https://doi.org/10.7494/miag.20234.1.557.7

ADAM KALWAR
ROMAN FILIPEK
PAWEŁ MADEJSKI
KRZYSZTOF PYTEL
FRANCISZEK KURDZIEL

The energy balance of a CHP unit fuelled by mine gas

This paper presents the results of a study of a gas engine heat recovery system in terms of efficient use of the energy contained in the fuel, with the study performed determining the most efficient variant of gas engine operation. A comparison between the manufacturer's data and the performance results was also made. Simulations performed on the system model allowed the optimum engine load range to be determined. The results of the analyses also indicated which variant of the engine heat recovery system is the most effective.

Key words: *gas engines, mine gas, coke-oven gas, gas fuel, cogeneration*

1. INTRODUCTION

The energy balance of cogeneration units is an important element on the basis of which it is possible to assess their efficiency and profitability. The results of the balance sheet make it possible to determine the conditions under which it is possible to maximize the use of the energy generated and minimize losses, which translates into better operational efficiency and environmental benefits [1].

The energy balance of gas engine-driven cogeneration units presents an analysis of the energy efficiency of these systems, taking into account both electricity and heat production [2]. The basic aspects of the energy balance of CHP units take into account the production of electricity and heat, the energy balance of a CHP unit includes an analysis of the amount of energy produced and consumed in the system, the efficiency of energy production in the system, and a consideration of environmental aspects [3].

2. INDUSTRIAL INSTALLATIONS SELECTED FOR TESTING

2.1. Cogeneration system powered by gas from mine de-methanation

Two gas engines of the same series (TCG 2032 V16 made by MWM Deutz) powered with the same fuel – mine gas, and one engine fuelled with coke oven gas (also of the same series) were selected as test stands. The engines fuelled by mine gas use two different heat recovery system solutions. The engines powered by mine gas are installed at the "Moszczenica" Combined Heat and Power Plant in Jastrzębie-Zdrój. Engine No. 1 (hereinafter referred to as SG-1) is a TCG 2032 V16 engine put into operation in December 2011, the electric power is 4.0 MWe and 3.9 MWt. Engine No. 2 (hereinafter referred to as SG-2) is a CG 260 16V engine (renamed after the change of ownership of MWM GmbH) put into operation in November 2014, electric power is 4.3 MWe and 3.9 MWt.

The difference in the electrical power of the engines is due solely to the model of generator used.

Both engines operated at maximum hours in connection with the national electric power system. Thermal energy from the engines is transferred to the district heating network as:
- hot water,
- central heating.

The basic parameter of operation is to maximize the electricity generated [4]. The only difference in the installations of these engines is the method of receiving heat from the engine. For the SG-1 engine, the heat is received into a single heat exchanger, and the exchanger produces a constant-temperature or variable-temperature parameter as required, while the SG-2 engine installation has two exchangers built in, one for the constant-temperature parameter and one for the variable-temperature parameter. The fixed-temperature parameter is otherwise called hot water, and the variable-temperature parameter is called central heating.

2.2. Cogeneration system powered by coke oven gas

A coke-gas-fuelled engine, commissioned in 2013, is installed at the "Nowa" Coking Plant in Częstochowa, it is also a TCG 2032 V16 engine but its electric power is reduced to 2.9 MW_e and 3.4 MW_t.

This engine was intended to be operated from the "Pniówek" Combined Heat and Power Plant in Pawlowice. This plan did not come to fruition due to the engine's operational difficulties, frequent shutdowns and failure rate. The engine produced electricity in conjunction with year-round production of process steam for the "Nowa" Coking Plant, its heat recovery system was coupled with a process steam generator.

This engine was decommissioned in 2022, after working nearly 56,724 rbh, due to the termination of the contract for the purchase of electricity and heat in process steam by the owners of the "Nowa" Coking Plant.

3. ENERGY BALANCE

The energy balance of the mine gas-fired genset is an important diagnostic tool for analysing and controlling the energy production process, playing an important role in determining the operating conditions under which the operational efficiency of the cogeneration unit is greatest [5]. It is important for monitoring, optimizing and managing the system that converts the chemical energy contained in mine gas into electricity and heat. The results of the energy balance of the cogeneration unit are shown in Tables 3, 4 and 5. This type of analysis is important for improving energy efficiency, achieving significant savings in energy consumption and maintaining compliance with the requirements governing energy production. Table 1 shows the declared parameters of engines powered by mine gas.

