})}{E_W \cdot f_B + E_f} \tag{2}$$

$\eta_e - efficiency\ of\ fuel\ conversion$

$Q_{prod} - total\ amount\ of\ produced\ energy\ (thermal\ and\ electrical)$

$I_{imp} - imported\ energy\ not\ involved\ in\ energy\ production$

$E_f - imported\ energy\ into\ the\ combustion\ process$

$E_W - energy\ released\ by\ burning\ waste$

$f_B - coefficient\ of\ the\ degree\ of\ combustion\ of\ combustibles\ in\ processed\ waste\ \ (chosen\ 0.97)$

For the use of waste suitable for processing, the following criteria must be met: The water content in the waste should be less than 50%, the ash content in the waste should not exceed 60%. The content of combustible substances should be higher than 25% [4].

The two most common ways of converting municipal waste into fuel are gasification and pyrolysis, which chemically decompose complex organic substances (municipal waste) into simpler molecules, such as saturated hydrocarbons and carbon oxides. The obtained gases are often referred to as synthesis gases [5]. During gasification, depending on the composition of municipal waste, individual gaseous components are formed in the following representation [3]: hydrogen (H_2) 36-57 %vol., carbon monoxide (CO) 15-32 %vol., carbon dioxide (CO_2) 10- 22%vol., methane (CH_4) 8-14%vol., ethane (C_2H_6) 0.2-1%vol., nitrogen (N_2) 0-1%vol. This variable output composition subsequently affects the external and internal parameters of the internal combustion engine, as demonstrated in previous research [6, 7]. Therefore, it is important to explore as many fuel combinations as possible in various scenarios in order to identify the best possible combination of gaseous components for an internal combustion engine within the effective working range of the gasifier.

The last part in the synthesis gas production process is cleaning of the impurities that arise during production. Syngas before cleaning contains various contaminants, including solid particles, tar, hydrogen sulfide (H_2S) and ammonia (NH_3). The most commonly used technologies for cleaning syngas include:

Mechanical filtration - it serves mainly to capture solid particles from synthesis gas - especially hydrocarbons and soot. This purpose is mainly served by cyclones and filters. Cyclones use centrifugal force to separate solid particles from the gas, when the air current causes the heavier particles to separate and sink to the bottom of the cyclone. For capturing fine solid fractions, it is also possible to use pulsed bag filters, in some cases ceramic candle filters.

Chemical processes – are used to remove tar and acid gases, which mainly include hydrogen sulfide (H_2S), ammonia (NH_3) and carbon dioxide (CO_2). These components must be effectively removed in order to ensure a long service life of technological systems (In the case of combustion engines, the presence of sulfur in the fuel leads to the destruction of catalysts). The following methods are used to remove the above-mentioned components from synthesis gases:

Absorption in solvents – physical absorption works on the principle of physical absorption of acidic components into solvent molecules, the most important being dimethyl ethers and polyethylene glycol.

Adsorption processes – The following adsorbents have the ability to adsorb gaseous acid components of synthesis gas: zirconium dioxide (ZnO_2), copper oxide (Cu(II)O), chromium oxide (Cr_2O_3), aluminum oxide (Al_2O_3). During the adsorption of hydrogen sulfide by zinc oxide, H2S is transformed into metal sulfide compounds at temperatures of 315-530 °C.

This article presents the effect of selected gaseous fuels on the operation of a mechanically supercharged internal combustion engine. The investigated fuels represent synthesis gases obtained from municipal waste and plastic gasification with constant share of inert gases (25% by volume) with only the mutual ratio between the gases being changed. The results of the measurements are intended to help in setting the correct boundary conditions for syngas production in order to achieve its optimum composition for the intended use. The properties of these fuel mixtures are listed in Tab. 1 and the graphic representation of their composition is shown in Fig. 3. Natural gas with the following composition was used as a reference fuel: methane 93.7% vol., ethane 3.7% vol., higher hydrocarbons 1.3% vol., inert gases 1.3% vol..

