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ENERGETIC EVALUATION OF PROCESS GASES IN INTERNAL COMBUSTION ENGINE

Abstrakt. Process gases produced from renewable energy sources (RES) are a sustainable source of alternative fuels that can be utilised in internal combustion engines. The presented article points to the possibility of using them to power cogeneration units, introducing specific example of their applications for the engine of a micro-cogeneration unit.
Keywords. Alternative fuels, hydrogen, natural gas, process gases, SI engine.

ENERGETYCZNA OCENA GAZÓW PROCESOWYCH W SILNIKU SPALINOWYM

Streszczenie. Gazy procesowe produkowane z odnawialnych źródeł energii (OŹE) stanowią trwałe źródło paliw alternatywnych, które można energetycznie ocenić w silnikach spalinowych. Przedstawiony artykuł wskazuje możliwości ich zastosowania w napędzie jednostek ko generacyjnych, z konkretnym przykładem ich zastosowania w silniku jednostki mikrogeneracyjnej.
Słowa kluczowe. Paliwa alternatywne, wodór, gaz ziemny, silnik zapłonowy.

1. INTRODUCTION

Nowadays the utilisation of alternative fuels is gaining prominence not only as an energy source to power vehicles, but also as a driving element in a cogeneration unit. In the world literature many studies deal with applications of process gases in internal combustion engines, for example. [1,2]. At present, our faculty has joined the endeavour and carries out research to analyse the influence of hydrogen admixture on the operation of the internal combustion engine LGW 702 powered by natural gas, which is primarily used as a driving unit in micro-cogeneration units. The research has been performed on various types of process gases as alternative fuels suitable for combustion in the motor. The most important process gases include synthesis gases obtained by gasification of municipal solid waste, mostly in gasifying reactors. The article also lists other gaseous fuels, which because of their properties are suitable to recover energy from. In the initial stage of research into process gases applications, a virtual one-zone model of the engine LGW 702 was used in the programming environment of Lotus Engine Simulation, which provided basic performance and operating parameters for a given engine fuel. This paper presents experimental results of mixtures of hydrogen and natural gas and simulation results of naturally aspirated and turbocharged engines using different types of process gases.

2. COMBUSTION ENGINE LGW 702

The main driving unit of the micro-cogeneration unit was a spark ignition internal combustion piston engine Lombardini LGW 702. Preparing of the gas mixture was prowidedby the mixer, which was equipped with a diffuser.

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Basic characteristics of the engine are shown in Table 1.

Table 1

Basic characteristics of the engine Lombardini LGW 702

Principle of work	Spark ignition
Number of cylinders, configuration	2, inline
Swept volume [cm^3]	686
Bore/stroke [mm / mm]	75 / 77.6
Compression ratio [–]	12.5 : 1
Crankshaft throw angle [°]	360
Valve gear/drive	OHC /Belt drive system
Intake	atmospheric (non-supercharged)
Preparation of mixture	External, in mixer, with electronic regulation of mixture richness (system VOILA Plus)

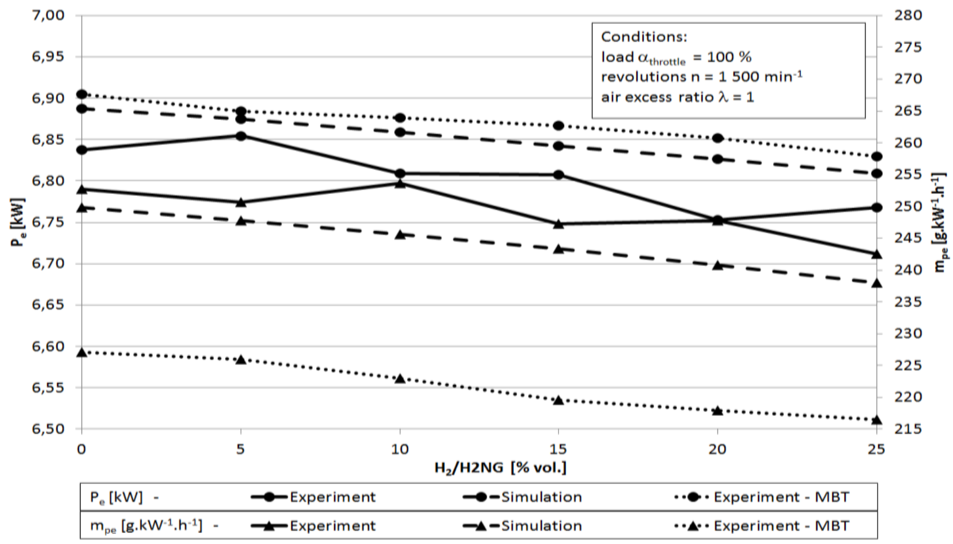

Fig. 1. Course of effective power P_e and specific fuel consumption m_{pe} in dependence on hydrogen proportion H_2/H2NG in mixture with natural gas (dashed and full lines – ignition advance 25° CA BTDC; dotted lines – optimized advance angle to value of maximum brake torque MBT for each composition of mixture)