Table 1
Technical data of the motor series TCG 2032

Electrical power	4,000/4,300* kW_e
Heat from engine cooling	1,436 kW
Heat from cooling the mixture	367 kW
Exhaust heat	2,435 kW
Heat from the oil cooler	483 kW
Engine input power in fuel	9,946 kW
Electrical efficiency	43,2%
Thermal efficiency	43,8%
Overall efficiency	87,0%

* The 4,000-kilowatt output is for the Van Dyke generator engine, while 4,300 is for the Magnetti Marelli generator engine

4. NUMERICAL ANALYSIS

Numerical analysis of the aggregate input data was carried out in the Ebsilon environment [6]. Conducting the analysis was to answer the question of what the distribution of heat loads of heat recovery plants at different loads looks like, how the efficiency of the plant changes depending on its load, ultimately, this information was passed on to the services operating engines fuelled by mine gas.

For the purposes of the analysis, the following assumptions were made [7] and gas engine technical parameters:
- power of the generator: 4.3/4.0/3.0 MW_e, (depends on the type of fuel),
- unit heat consumption: 8 225.6 kJ/kWh,
- electric efficiency: 43.77%,
- exhaust gas stream: 6.34 kg/s,
- exhaust gas outlet temperature: 453°C.

Gas engine parameters
- degree of opening of the exhaust flap [%] – indicating the flue gas flow through the recovery boiler,
- temperatures on the power supply c.o., c.w.u.,
- flow of c.o., c.w.u.,
- water temperature in the return flow.

Composition of the mine gas

Composition of the mine gas is analysed live by chromatograph and the results of the data analysis are available in the SCADA system, making it possible to carry out analyses at any time from any period of the plant's operation. The gas analysis results shown below are averages from 2017 to 2019. Data sampling was conducted every hour with hourly averaged values:

- 33.46% N_2,
- 6.73% O_2,
- 3.91% CO_2,
- 55.69% CH_4,
- 0.02% C_2H_6,
- 0.01% C_3H_8.

Analysing the data in Table 2 and the graph in Figure 1, it can be seen that in 2017 the content of pure CH_4 in the mixture ranged from 64,7 to 50,6%, while in 2018 the content of pure CH_4 varied from 56,8 to 50,8%. Much of the stabilization in the composition of the gas mixture is due to the use of gas intake from the inactive mine workings of the former Jas-Mos mine.

The input data cited above were implemented into a model of a gas engine together with a heat recovery system in the Ebsilon environment, on the basis of the input data in the implemented model of the cogeneration unit. Analyses were carried out on the basis of which results were obtained showing the distribution of the thermal load on the elements of the heat recovery system and the flow values at various points in the system, assigned to the engine load values in the range from 50 to 100% with a step of 10%.

The use of gas extraction from inactive mining areas of the former JasMos mine provides significant stabilization in the composition of the gas mixture.

Table 2

Pure content CH_4 in the mixture [2]

Month	2017	2018	2019
January	56.13	50.24	55.50
February	61.24	48.75	55.96
March	63.41	52.67	54.31
April	64.70	53.97	55.70
May	62.39	55.48	56.20
June	60.77	56.23	56.12
July	58.26	59.12	55.63
August	52.47	61.66	56.85
September	52.88	60.58	51.72
October	52.37	58.22	51.48
November	54.10	54.34	51.66
December	50.60	52.81	50.79
Yearly average	**57.44**	**55.34**	**54.33**