Tab. 1 Physical and chemical properties of natural gas (NG) and synthesis gases (G), (*LHV* – lover 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)

Parameter	Unit	NG	G1	G2	G3	G4	G5	G6
CH_4	[% vol.]	93.7	10	5	10	5	10	20
H_2	[% vol.]	0	15	25	35	35	25	20
CO	[% vol.]	0	50	45	30	35	40	35
CO_2	[% vol.]	0.6	15	10	20	15	10	10
N_2	[% vol.]	0.7	10	15	5	10	15	15
LHV	**[MJ.kg^{-1}]**	**48.370**	**10.187**	**10.124**	**11.938**	**10.808**	**11.585**	**13.980**
LHV	[MJ.m^{-3}]	34.657	10.721	9.476	10.380	9.308	10.555	12.797
A/F ratio	[kg.kg^{-1}]	16.77	2.85	2.75	3.45	2.98	3.29	4.21
M	[g.mol^{-1}]	17.2	25.3	22.5	20.9	20.7	21.9	22.0
Fuel in air	[% vol.]	9.1	28.6	31.8	28.6	31.9	28.6	23.7
$\rho_{NTP\ fuel}$	[kg.m^{-3}]	0.716	1.052	0.936	0.870	0.861	0.911	0.915
$\rho_{NTP\ mixture}$	[kg.m^{-3}]	1.160	1.160	1.119	1.108	1.095	1.120	1.135
$LHV_{mixture}$	[MJ.kg^{-1}]	2.761	2.646	2.700	2.682	2.716	2.700	2.683
$LHV_{mixture}$	**[MJ.m^{-3}]**	**3.147**	**3.064**	**3.014**	**2.966**	**2.965**	**3.018**	**3.038**

From a basic comparison of the volumetric heating value of the mixture, which has the largest share in the output and is also a determining parameter for the preliminary estimation of the output, it follows that the highest output can be expected for the G1 gas (3,064 kJ.m^{-3}).On the contrary, the worst parameters are expected for the gas labelled G4, which has the lowest heating value of the stoichiometric mixture (2,965 kJ.m^{-3}). Syngas G3 and G4 have the largest proportion of hydrogen in the mixture, which leads to a postponed ignition of the mixture compared to natural gas operation because of a faster fuel burnout. In addition to the positives for the heat release process, hydrogen also has negatives, which is mainly the effect on the stability of combustion (occurrence of abnormal phenomena - detonation combustion, ignition of the mixture in the intake manifold).

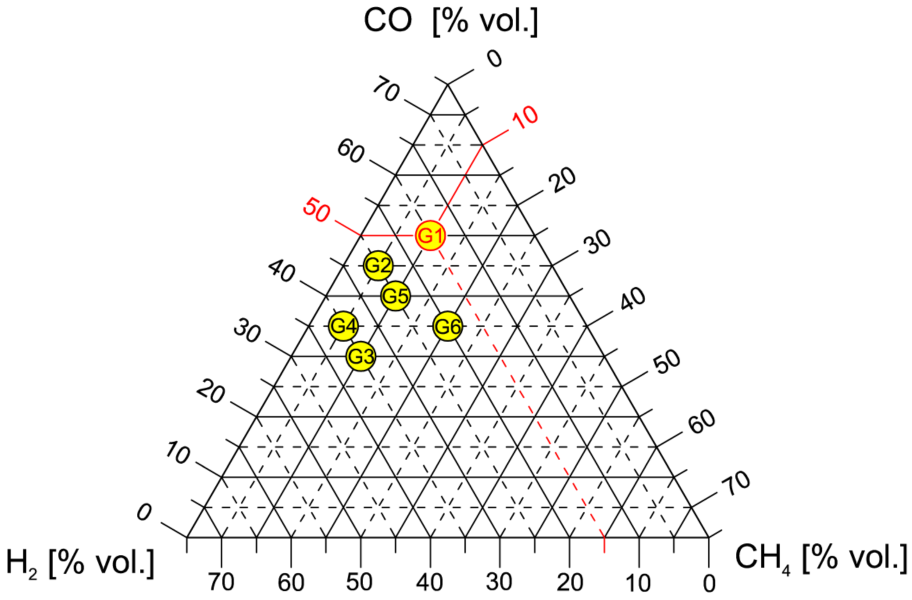

Fig. 3 Ternary diagram of chosen syngas composition with constant amount of the inert gases (25 % vol.), with highlighted example of syngas G1 composition (10 %vol. CH_4, 15 %vol. H_2, 50 %vol. CO).

2 Research methods

The experimental measurements were carried out on the supercharged spark-ignition combustion engine LGW 702 from the Lombardini Company, which in its modified version has been used for many years as an experimental engine for the application of alternative gaseous fuels at the Institute of Automotive Engineering and Design. The supercharging of the internal combustion engine was carried out using a mechanically driven compressor AISIN AMR 300, which was driven utilizing a controllable asynchronous motor. The internal combustion engine is part of the micro-cogeneration unit, the parameters of which are described in more detail, e.g. in [6, 7].

