

ANALYSIS OF THE INFLUENCE OF GAS COMPOSITION FROM RENEWABLE ENERGY SOURCES ON THE INTEGRAL PARAMETERS OF A TURBOCHARGED INTERNAL COMBUSTION ENGINE

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Abstract: This study explores municipal waste-derived synthesis gas as a sustainable alternative fuel for internal combustion engines. Syngas properties, including lower heating value and combustion behavior, were linked to the feedstock characteristics and production method. Experimental investigations conducted on a turbocharged Lombardini LGW 702 spark-ignition engine showed that syngas mixtures with higher lower heating values (approximately 11–12 MJ/kg) achieved torque and mean effective pressure values close to those obtained with natural gas. In contrast, low-calorific syngases (approximately 8–9 MJ/kg) resulted in a torque reduction of about 6–15% and a significant increase in specific fuel consumption. The calculated specific energy of the stoichiometric fuel–air mixture ranged from approximately 2.3 to 2.8 MJ/kg under full-load conditions. The results confirm the technical feasibility of municipal waste-derived syngas for engine applications and its potential contribution to greenhouse gas reduction and the development of renewable energy systems.

KEYWORDS: alternative fuel, synthesis gases, internal combustion engine, municipal waste, fuel consumption

1 Introduction

Currently, the world is facing many environmental and energy challenges, which are associated with the growing demand for renewable energy sources with the minimization of the use of traditional fossil fuels due to their negative impact on the environment. Climate change, air pollution and the depletion of non-renewable energy sources require urgent and innovative approaches to energy production and consumption. In this context, gaseous fuels from renewable energy sources, such as natural gas and syngases, are becoming increasingly important. These alternative fuels offer the potential to reduce greenhouse gas emissions and contribute to a more sustainable development of energy systems.

An important role in the use of syngases as alternative fuels from renewable energy sources is played by the input raw material – municipal waste – but also by the method of their production, as the method of production of a given product directly affects its composition, or physical and chemical properties. By reusing municipal waste, we also contribute to the gradual reduction of landfilling in the European Union and thus to the double minimization of greenhouse gas production.

Fig. 1 shows the course of the development of CO₂ dioxide production per capita in the EU27 countries and Slovakia from 2000 to the present is shown. As can be seen in the graph, this indicator fluctuated slightly year-on-year between 2000 and 2008, but since 2009 we have recorded an almost constant decrease in carbon dioxide production. At present, there is an annual production of 5.7 tons of carbon dioxide per capita in Slovakia, which is almost a 30% decrease compared to 2000, when one inhabitant produced 8.5 tons of this gas.

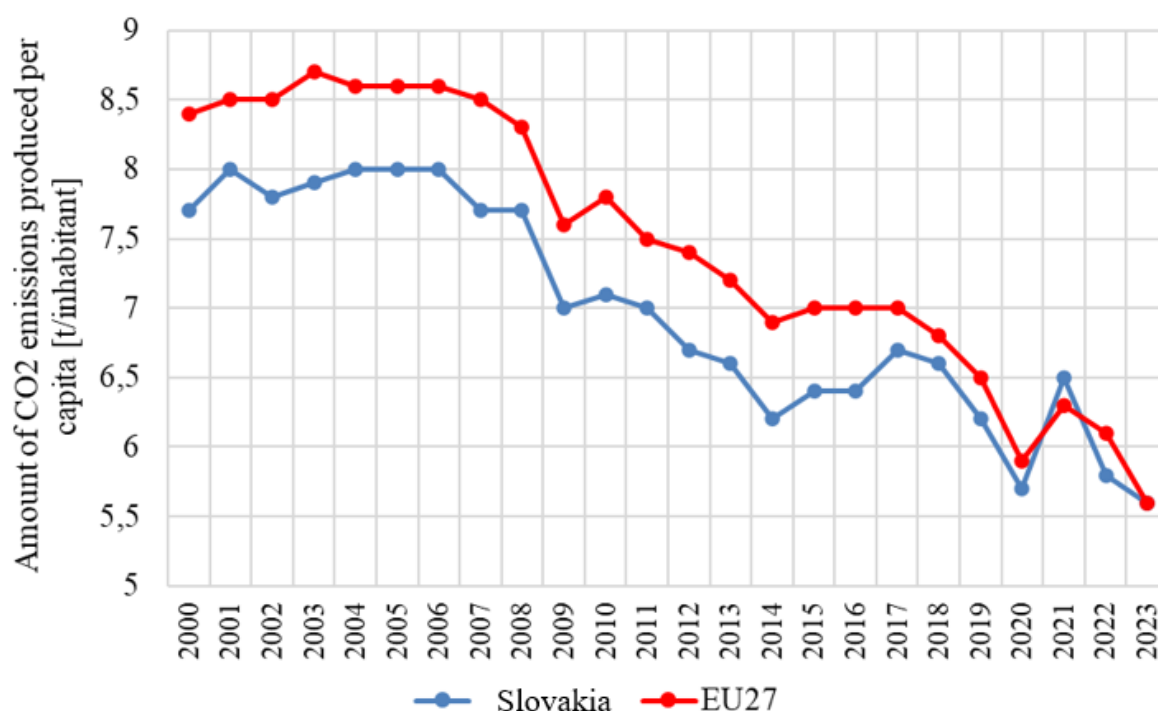


Fig. 1 Development of carbon dioxide production per capita in Slovakia and in the EU-27 in the period 2000 – 2023 [1]