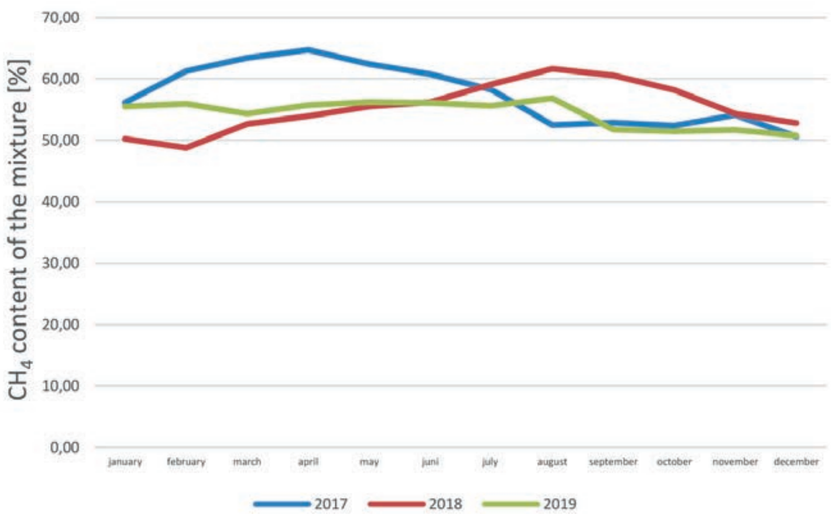

Fig. 1. Pure content CH_4 in the mixture [2]

Composition of the coke oven gas

The composition of coke oven gas is not tested continuously, the result presented below is averaged from analyses performed over 8 days in December 2014 and 8 days in January 2015:

- 4.2% N_2,
- 1.0% O_2,
- 3.5% CO_2,
- 7.6% CO,
- 24.2% CH_4,
- 3.0% C_2H_6,
- 56.5% H_2.

The lack of continuous monitoring or cyclical analyses of the gas composition does not allow any conclusions to be drawn regarding changes in the gas composition and its impact on the operation of the engine fuelled with this fuel.

5. CALCULATION MODEL OF THE ENGINE

Calculation model of the engine implemented in the Ebsilon environment represent: Figure 2 for a fossil gas engine with two heat exchangers, Figure 3 for an engine fuelled by coke oven gas with a steam generator.

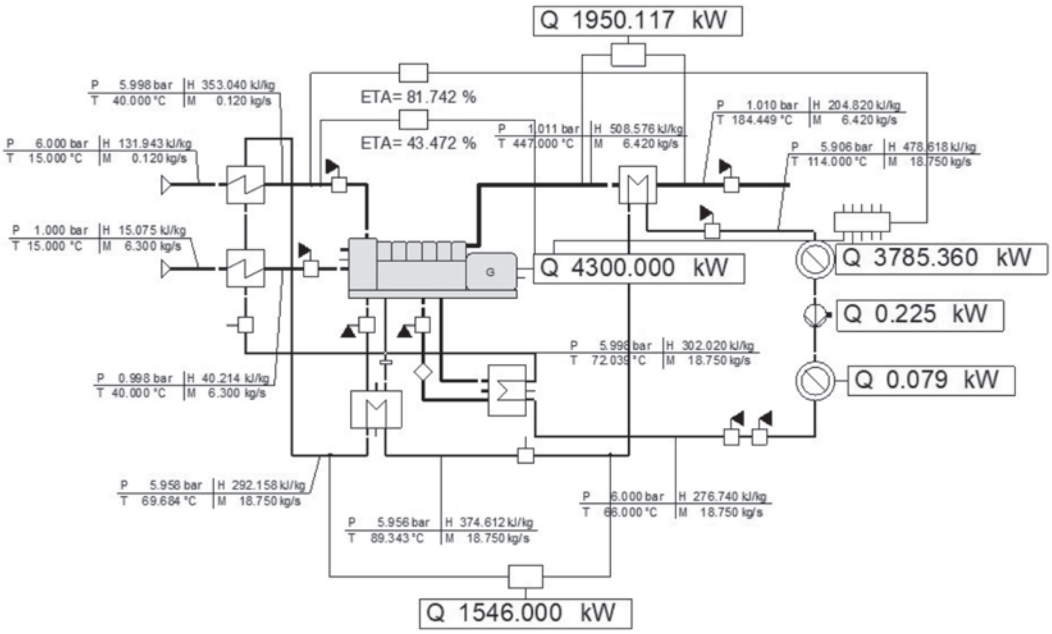

Fig. 2. Model engine CG 260 16V [3]