Rys. 1. Przebieg efektywnej mocy Pe oraz średniego zużycia paliwa mpe w zależności od udziału wodoru H2/H2NG w mieszance z gazem ziemnym (czerwone i niebieskie linie – wyprzedzenie zapłonu 25° przed GMP, zielone linie – zoptymalizowany kąt wyprzedzenia dla każdego składu mieszanki do wartości momentu maksymalnego)

After successful conversion of the engine to drive the micro-cogeneration unit by natural gas [3], the next stage of the research focused on application of a mixture of natural gas and hydrogen, whose generic name is H2NG, that varied only in the amount of hydrogen (up to 25% vol. H_2). Hydrogen gives significant positive characteristics to the overall character of the engine operation. With increasing proportion of hydrogen the mass calorific value of a fuel increases, there is also a faster fire-through of the mixture, there occurs an increasing flammability limit of the mixture and least but not last the admixture of hydrogen has a positive effect on emission parameters of the engine. Due to increasing proportion of hydrogen, CO_2 emissions decrease, in the case of 25% vol. H_2 in mixture H2NG from approximately 11.5% vol. to 10.5% vol. Due to decreasing density of the mixture caused by added hydrogen, the calorific value of the stoichiometric mixture also decreases, resulting in a reduction of engine performance parameters. The internal combustion engine in the micro-cogeneration unit is operate at working revolutions 1500 min^{-1}, therefore we have focused on the characteristics pertaining to these revolutions.

In Fig. 1 one can see the progress of effective performance and specific fuel consumption for a mixture of natural gas and hydrogen (hydrogen share from 0% vol. to 25% vol.) at operating revolutions of 1500 min^{-1}. The simulation results are compared with the experimental results and the difference in the results ranges up to 1% for performance and up to 2% for specific fuel consumption at a constant angle of ignition advance (25° CA BTDC). As the combustion of the mixture with an increasing proportion of hydrogen was more rapid, the experiment with an optimized angle of ignition advance was performed in order to achieve maximum brake torque (MBT). The value of ignition advance varied from 23 ° for 0% H_2 to 15.5 ° CA BTDC for 25% H_2. The resulting difference in effective performance was on average a 1% increase in the whole composition range of mixtures, and a decrease in specific fuel consumption was on average by 10% lower.

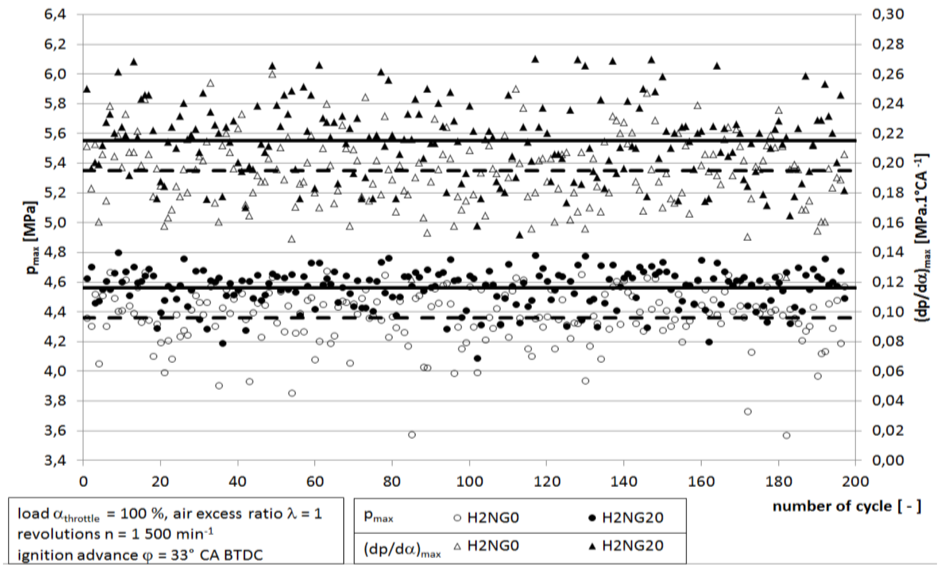

Fig. 2 Values of maximum pressure p_{max} in the combustion chamber and pressure increase rate $(dp/d\alpha)_{max}$ of combustion engine powered with a mixture H2NG0 and H2NG20 for number of cycles 197 (indication of average values: H2NG0 - dashed line, H2NG20 – full line)