The diagram of the combustion engine together with the AVL dynamometer is shown in the figure below (Figure 4). The internal combustion engine was equipped with pressure sensors from Kistler. A piezoelectric pressure sensor was integrated in the pressure spark plugs (6118CC-4CQ02-4-1), which sensed the dynamic course of pressure in the cylinder. To reduce this pressure to absolute values, a pressure correction method was used based on sensing the absolute pressure in the intake manifold using a 4075A10 piezo-resistive sensor. The current position of the crankshaft was sensed using the 2613B1 encoder. The start of ignition angle was varied using the IMF Soft programmable control unit and was recorded on the data bus using an opto-coupler connected in parallel with the Bosch P65-T combined ignition coil.

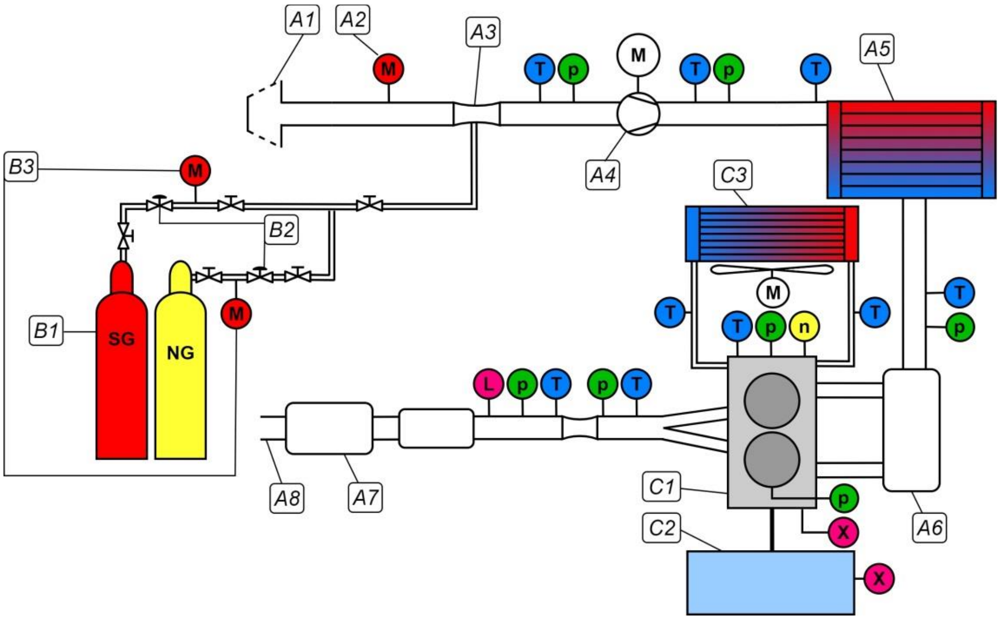

Fig. 4 The basic scheme of the supercharged internal combustion engine Lombardini LGW 702K (A1 – air filter, A2 – mass air flow sensor (MAF), A3 - mixer with diffuser, A4 – mechanical compressor AISIN AMR 300, A5 – water intercooler of the compressed mixture, A6 – collection container, A7 – silencer, A8 – exhaust tip for discharging exhaust gases, B1 - pressure bottle with syngas or natural gas, B2 – pressure regulators, B3 – fuel mass flow and volumetric fuel consumption sensors, C1 – internal combustion engine Lombardini LGW 702K, C2 – dynamometer AVL P80, C3 – engine cooler, T – temperature sensor, p – pressure sensor, M – electric motor, n – engine speed, L – broadband lambda probe).

All measured data were post-processed using a program created in the Matlab environment. From the measured pressure curves in the cylinder, the course of fuel combustion in the combustion chamber is evaluated using a single-zone-zero-dimensional thermodynamic model. This model, based on the use of the law of conservation of energy, will be used for combustion analysis only when the system is closed (i.e. both the intake and exhaust valves are closed). The course of the gradual release of heat from the fuel was determined based on the Rassweiler-Withrow method. The required start and end of combustion angle for combustion analysis are determined from the entropy change during the supply and realise of heat [9].