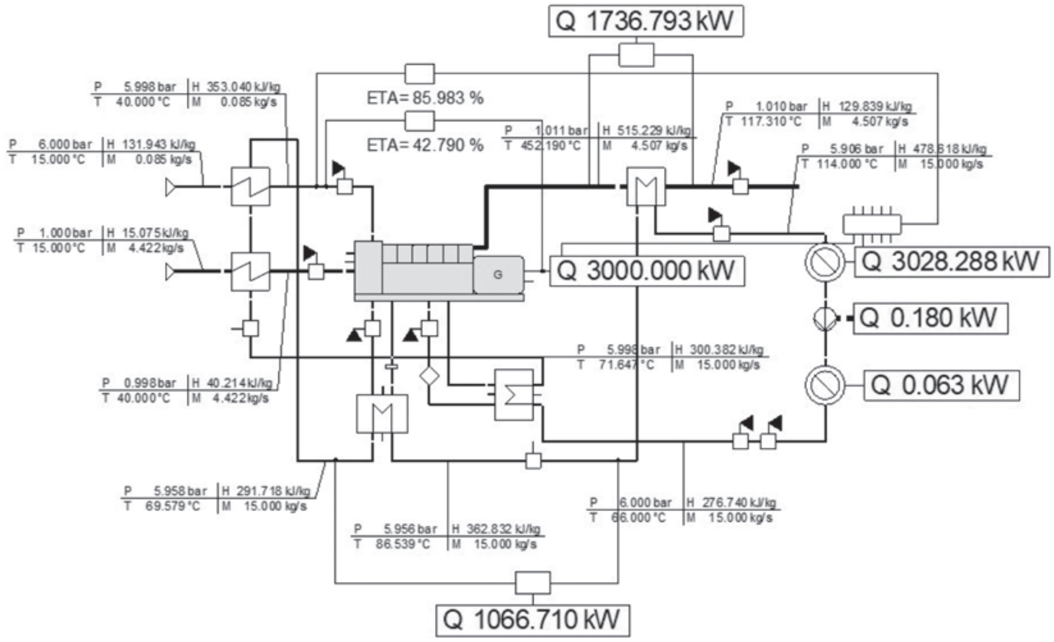

Fig. 3. Model engine TCG 2032 V16 by coke oven gas [3]

Table 3

Load characteristics of the engine and heat recovery system CG-260 16V [2]

Parameter	Engine load					
	100	90	80	70	60	50
Electric power [kW]	4,300	3 870	3 440	3 010	2 580	2 150
Thermal power from the engine cooling system [kW]	1,546.0	1,388.4	1,230.8	1,081.8	941.4	801.0
Heat power recovered from the exhaust gas [kW]	1,932.6	1,819.5	1,691.6	1,559.1	1,420.8	1,266.5
Thermal power [kW]	3,785.4	3,498.9	3,197.8	2,905.1	2,619.9	2,318.6
Exhaust gas temperature [°C]	179.0	179.0	179.0	179.0	179.0	179.0
Exhaust gas flow [kg/s]	6.420	5.808	5.196	4.601	4.024	3.447
Gas consumption [kg/s]	0.352	0.321	0.289	0.258	0.227	0.197
Air flow [kg/s]	6.068	5.487	4.907	4.343	3.797	3.250
Electrical efficiency [%]	43.550	43.490	42.433	41.610	40.496	39.033
Total efficiency [%]	81.890	81.971	81.879	81.769	81.617	81.126

For services operating gas engines, the most important indicator of gas fuel quality is the content of pure CH_4 in the mixture. The engine can even operate with less than 40% CH_4 in the mixture, but starting the engine is possible only with CH_4 concentrations above 40%, which is why it is so important to ventilate the gas system using a gas boiler – such a solution allows gas with too low a content of pure CH_4 to be efficiently and effectively removed from a section of the network (about 5 km). Carrying out this process without the use of a water boiler for this purpose would involve the prolonged release of gas into the atmosphere through process blowpipes built on the gas installation of gas engines.

For testing engines fuelled by mine gas, measurements were used at the points of gas injection into the network and at the points of gas injection into the gas system of gas engines.

Comparing the graphs in Figures 4 and 5, it can be observed that these engines achieve the best overall efficiency at a load of 90%, reaching an overall efficiency of 82% for the CG 260 16V engine and 85% for the TCG 2032 V16 engine.

The engine fuelled by coke gas (Fig. 6) also achieves the highest efficiency at 100% load and is close to 86%.