The production of greenhouse gases and the rate of landfilling or reuse of municipal waste are closely related to its production, which fluctuates year-on-year on a pan-European scale, but is progressing negatively worldwide. Despite the efforts of many great powers and interest organizations, this indicator cannot be reduced to a sufficient extent. Every year, SENSONEO conducts measurement and research related to the production of municipal waste in 38 OECD countries. The Global Waste Index also examines the methods of municipal waste management, focusing on landfilling, incineration and recycling of municipal waste. This comparison can be seen in Fig. 2, which compares countries with excellent, average or worse results, while several indicators contribute to the overall assessment of the country, not only the recycling and landfilling rate. Among all the countries surveyed, Japan achieves the best results with a landfill rate of less than 1% and the amount of waste produced per capita of 326 kg, the second place in this ranking was occupied by South Korea with a landfill rate of less than 12% and waste production of 438 kg per capita. Third place also belongs to the European leader in this ranking, Estonia, which, with a production of 373 kg of waste per capita and a landfill rate of less than 1%, surpasses Germany with a production of 601 kg of waste per capita and a landfill rate of 1.10%. The fifth country in line is Austria, the European Union country with the highest recycling rate of municipal waste, with up to 334 kg, or 42%, of the 803 kg of waste produced per capita, being recycled. At the time of data collection, Austria is still a country without a national packaging deposit system. It was this system that was crucial for the position of the Slovak Republic in the Global Waste Index ranking, as its position improved by seven places. Currently, Slovakia is in 21st place with a production of 472 kg of waste per capita and a landfill rate of 38%.

Paradoxically, the worst results are achieved by non-European countries, i.e. those for which the so-called "Green Deals," such as the Green Deal, are not binding. Israel produces 650 kg of waste per capita per year, of which more than 80% is landfilled. Chile is even worse, as almost 95% of the total amount of 437 kg of waste per capita is landfilled. The third worst country in the ranking is the United States, where an incredible 951 kg of waste is produced per capita and landfilling reaches 47%.