Rys. 2. Wartości ciśnienia maksymalnego w silniku spalinowym p_{max} oraz twardości pracy $(dp/d\alpha)_{max}$ silnika spalinowego napędzanego mieszanką H2NG0 oraz H2NG20 dla 197 cykli (wyznaczenie średnich wartości: H2NG0 – linia przerywana, H2NG20 – linia ciągła)

The positive effect of hydrogen admixtures can be demonstrated in the nature of combustion. For this purpose an analysis of pressure in the combustion chamber was made with a piezoelectric Kistler sensor fitted in the spark plug. The parameter expressing the cyclic variability of the internal combustion engine is called the coefficient of variation (COV), which is calculated as a ratio of standard deviation, to the arithmetic mean value of the choice of data [4]. As can be seen from the experiment, the coefficient of variation for a maximum attained pressure during each cycle out of 197 cycles at 0% and 20% H_2 decreases from the value 4.42% to 2.78%. Figure 2 shows the maximum pressure achieved in every cycle, as well as the average value for mixtures H2NG0 and H2NG20. The mixture H2NG0 has achieved the average maximum pressure 4.36 MPa and the mixture H2NG20 has had this value increased by 0.2 MPa to 4.56 MPa. The maximum values of pressure move closed to TDC by around 0.4 ° CA with an increase of hydrogen by 5% vol. The graph also shows the pressure increase rate. The maximum pressure increase per one degree of rotation of CA for H2NG0 mixture is on average 0.195 MPa/1° CA, for the mixture H2NG20 this value is

0.215 MPa/1° CA. The difference represents an increase of 10.5% in the pressure increase rate of the operation which significantly influences mechanical stress of engine.

The utilisation of other alternative fuels in the internal combustion engine is preceded by certain preparation, which mainly includes specific fuel analysis and subsequent application in a virtual model. Table 2 introduces basic data on gaseous alternative fuels. As shown, the highest mass calorific value (LCV) is declared for the mixture Hythane (20% H_2, 80% NG). On the contrary, the lowest one is declated for syngas that is obtained by gasification of communal waste in gasifying reactor.

Table 2

Basic properties of selected alternative gaseous fuels

Fuel name		Syngas	Coke-oven gas	Landfill gas	Sewer gas	Hythane	Natural gas
CH_4	**[% vol.]**	20	29.5	52	69	Natural gas 80% vol. Hydrogen 20% vol.	Natural gas 100 % vol.
H_2	**[% vol.]**	20	56.8	0	0		
CO	**[% vol.]**	30	5.9	0.5	0.2		
CO_2	**[% vol.]**	25	2.2	27	27.4		
N_2	**[% vol.]**	5	5.6	20.5	3.4		
LCV	**[kJ.kg^{-1}]**	12 027	38 809	16 033	22 959	50 916	48 825
Density	**[kg.m^{-3}]**	0.998	0.412	1.067	0.987	0.582	0.705
M_{molar}	**[kg.kmol^{-1}]**	24.42	10.07	26.11	24.14	13.72	16.64
LCV mix.	**[kJ.m^{-3}]**	2 774	3 017	2 905	3 028	3 122	3 135
A/F mix.	**[kg.kg^{-1}]**	4.00	12.52	5.50	7.88	17.51	17.00