Table 4

Load characteristics of the engine and heat recovery system TCG 2032 V16 [2]

Parameter	Engine load					
	100	90	80	70	60	50
Electric power [kW]	4,000	3,600	3,200	2,800	2,400	2,000
Thermal power from the engine cooling system [kW]	1,546.0	1,388.4	1,230.8	1,081.8	941.4	801.0
Heat power recovered from the exhaust gas [kW]	1,951.7	1,836.2	1,706.3	1,571.7	1,431.5	1,275.4
Thermal power [kW]	3,804.9	3,516.1	3,212.8	2,918.1	2,630.9	2,327.7
Exhaust gas temperature [°C]	175.0	175.0	175.0	175.0	175.0	175.0
Exhaust gas flow [kg/s]	6.420	5.808	5.196	4.601	4.024	3.447
Gas consumption [kg/s]	0.328	0.298	0.269	0.240	0.212	0.183
Air flow [kg/s]	6.092	5.510	4.927	4.361	3.812	3.264
Electrical efficiency [%]	43.555	43.490	42.433	41.610	40.496	39.033
Total efficiency [%]	84.985	85.095	85.037	84.974	84.887	84.461

Table 5

Load characteristics of the engine and heat recovery system TCG-2032 V16 [2]

Parameter	Engine load					
	100	90	80	70	60	50
Electric power [kW]	3,000	2,700	2,400	2,100	1,800	1,500
Thermal power from the engine cooling system [kW]	1,066.7	956.5	850.9	1 313.2	657.9	615.0
Heat power recovered from the exhaust gas [kW]	1,736.8	1,480.1	1,404.6	754.4	1,221.8	1,076.1
Thermal power [kW]	3,028.3	2,649.8	2,460.48	2,271.2	2,081.9	1,892.7
Exhaust gas temperature [°C]	117.3	148.7	141.5	136.2	126.6	155.1
Exhaust gas flow [kg/s]	4.507	4.082	3.668	3.277	2.886	2.711
Gas consumption [kg/s]	0.085	0.078	0.070	0.063	0.056	0.053
Air flow [kg/s]	4.422	4.004	3.598	3.214	2.830	2.659
Electrical efficiency [%]	42.790	42.245	41.517	40.471	39.156	34.614
Total efficiency [%]	85.983	83.704	84.080	84.242	84.446	78.289

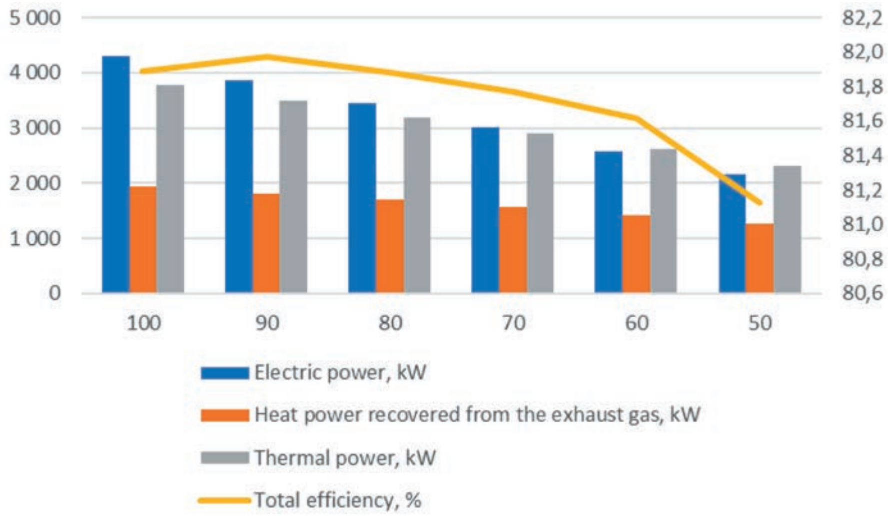

Fig. 4. Variation of engine power (CG 260 16V) and total efficiency with change in load – mine gas