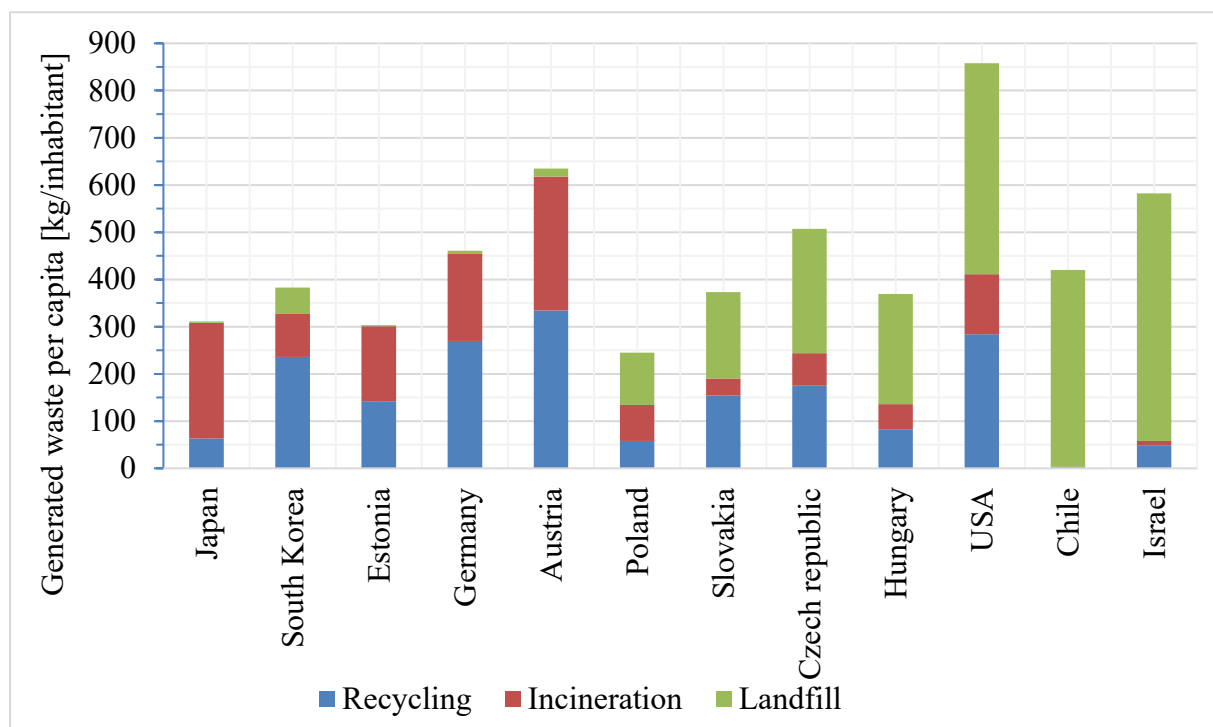


Fig. 2 Global waste index 2025 – Comparison of municipal waste production and treatment by country in 2025 [2]

Research carried out at the Institute of Automotive Engineering and Design of the Faculty of Mechanical Engineering of the Slovak University of Technology in Bratislava deals with synthesis gases from renewable energy sources, especially from municipal waste, as an alternative fuel for propulsion systems and cogeneration units. In the process of municipal waste processing, or the production of alternative fuel, several aspects are important that indicate other methods of production. The most important property of input raw materials is the calorific value of waste. In the case of sorted municipal waste, its calorific value is in the range of 9-10 MJ/kg, but for specific types of waste it is possible to obtain a calorific value of 20-25 MJ/kg. However, the calorific value of the final product depends not only on the calorific value of the input medium, but also on the method of processing. In the case of synthesis gas production by gasification, we can obtain a product with a calorific value of 6.10 – 10.40 MJ/kg, while pyrolysis produces gases with a calorific value in the range of 9.00 – 15.50 MJ/kg. The last process affecting the resulting properties of syngas is purification. Depending on the use of the process or the type of reagent, we obtain tabular values of calorific value.

The amount of air required for the perfect combustion of a unit amount of a mixture with a specific composition is characterized by the quantity theoretical amount of air L_t . Basically, it is the necessary amount of oxygen present in the air for perfect oxidation of the fuel to take place, i.e. for perfect combustion to occur. The products of perfect combustion are carbon dioxide and water vapor. Similarly to calorific value, the theoretical amount of air directly depends on the composition of the fuel and the amount of flammable substances in the fuel.

Mathematically, this parameter is described by the so-called stoichiometric equation (1) for fuel with the general form $C_cH_hO_oN_n$.

$$C_cH_hO_oN_n + \left(c + \frac{h}{4} - \frac{o}{2}\right)(O_2 + 3,773N_2) \rightarrow cCO_2 + \frac{h}{2}H_2O + \left[\frac{n}{2} + 3,773\left(c + \frac{h}{4} - \frac{o}{2}\right)\right]N_2 \quad (1)$$

Table No. 1. – Physicochemical properties and composition of synthesis gases and reference natural gas

		NG	SG1	SG2	SG3	SG4	SG5	SG6	SG7	SG8
H₂	[% vol.]	0	20	20	20	20	15	15	20	10
CH₄	[% vol.]	92.79	5	15	15	20	20	22	15	10
CO	[% vol.]	0	45	25	20	10	20	25	35	10
C₂H₆	[% vol.]	4.39	0	0	0	0	0	0	0	15
CO₂	[% vol.]	0.74	20	35	20	25	25	20	10	25
N₂	[% vol.]	0.86	10	5	25	25	20	18	20	30
LHV	[kJ/kg]	48 035	8 499	8 991	9 299	9 710	9 857	11 493	11 836	12 162
LHV	[kJ/m ³]	34 654	8 979	9 948	9 363	9 857	10 540	11 792	11 130	14 422
ρ_{NTP fuel}	[kg/m ³]	0.721	1.057	1.107	1.007	1.015	1.069	1.026	0.940	1.186
LHV_{mixture}	[MJ/kg]	2.714	2.575	2.423	2.428	2.374	2.416	2.515	2.636	2.447
LHV_{mixture}	[MJ/m ³]	3.140	2.969	2.843	2.775	2.728	2.815	2.910	2.981	2.929
A/F ratio	[kg/kg]	16.70	2.30	2.71	2.83	3.09	3.08	3.57	3.49	3.97
MN	[–]	91	37	51	54	62	64	61	45	87
Fuel in mix.	[% vol.]	9.06	33.06	28.58	29.64	27.67	26.71	24.68	26.78	20.31

LHV – Lower Heating Value, MN – Methane Number, NTP = Normal Pressure and Temperature

2 Research method

Experimental measurements were carried out on a turbocharged combustion engine LGW 702T (Lombardini). The engine in a modified version has long been used as an experimental platform for research on the application of alternative gaseous fuels at the Institute of Automotive Engineering and Design. The two-stage turbocharging of the internal combustion engine was provided by a mechanically driven AISIN AMR 300 compressor, which was driven by a controllable asynchronous electric motor and a Garret GT 0632 SZ turbocharger.