In addition to the above-mentioned analysis, an evaluation of the mean indicated pressure and a statistical analysis of the parameters for the evaluation of the uniformity of the engine operation, which are represented by the so-called coefficient of variation (COV). The coefficient of variation is calculated as the ratio of the standard deviation to the arithmetic mean of the investigated parameter:

$$COV = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n} x_i - \bar{x}}}{\bar{x}}.100 \qquad [\%] \tag{3}$$

where n is the total number of consecutive cycles, x_i is the i-th value of the investigated parameter in the given cycle and $\bar{x}$ is the average value of the investigated parameter from the given number of cycles. Cycle variability has a significant impact on the overall life of the combustion engine as well as on its performance parameters. During one working mode of the engine, approximately 195 consecutive cycles were recorded at an operating speed of 1500 min^{-1}.

2.1 Analysis of the course of pressure in the combustion chamber

In the initial phase of investigating the effect of supercharging on the parameters of an internal combustion engine powered by syngas, a charging pressure of 1.25 bar was first started, due to the high compression ratio (12.5:1) and the increased risk of abnormal (detonation) combustion. From the analysis of the integral performance parameters of the examined synthesis gases, it follows that the highest torque (54.9 N.m) at an operating speed of 1,500 min^{-1} is achieved when burning synthesis gas G6. Conversely, the lowest torque (50.0 N.m) occurs when operating at G4. The highest mass consumption of fuel (12.30 $kg.h^{-1}$) occurs when operating on synthesis gas G1. On the contrary, the lowest consumption (7.90 $kg.h^{-1}$) is when operating on gas G6, which fully corresponds to the expectations that resulted from the preliminary analysis based on mass percentage of fuel in the stoichiometric mixture.

The following figure (Figure 5) shows the IMEP values depending on the angle at which 50% of the fuel weight is burned. The graph was created from a gradual change in the start of ignition angle from 25°CA BTDC to approximately 10°CA BTDC, depending on the gas composition when there is still the possibility of regular engine operation without misfiring or abnormal detonation combustion. The highest average values of IMEP (1.391 MPa) are achieved when burning the reference fuel, that is natural gas. This value of maximum IMEP corresponds to the angle α_{50MFB} 6.4° CA ATDC.

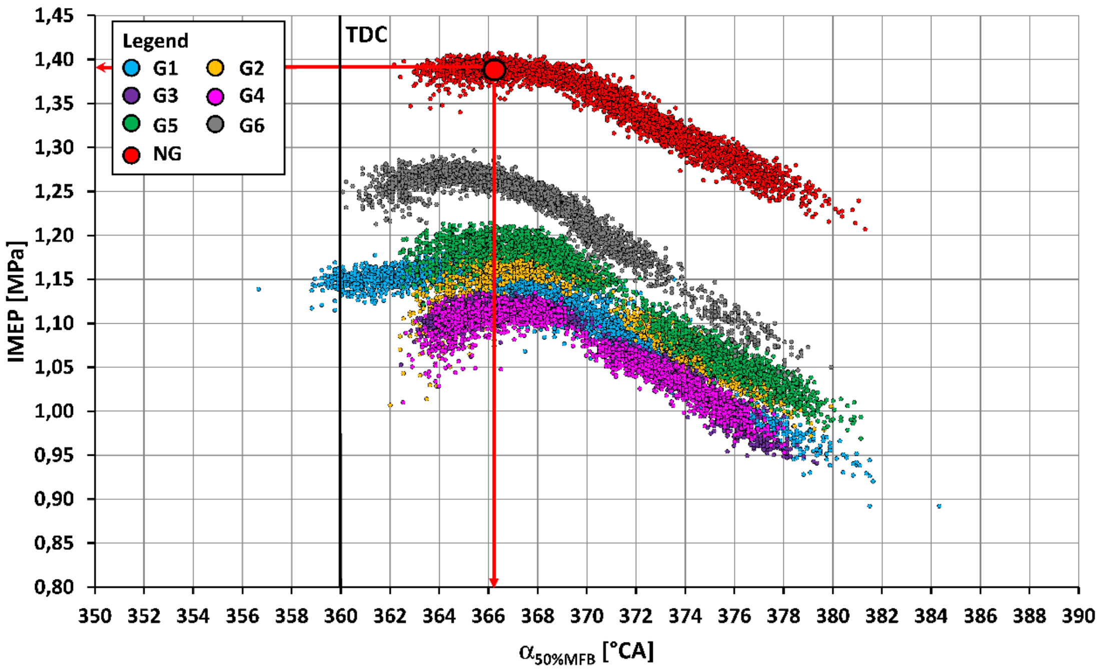

Fig. 5 Course of the mean indicated pressure (IMEP) depending on the angle when 50% of the fuel mass is burned for natural gas and synthesis gases, with a marking of max. IMEP values for natural gas (optimal start of ignition (SOI) angle 26°CA BTDC). Conditions: speed 1500 min^{-1}, full load, the stoichiometric ratio of the mixture, the proportional compression on the compressor 1.25