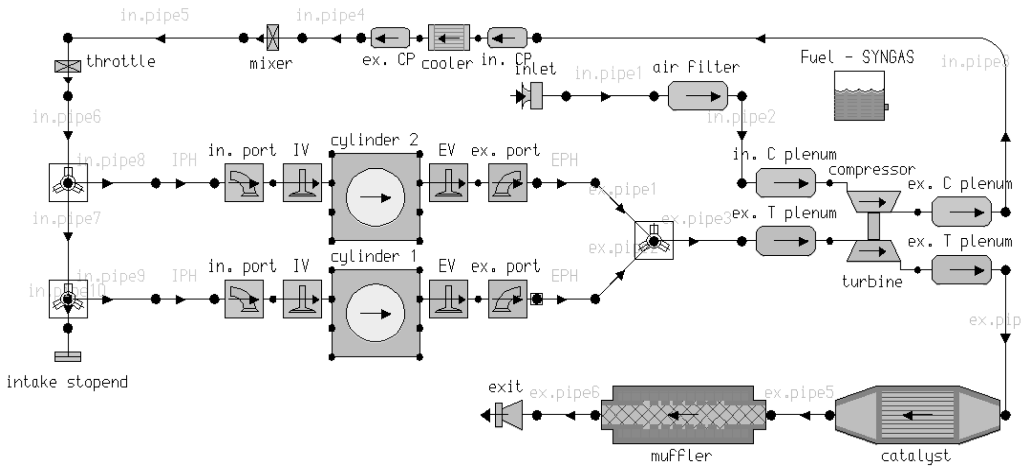

Fig. 3. Model of turbocharged engine LGW 702 in program Lotus Engine Simulation
Rys. 3. Model silnika doładowanego LGW 702 w programie Lotus Engine Simulation

A complete combustion of 1 kg of gas requires the least amount of air in the case of syngas (4 kg.kg^{-1}). Conversely, the largest amount of air has to be pumped into the combustion chamber to burn Hythane (17.5 kg.kg^{-1}). The volumetric calorific value of the stoichiometric mixture (LCV mix.) is the highest for natural gas (3135 kJ.m^{-3}) and the lowest for syngas (2774 kJ.m^{-3}), which parameters get reflected in the internal combustion engine performance. Fig. 3 shows a virtual model of turbocharged engine LGW 702 in the programming environment of Lotus Engine Simulations.

Firstly, the calculations after this model were done using modified turbocharger characteristics from Garrett GT1241 turbocharger [5]. After a preliminary analysis of fuels, simulation calculations were performed to obtain basic performance and economic parameters for all gaseous fuels, which are listed in Table 2. Secondly, this model has served to optimize the design parameters selected to gain more effective working cycle of the engine.

In Figure 4 are the models results for torque M_t of naturally aspirated and turbocharged internal combustion engine LGW 702 powered by a variety of process gases. As can be seen, the greatest torque is generated by the combustion of natural gas (about 98% CH_4), and the lowest value of M_t is reached by the combustion of landfill gas (52% CH_4). Because of supercharging, the engine torque has increased on average by 49% for each fuel type, thus the performance for each type of process gas exceeds the output of naturally aspirated engine burning natural gas.

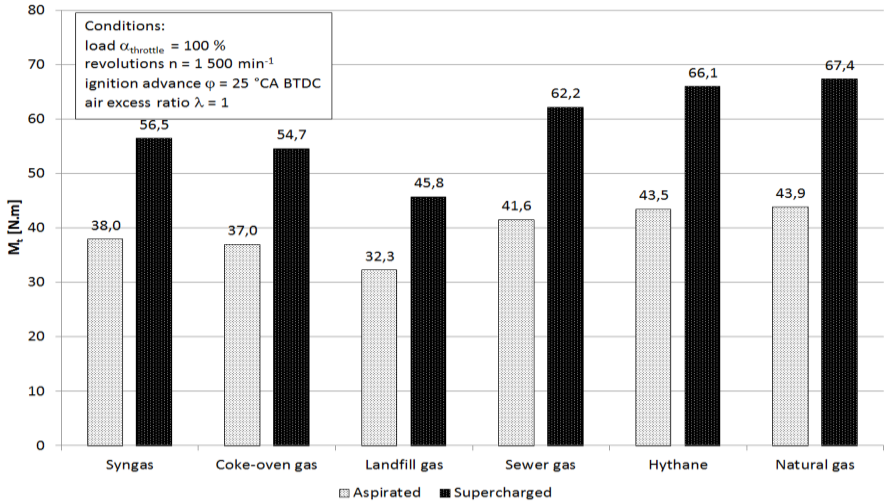

Fig. 4 Torque values for each of the alternative gaseous fuels, obtained by simulation
Rys. 4. Wartości momentu obrotowego dla poszczególnych paliw alternatywnych, uzyskane dzięki symulacji

Figure 5 shows the calculated results of mass fuel consumption per hour (M_F) and effective efficiency (η_e) of naturally aspirated and turbocharged engine powered by different types of fuels. The greatest consumption is for syngas (6.4 or 8.9 $kg.h^{-1}$), since the creation of the stoichiometric mixture requires up to 23.1% vol. of fuel, which is the highest amount of all fuels considered. Out of process gases the lowest mass consumption is for coke oven gas (1.9 or 2.5 $kg.h^{-1}$), which is related to its low density (0.412 $kg.m^{-3}$). The effective engine efficiency is the highest for sewer gas (29.7% or 31.8%) out of all process gases considered.