The internal combustion engine is equipped with a series of different sensors that monitor thermodynamic parameters. Several thermocouples from THERMASGARD HTF 50, model PT 100 compliant with the DIN EN 60 751 standard have been placed in the intake manifold, which sense the current temperature at the sensor location by changing the resistance due to temperature changes. In addition to thermocouples, pressure sensors are also located in the suction arm, namely GEMS 3500 Series, model 3500 S 02B5. These pressure sensors provide an output voltage range of 0 – 10 V, have a wide range of pressure ranges up to 16 bar expressing absolute pressure.

Similarly, we also monitor the exhaust branch of the internal combustion engine, where, due to high temperatures, we use a thermocouple manufactured by HERZ type K capable of recording a temperature of up to 1500 K. In addition to sensors, there are also two lambda sensors in the exhaust system, one narrowband and the other wideband, as well as a three-way catalyst. Temperature and pressure sensors are also located in front of and behind the turbine or blower, we also monitor the temperature of the liquid in the water-air exchanger and the oil temperature. A schematic representation of the Lombardini LGW 702T turbocharged internal combustion engine is shown in Figure 3.

The Lombardini LGW 702 combustion engine is connected to a water-cooled eddy current dynamometer AVL DP 80 via a flexible coupling.

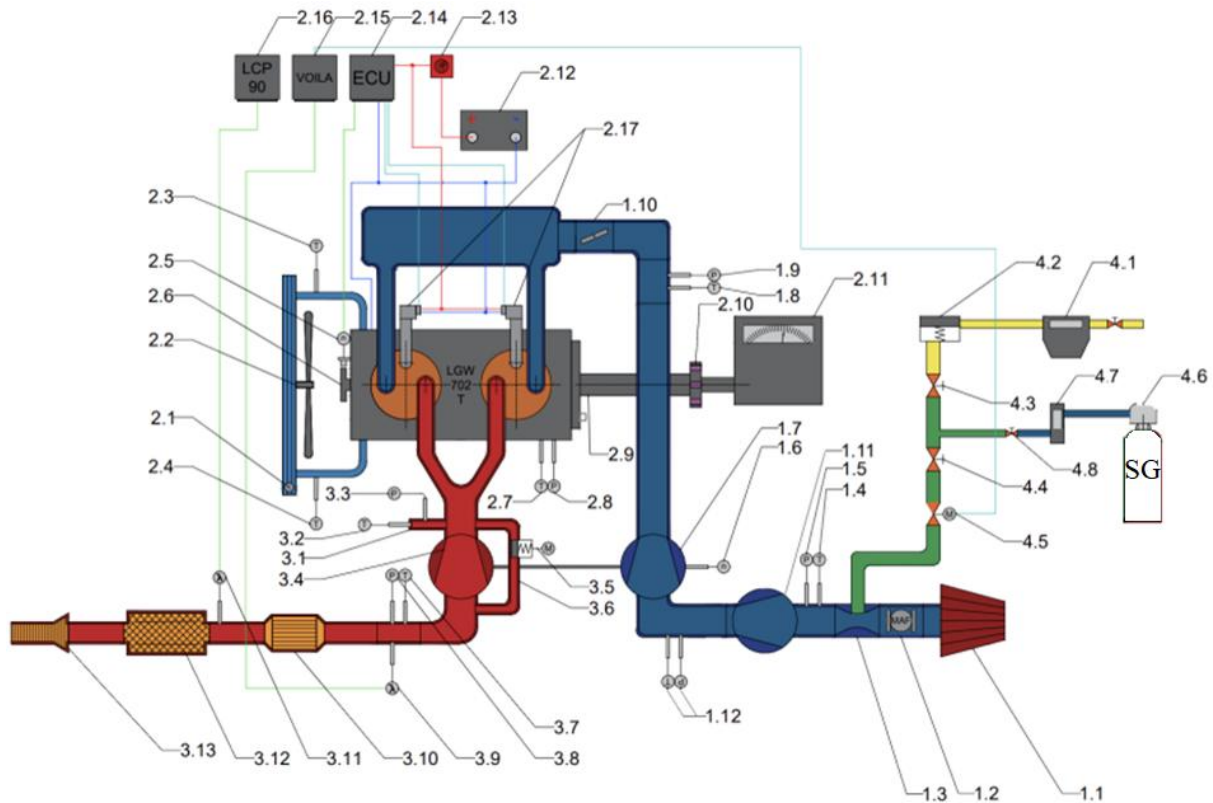


Fig. 3 Diagram of the Lombardini LGW702T turbocharged internal combustion engine [6]