When burning synthesis gas G6, the largest IMEP value (1.269 MPa) has been reached at approx. 5.4 °CA ATDC, when 50% of the fuel is burned. The volumetric heating value of the stoichiometric gas mixture G6 (3,038 $kJ.m^{-3}$) is also the second highest from among the investigated gases (following G1 – 3,064 $kJ.m^{-3}$), however, due to the better filling efficiency, this gas achieves the highest performance parameters. On the contrary, the lowest value of IMEP (1.112 MPa) has the synthesis gas G4, which also has the largest angle (7.8 °CA ATDC), when 50% of the fuel is burned. This gas also contains a high proportion of hydrogen

(35% vol.) and a low proportion of methane (5% vol.). The coefficient of variation (COV) of IMEP for natural gas was 0.61% at the optimal pre-ignition angle. The highest value from among the synthesis gases (also at the optimal pre-ignition angle) was when burning synthesis gas G4 (0.65%), which can also be seen in the dispersion of values in the previous graph. On the contrary, G6 gas has the lowest value (0.43%). In general, the coefficient of variation of IMEP decreases with increasing pre-ignition.

The following developed p – α diagram shows the course of the average pressure curve (created from 195 consecutive cycles) in the combustion chamber of the engine in the region of the top dead centre at the time of combustion. Pressure curves for selected synthesis gases and natural gas are shown, always for the optimal start of ignition angle, which is different depending on the fuel composition.

The highest maximum pressure (9.82 MPa) is reached when synthesis gas G6 is burned. The lowest value of the maximum pressure (8.36 MPa) is achieved when burning G4 gas. The position of the maximum pressure had a narrow interval for all gases (from 10.4 to 13.8 °CA ATDC). The coefficient of variation of the maximum pressure was 6.9% for natural gas. Among the synthesis gases, G5 gas had the lowest value (3.3%) and G1 gas had the highest value (4.6%).