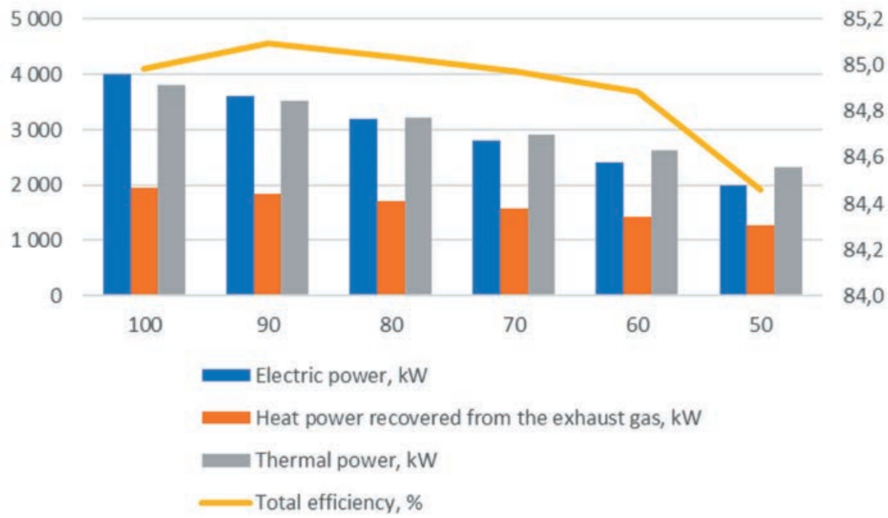

Fig. 5. Change in engine power (TCG 2032 V16) and total efficiency with change in load – mine gas

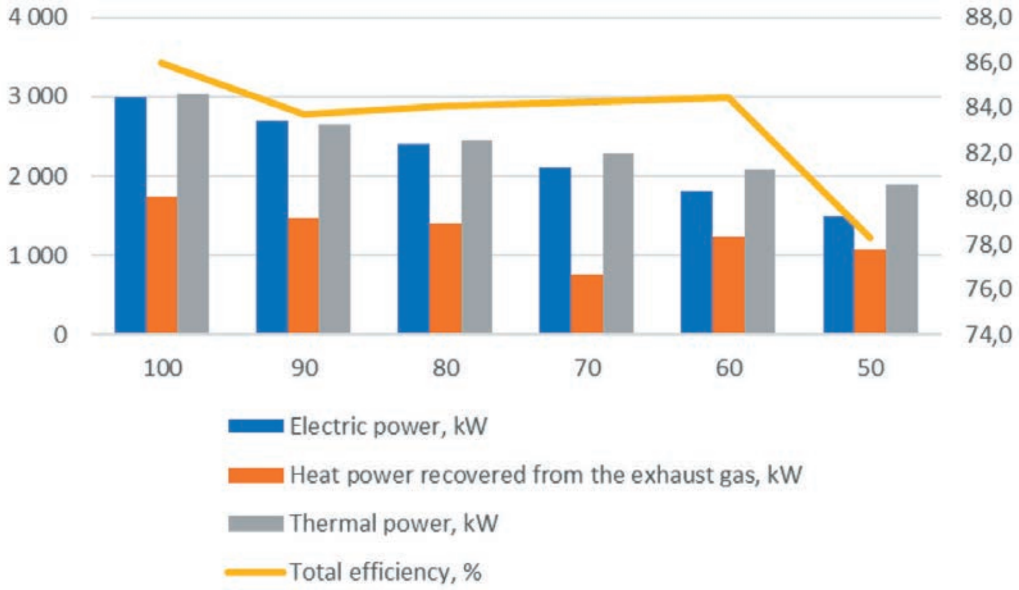

Fig. 6. Variation of engine power and total efficiency with load change – coke oven gas

6. RESULTS

For the TCG 2032 V16 engine in this range, the efficiency increases from 84.9 to 85.1%, for the CG 260 16V the range is between 82.0 and 82.2%. In contrast, the engine fuelled by coke gas has a range of efficiency changes from 84.45 to 86%.

For all the engines tested, it is confirmed that the effective operating range of the engine is between 60 and 100%, which coincides with the engine manufacturer's recommended load range, with efficiency changes ranging from 0.2 to 1.15%. All these values are illustrated in Figure 7.