Legend: 1.1 - Air filter, 1.2 - Mass air flow meter, 1.3 - Mixer with diffuser, 1.4 - Intake air temperature sensor, 1.5 - Intake manifold pressure sensor, 1.6 - Turbocharger speed sensor, 1.7 - Compressor, 1.8 - Post-turbo temperature sensor, 1.9 - Boost pressure sensor, 1.10 - Throttle body, 1.11 - Mechanical compressor, 1.12 - Temperature & pressure sensors after compressor, 2.1 - Coolant radiator, 2.2 - Electric radiator fan, 2.3 - Coolant inlet temperature sensor, 2.4 - Engine speed sensor (flywheel), 2.5 - Engine speed sensor (flywheel), 2.6 - Gear wheel, 2.7 - Oil temperature sensor, 2.8 - Oil pressure sensor, 2.9 - Shaft, 2.10 - Flexible coupling, 2.11 - Dynamometer AVL DP 80, 2.12 - Battery, 2.13 - Main switch, 2.14 - Control unit, 2.15 - Narrowband lambda controller, 2.16 - Wideband lambda controller, 2.17 - Ignition coils, 3.1 - EGR reduction, 3.2 - Turbine inlet pressure sensor, 3.3 - Pre-turbine pressure sensor, 3.4 - Turbine, 3.5 - Turbine flow controller, 3.6 - Turbine flow, 3.7 - Post-turbine temperature sensor, 3.8 - Turbine output pressure sensor, 3.9 - Narrowband lambda sensor, 3.10 - Three-way catalytic converter, 3.11 - Wideband lambda sensor, 3.12 - Muffler, 3.13 - Exhaust tailpipe, 4.1 - Gas volumetric flow meter, 4.2 - Natural gas pressure regulator, 4.3 - Natural gas flow regulator, 4.4 - Mixture richness control valve, 4.5 - Stepper motor, 4.6 - Pressurized gas cylinder, 4.7 - Mass flow meter for inert gas, 4.8 - Adjustment screw

2.1 Integral parameters

The following graphs illustrate the integral parameters of the Lombardini LGW 702T internal combustion engine. In this study, natural gas was selected as the reference fuel due to its widespread use and well-documented performance characteristics in spark-ignition engines. The engine was operated under controlled laboratory conditions to ensure reproducibility and accurate comparison between fuels.