3. CONCLUSION

From the results of modelling and experiments the following conclusions can be derived:

a) Adding hydrogen to natural gas increases the maximum pressure (Fig. 2). With increasing proportion of hydrogen in a mixture with natural gas the angle at which the maximum pressure is reached gets shifted by about 0.4 ° CA TDC for every increase of hydrogen by 5% vol. Pressure increase rate also increases with increasing proportion of hydrogen.

b) Cyclic variation of operation decreases with growing proportion of hydrogen by about 50% with increasing proportion of hydrogen by 25% vol.

c) To secure the maximum torque, with increasing proportion of hydrogen it is necessary to reduce the ignition advance. With increasing share of hydrogen the efficient fuel consumption decreases and the overall efficiency of the engine increases.

d) With increasing hydrogen, the proportion of carbon dioxide and unburned hydrocarbons in exhaust gases decreases, however, on the contrary, the proportion of NOx increases, which relates to increased combustion temperature caused by adding hydrogen.

e) From the simulation results of the process gas applications in the combustion engine it can be concluded that the naturally aspirated engine has the highest power when powered by sewage gas, the lowest power is drawn from landfill gas, which contains about 50% of inert gases.

f) The utilisation of supercharging in internal combustion engines leads to higher performance parameters for all process gases compared with naturally aspirated combustion engine powered by natural gas.

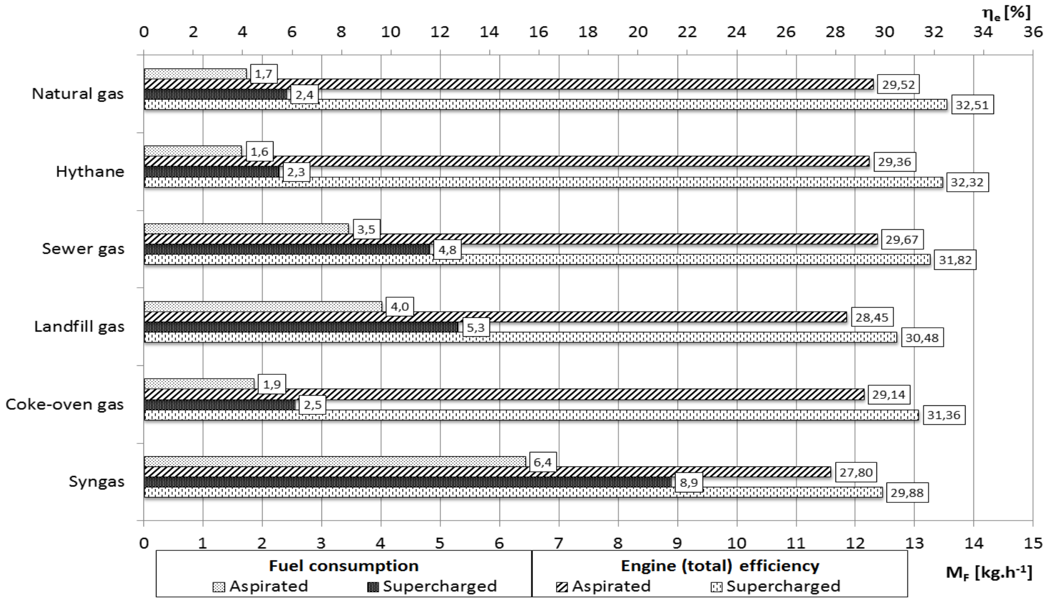

Fig. 5. Calculated results of mass fuel consumption per hour M_F and effective (total) efficiency η_e of naturally aspirated and turbocharged engine powered by various alternative fuels

Rys. 5. Obliczone wyniki godzinnego zużycia paliwaM_F oraz efektywnej (całkowitej) skuteczności η_e doładowanego i niedoładowanego silnika napędzanego różnymi paliwami alternatywnym

Efficient evaluation of low-energy process gases in micro-cogeneration unit has many indisputable advantages. The simulation results show that the use of these fuels leads to decrease in performance parameters, but these reductions in performance can be compensated by turbocharging of internal combustion engine.

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