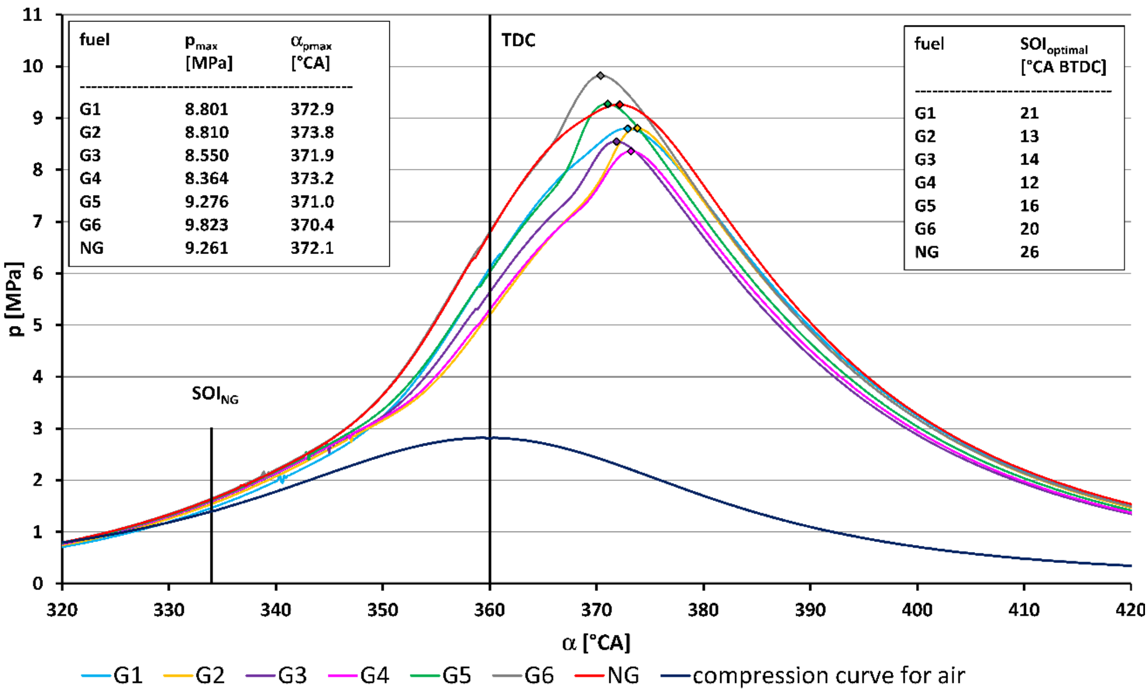

Fig. 6 Course of pressure in the cylinder of the internal combustion engine when operating on natural gas and synthesis gases, Conditions: speed 1500 min^{-1}, full load, the stoichiometric ratio of mixture, the optimal start of ignition angle for each fuel, the proportional compression on the compressor 1.25

Another parameter affecting the life and operation of the engine is the parameter of the maximum pressure rise rate per degree of rotation of the crankshaft. This value when burning natural gas is 0.338 MPa/1°CA. The highest value (0.712 MPa/1°CA) was recorded for gas labelled G2. On the contrary, the lowest value (approx. 0.440 MPa/1°CA) was when burning gas marked as G1.

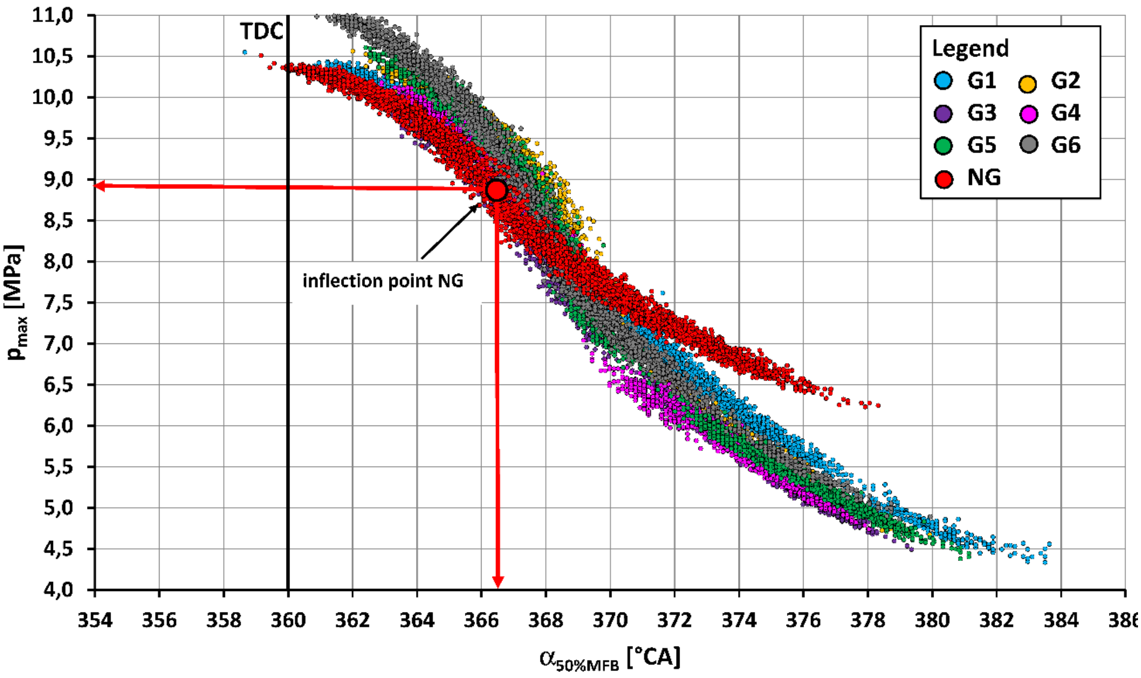

Fig. 7 Course of the maximum pressure depending on the angle when 50% of the fuel for natural gas and synthesis gases is burned. Conditions: speed 1500 min^{-1}, full load, the stoichiometric ratio of the mixture, the proportional compression on the compressor 1.25