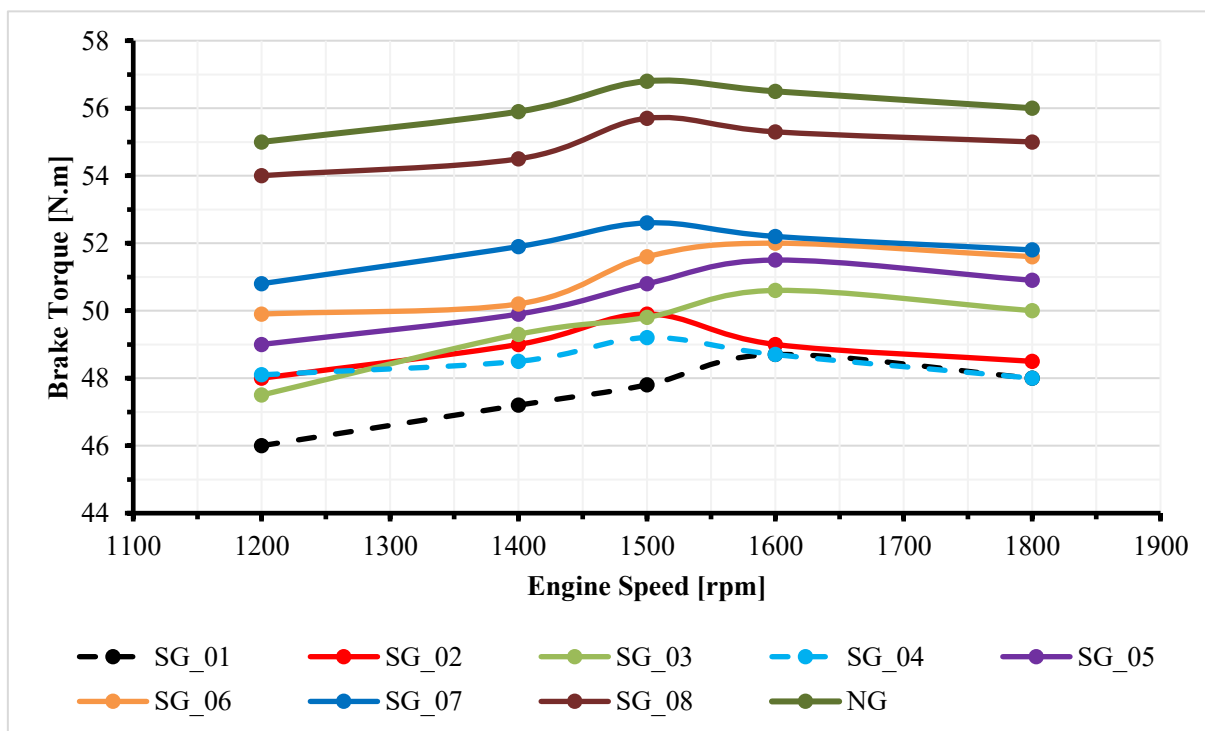


Fig. 4 Course of brake torque (M_t) in the engine speed characteristics for natural gas and synthesis gases (conditions: full load, stoichiometric air–fuel ratio, boost pressure 1.35 bar, optimal ignition timing for each fuel at each engine speed)

As can be seen from Fig. 4, when burning individual synthesis gases with different compositions, there is a slight, sometimes even significant decrease in the maximum value of torque compared to operation on natural gas. Under the given conditions, this decrease ranges from 6% to 15%. The most promising performance parameters under the given laboratory conditions and full load were shown by the SG8 synthesis gas ($M_t = 55.7$ N.m/1500 rpm), whose torque is only 2% lower compared to the reference fuel. A slightly lower torque value ($M_t = 54.4$ N.m/1500 rpm) was achieved by SG6 syngas, which is 5% lower compared to natural gas. On the contrary, the lowest torque among all the investigated gases was achieved by synthesis gas SG1 ($M_t = 48.7$ N.m/1500 rpm), while differing from the torque of the reference fuel by almost 14%. The investigated synthesis gases SG2, SG3, SG4, SG5 and SG7 achieved similar performance parameters.

When comparing Table 1 and Fig. 4, it is possible to see a proportional relationship between the performance parameters and the values of the lower calorific value of individual fuels. Like torque, SG8 gas has the highest value of lower calorific value, while SG1 gas has the lowest value.

Fig. 5 shows the course of the exhaust gas temperature depending on the speed and fuel used compared to the reference fuel. As can be seen from the graph, the highest exhaust gas temperature is achieved by synthesis gases SG1 and SG2, namely 530°C. This phenomenon may be due to the relatively high proportion of carbon dioxide in the syngas, which increases the temperature of the exhaust gases.