For comparison, the data for the pure CH_4 content in the mix in 2016–2023 are also collated (Fig. 8), the graph allows us to see the increase in concentration variability in 2019–2022, in 2023. There are many factors influencing the variation in concentration, so in order to get an accurate idea of the reasons for the changes in pure CH_4 concentration, it would be necessary to compare the results at the point of consumption with the results of the gas composition analyses at the point of gas supply to the grid. The table presented here, therefore, is purely illustrative.

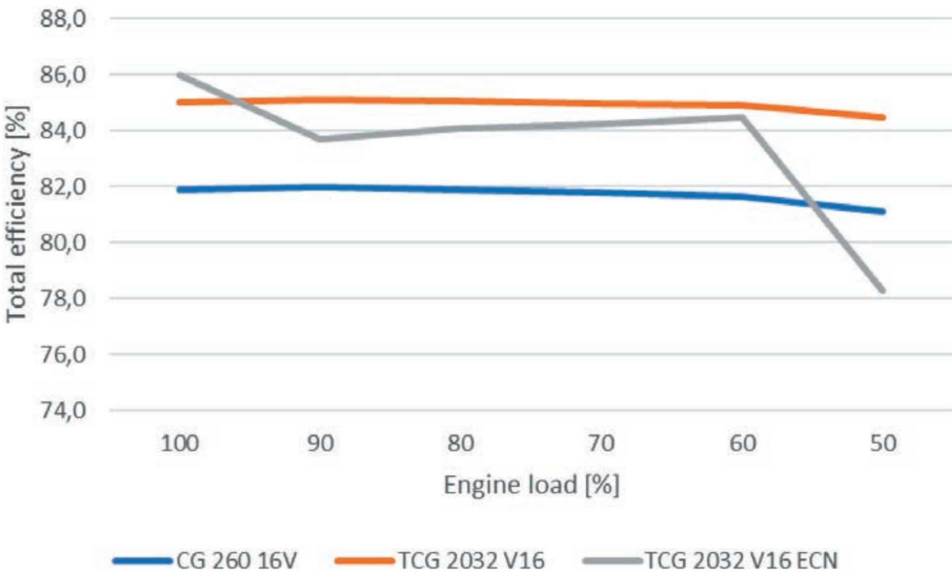

Fig. 7. Comparison of total engine efficiency

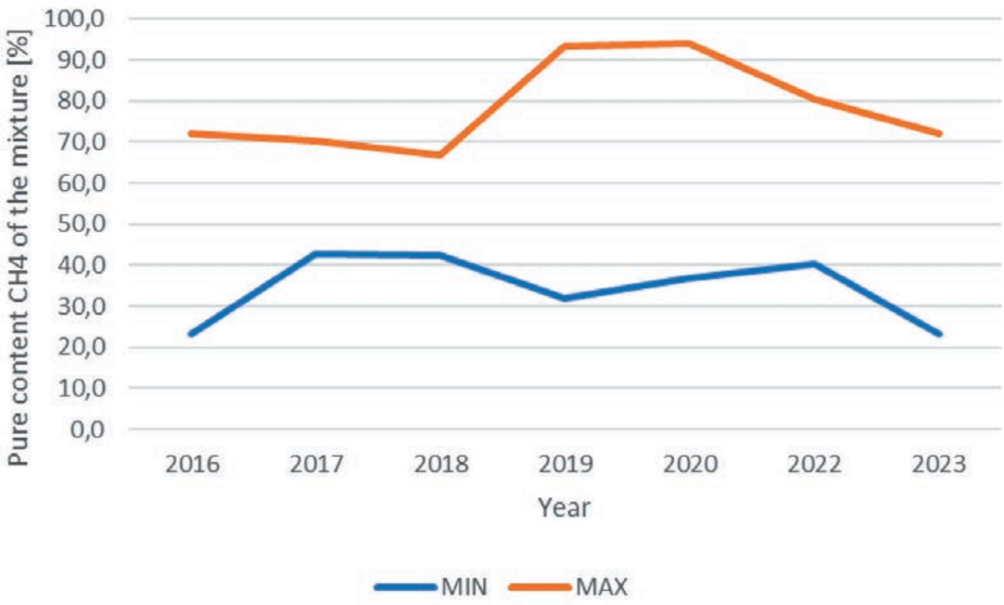

Fig. 8. Change in pure CH_4 concentration in the mixture

To understand the reasons for variations in pure CH_4 concentration, it is necessary to compare consumption point results with gas composition analyses at the grid supply point.