The previsting figure (Figure 7) shows the course of the maximum pressure for each cycle depending on the angle at which 50% of the mass of the fuel is burned. The graph was created similarly to the IMEP graph as a set of data (195 cycles for each operating point – start of ignition) with the start of ignitions from approx. 10°CA BTDC to 25°CA BTDC with 1°CA step. As it can be seen from the course of the pressure, by increasing the value of the pre-ignition angle, the value of the maximum pressure for natural gas stabilizes at the level of 10.4 MPa, and on the contrary, with decreasing pre-ignition, the value of maximum pressure stabilizes at 6.2 MPa. Approximately at the location (angle α_{50MFB}) of the maximum mean indicated pressure there is also the location of the inflection point during the maximum pressure, which can also be seen in Figure 7. The position of the inflection point corresponds to the pressure value of 8.9 MPa and the angle α_{50MFB} 6.3 °CA ATDC. Synthesis gases generally have a stabilized lowest maximum pressure at the level of 4.5 MPa. The level of the highest values of maximum pressure varies significantly between individual gases. The highest values of maximum pressure (around 11 MPa) under gradually increasing pre-ignition gas are with G6.

All synthesis gases had approximate inflection points at the α_{50MFB} angle when the highest performance parameters (max. IMEP) are also achieved at this angle, and thus the optimal value of the start of ignition angle also corresponds to this condition.

The next figure (Fig. 8) shows the mass fraction of burned fuel depending on the angle of rotation of the crankshaft for selected compositions of the synthesis gas mixture compared to natural gas. The analysis of the burning process of the reference fuel (natural gas) shows that the time between the start of ignition (SOI) and the start of visible combustion (SOC) is approximately 11.1 °CA. The period between the moment of SOI and 5% wt. of burned natural gas is approximately 15.9 °CA. The main burning period (10-90) %MFB for natural gas lasts 20.1 °CA. The total burning period (from SOC to EOC) for natural gas is approximately 40 °CA. When analysing the main combustion period of synthesis gases, it can be generally concluded that the presence of hydrogen in the fuel shortens the main combustion period, and conversely, a high proportion of carbon monoxide (G1) extends this period, in the case of a constant amount of inert gases. The period between SOI and the moment of burning 5% of the fuel is the shortest (9.6 °CA) when burning synthesis gas G4 and, conversely, the longest (14.3 °CA) when burning gas G6.

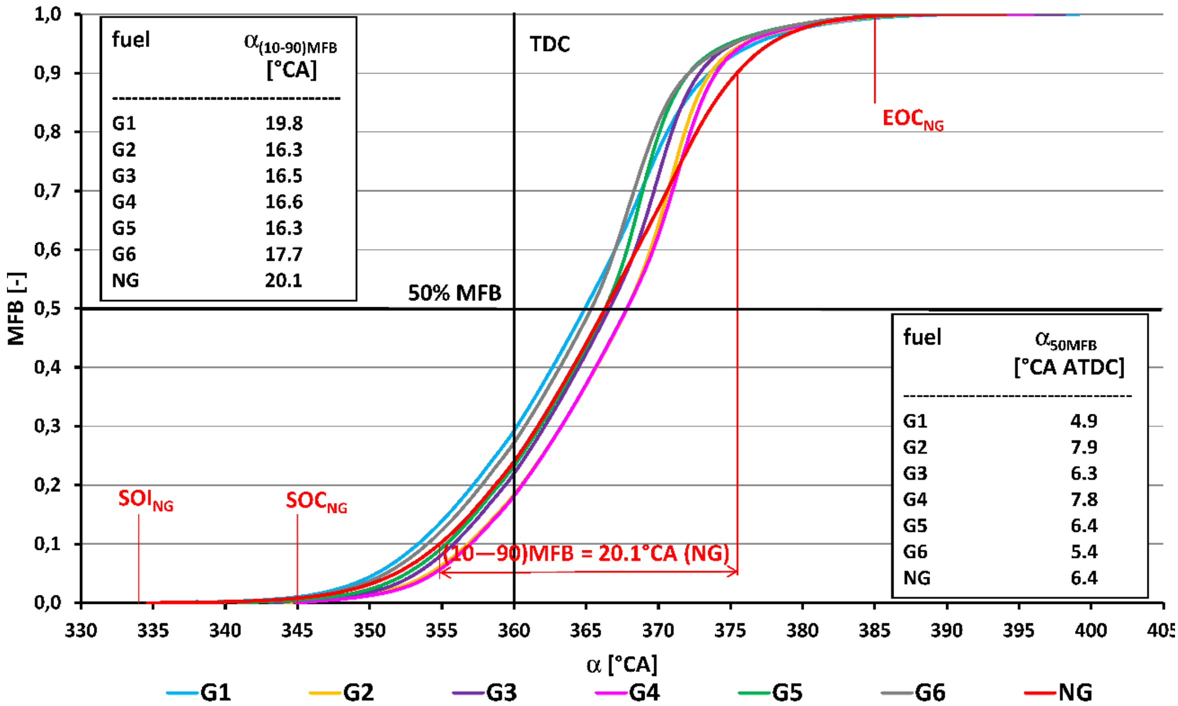

Fig. 8 Course of the maximum pressure depending on the angle when 50% of natural gas and synthesis gases is burned. Conditions: speed 1500 min^{-1}, full load, the stoichiometric ratio of the mixture, the proportional compression on the compressor 1.25