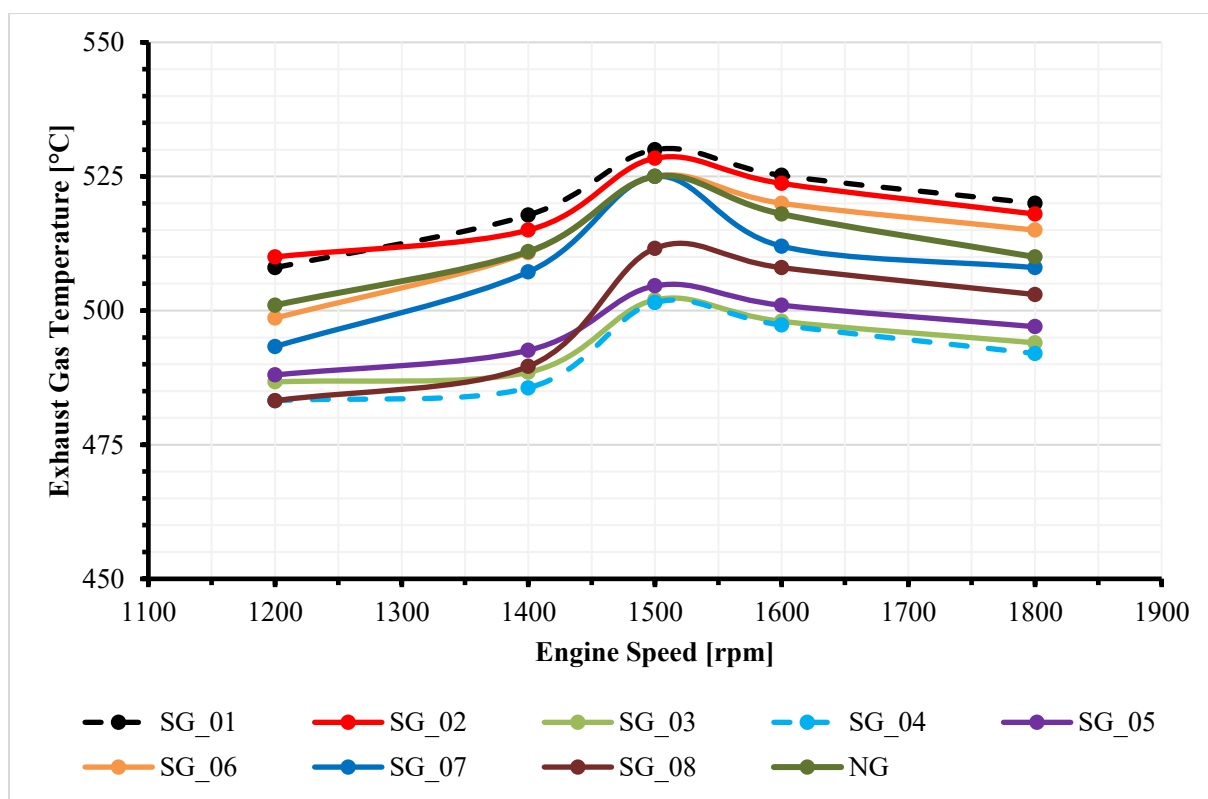


Fig. 5 Course of exhaust gas temperature as a function of engine speed for natural gas and synthetic gases (conditions: full load, stoichiometric air–fuel ratio, boost pressure 1.35 bar, optimal ignition timing for each fuel at each engine speed)

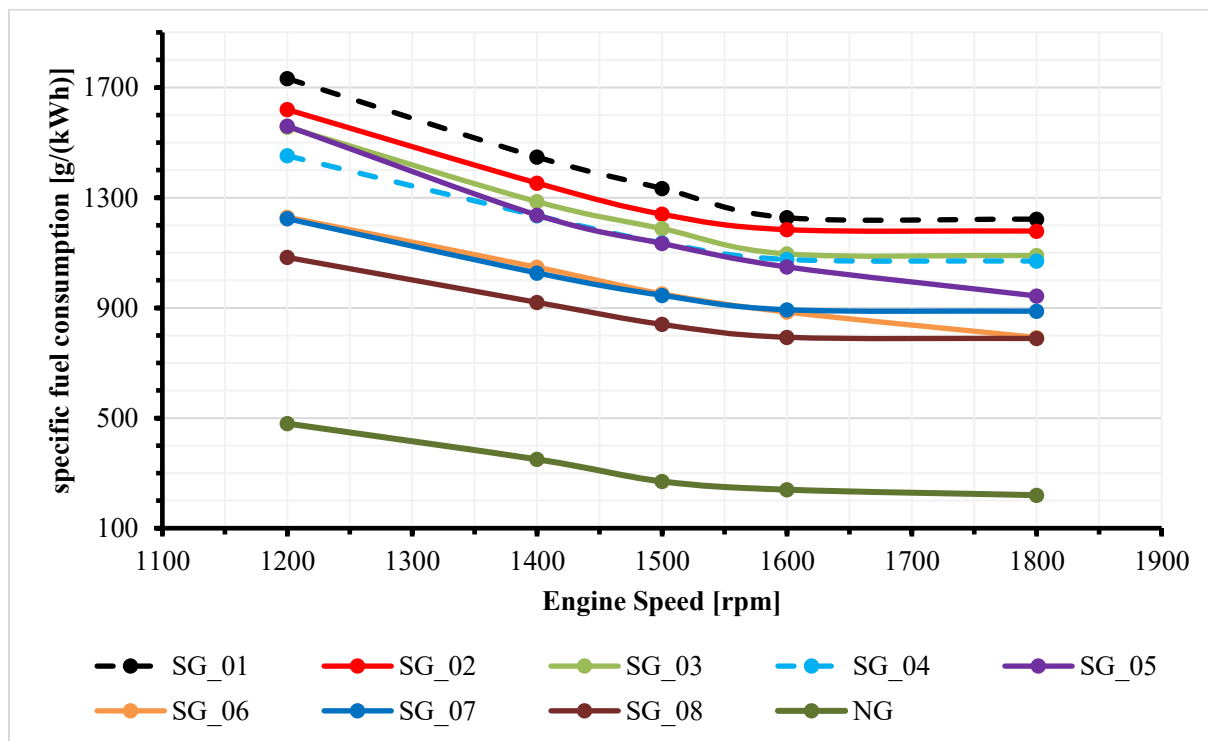


Fig. 6 Course of specific fuel consumption as a function of engine speed for natural gas and synthetic gases (conditions: full load, stoichiometric air–fuel ratio, boost pressure 1.35 bar, optimal ignition timing for each fuel at each engine speed)

On the other hand, the lowest temperature values are achieved by syngases SG3 and SG4 (504°C), as they contain the highest volumetric percentages of nitrogen among all syngases, which results in a reduction in the temperature of the exhaust gases.