7. SUMMARY

The simulations conducted allowed for the analysis of the change in thermal power of the cogeneration unit depending on engine load, with simulations performed for three different systems:

- an engine powered by mine gas transferring heat to a single heating exchanger,
- an engine powered by mine gas transferring heat to two heating exchangers,
- an engine powered by coke oven gas transferring heat to a steam generator.

For technological reasons, gas engines can operate continuously within a load range of 65% to 100%, while they can operate periodically within a range of 50% to 65%, provided the conditions specified by the manufacturer in the engine's technical documentation are met.

An interesting conclusion from the analysis is that the engine with a single heating exchanger of higher power has better efficiency than with two exchangers, even though the two-exchanger system is generally considered better by operators. Another noteworthy finding is the operating point at which the engine achieves the highest overall efficiency. The analyses pointed to a specific operating point where maximum overall efficiency is attained, highlighting the importance of precisely adjusting the engine load to optimize its performance.

The simulation results were based on actual values of the gas composition and technical data provided by the manufacturer, increasing the reliability of the findings. The simulations provided additional insights into engine operating systems, with the results obtained from real gas composition values and data from engine information sheets provided by the manufacturer [8].

The next stage of analysis involves performing simulations for the actual operating parameters of the heat recovery system and engines powered by gas from mine methane drainage, as the engine powered by coke oven gas is no longer in operation.

References

[1] Ciuła J., Kowalski S., Generowicz A., Barbusiński K., Matuszak Z., Gaska K.: *Analysis of Energy Generation Efficiency and Reliability of a Cogeneration Unit Powered by Biogas*. Energies 2023, 16, 2180. https://doi.org/10.3390/en16052180.

[2] Gong H., Chen Z., Yu H., Wu W., Wang W., Pang H., Du M.N.: *Methane recovery in a combined amine absorption and gas steam boiler as a self-provided system for biogas upgrading*. Energy 2018, 157: 744–751.

[3] Salemdeeb R., Saint R., Clark W., Lenaghan M., Pratt K., Millar F.: *A pragmatic and industry-oriented framework for data quality assessment of environmental footprint tools*. Resources, Environment and Sustainability 2021, 3: 100019. http://dx.doi.org/10.1016/j.resenv.2021.100019.

[4] Salomón M., Savola T., Kirjavainen M., Martin A.R., Fogelholm C.J.: *Distributed Combined Heat and Power Generation with Small-Scale Biomass Plants – State of the Art Review*. Second International Symposium on Distributed Generation: Power System and Market Aspects, 2–4 October 2002, Stockholm, Sweden.

[5] Themelis N.J., Ulloa P.A.: *Methane generation in landfills*. Renewable Energy 2007, 32, 7: 1243–1257. https://doi.org/10.1016/j.renene.2006.04.020.

[6] Zhao S., Wang W., Ge Z.: *Energy and Exergy Evaluations of a Combined Heat and Power System with a High Back-Pressure Turbine under Full Operating Conditions*. Energies 2020, 13: 4484. https://doi.org/10.3390/en13174484.

[7] Technical and operational documentation MWM Deutz, 2011.

[8] Xue Y., Ge Z., Yang L., Du X.: *Peak shaving performance of coal-fired power generating unit integrated with multi-effect distillation seawater desalination*. Applied Energy 2019, 250: 175–184. https://doi.org/10.1016/j.apenergy.2019.04.190.

ADAM KALWAR, Ph.D. Eng.
adam.kalwar@termika.pgnig.pl

FRANCISZEK KURDZIEL, Ph.D. Eng.
franciszek.kurdziel@termika.pgnig.pl

PGNiG TERMIKA
Energetyka Przemysłowa S.A.
ul. Rybnicka 6C
44-335 Jastrzębie-Zdrój, Poland

ROMAN FILIPEK, Ph.D. Eng.
romanf@agh.edu.pl

PAWEŁ MADEJSKI, prof.
madejski@agh.edu.pl

KRZYSZTOF PYTEL, prof.
kpytel@agh.edu.pl

AGH University of Krakow
al. Mickiewicza 30
30-059 Krakow, Poland