The coefficient of variation of position (COV) generally increases with the increasing proportion of fuel burned. For natural gas, these values are as follows: $COV_{\alpha 10\%MFB}$ = 0.19%, $COV_{\alpha 50\%MFB}$ = 0.36%, $COV_{\alpha 90\%MFB}$ = 0.57%. When burning syngas, the highest values in the entire range are for syngas labelled G1 ($COV_{\alpha 10\%MFB}$ = 0.18%, $COV_{\alpha 50\%MFB}$ = 0.29%, $COV_{\alpha 90\%MFB}$ = 0.35%). Synthesis gas labelled G54 has the lowest values ($COV_{\alpha 10\%MFB}$ = 0.12%, $COV_{\alpha 50\%MFB}$ = 0.20%, $COV_{\alpha 90\%MFB}$ = 0.42%).

CONCLUSION

The utilisation of synthesis gas produced from municipal waste by means of gasification is of irreplaceable importance both for reducing the production of carbon dioxide released into the atmosphere, and for partially saving classic resources and replacing them with renewable ones, since in the current situation in fuels there may be a problem with a lack of resources both due to the influence of the geopolitical situation and due to the tightening legislation regarding the protection of the living environment. The above-mentioned synthesis gases can be effectively used in stationary cogeneration units. (due to their low heating value, but rather hight hourly consumption. The influence of the fuel composition on the internal parameters of a turbocharged internal combustion engine (compression ratio 1.25) at the operating speed of the cogeneration unit of 1,500 min^{-1} is summarized in the following points:

- the optimal start of ignition angle had to be changed from the value of 12°CA BTDC for synthesis gas G4 to the value of 21°CA BTDC for synthesis gas G1 (limit of stable ICE operation);

- the mean indicated pressure of the combustion engine cycle is reduced at least (by 9%) for the G6 synthesis gas (1.269 MPa) compared to natural gas (1.391 MPa). The greatest drop in performance parameters (by 20%) compared to natural gas is for the synthesis gas marked G4, which also has the lowest stoichiometric volume heating value (2.965 $kJ.m^{-3}$) out of the studied synthesis gases;

- from among synthesis gases, the maximum pressure value was at its highest (9.82 MPa) when G6 gas was burned. Synthesis gas G4 gas had the lowest value (8.36 MPa). Coefficients of variations of maximum pressure were the highest (4.6 %) when operating on G1 synthesis gas, and on the contrary, the lowest value was recorded when operating on G5 gas (3.3 %);

- the highest pressure rise rate (0.712 MPa/1°CA) was measured when operating on synthesis gas G2, which had the highest proportion of carbon monoxide and hydrogen (45% vol. respectively 25 % vol.). The lowest pressure rise rate value (0.440 MPa/1°CA) was measured when operating on synthesis gas G1;

- from the analysis of the course of fuel combustion, it follows that the longest main combustion period (i.e. 10-90MFB) characterizes the synthesis gas G1 and has the value of 19.8 °CA. On the contrary, G2 and G5 gases (16.3 °CA) have the shortest burning period. The combustion start period (SOI-5%MFB) was the shortest (9.6 °CA) for the operating synthesis gas G4 and, conversely, it was the longest (11.3 °CA) for the synthesis gas G6. The coefficients of variation of the course of fuel burning out were average, the lowest was for the synthesis gas G4 and the highest for the synthesis gas G1.

The presented results provide several important insights into how to set up waste gasification technologies to obtain optimum performance parameters and economic efficiency of the combustion engine in cogeneration units.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under Contracts No. APVV-23-0456, APVV-20-0046 and was also supported by the Slovak Cultural and Educational Grant Agency under Contracts No. KEGA 016STU-4/2023 and was also supported by the Scientific Grant Agency under the Contract No. VEGA 1/0666/24.

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