As with the previous integral parameters, there is a significant deterioration in the specific fuel consumption compared to natural gas. Fig. 6 shows that the highest fuel consumption is achieved by gases with the lowest values of calorific value, namely SG1 with a specific fuel consumption of 1 732 g/(kWh), SG3 with a value of 1 556 g/(kWh) and SG2 with a consumption of 1 202 g/(kWh). The specific consumption of natural gas under the given conditions is 251 g/(kWh), which represents an increase of 242% and 493% respectively for individual SG1-3 gases. The lowest values of specific fuel consumption were achieved by gases with the highest torque achieved. SG8 syngas achieved a specific fuel consumption of 919 g/(kWh), an increase of 191% compared to natural gas, while SG6 gas recorded an increase of 208%, namely 1 026 g/(kWh).

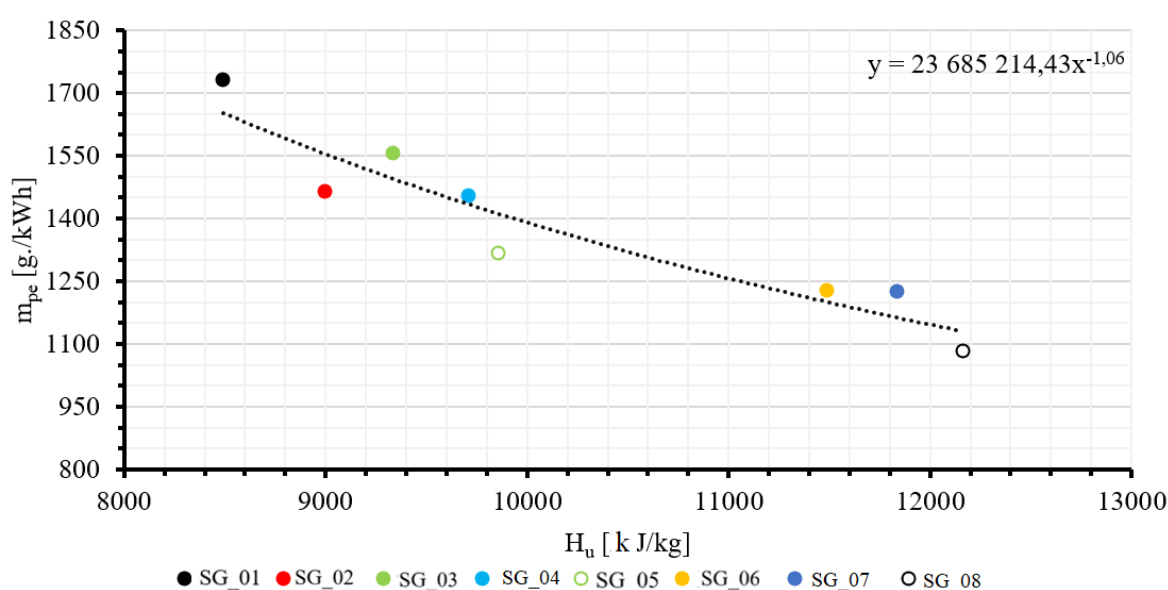


Fig. 7 Specific fuel consumption versus lower calorific value (conditions: full load, stoichiometric air–fuel ratio, boost pressure 1.35 bar, optimal ignition timing for each fuel at 1500 rpm)

The fact that the highest volume fuel consumption is achieved by gases with the lowest calorific values by volume is also evidenced by Fig. 7, which shows the dependence of specific fuel consumption and lower calorific value by volume.

Conclusion

This study examined the effect of municipal waste-derived synthesis gas composition on the integral performance parameters of a turbocharged spark-ignition internal combustion engine under full-load, stoichiometric conditions. Several syngas mixtures with different proportions of combustible and inert components were experimentally evaluated and compared with natural gas as a reference fuel. The results show that syngas composition significantly influences its lower heating value and stoichiometric air–fuel ratio, which directly affect engine performance and fuel consumption. Syngases with higher calorific values achieved torque levels closer to those of natural gas, whereas low-calorific mixtures led to a reduction in engine output and a substantial increase in specific fuel consumption.

Compared to natural gas, the torque reduction for individual syngases ranged from 2% for SG8 to approximately 14% for SG1. In terms of specific fuel consumption, syngas SG8 showed the lowest increase at 266% (919 g/kWh vs. 251 g/kWh for natural gas), while SG1 exhibited the highest consumption at 590% of the natural gas baseline (1 732 g/kWh). The specific fuel consumption increases for other investigated syngases ranged between these values, correlating directly with their lower heating values. A clear correlation between the lower heating value of the fuel and the achieved torque was observed for all tested mixtures. Despite the lower energy density of synthesis gases, stable engine operation was achieved without major modifications to the engine configuration. The calculated specific energy of the stoichiometric fuel–air mixture proved to be a suitable parameter for comparing highly diluted gaseous fuels with natural gas. The findings confirm the technical feasibility of municipal waste-derived syngas for turbocharged spark-ignition engines and highlight its potential contribution to sustainable energy utilization and greenhouse gas reduction.

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