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Evaluation of the thermodynamic combustion process in the engine supplied with gas having a low methane content

Abstract: Exploitation of coal deposits is accompanied by extraction of methane, which can be a fuel for internal combustion engines. Methane with other gases states mixture with different chemical composition. It is called mine gas. Differences in the composition and the ability to lean combustion is explored in this study, where the authors have focused their attention on the selected thermodynamic parameters and operating indicators of internal combustion engine. The assessment was made on the virtual engine, which is a compilation of the actual engine, demonstrating the need for assistive technology such as charging, variable valve timing and variable compression ratio. They provide energy, despite the restrictions of the poor in the methane deposits to maintain the desired output power and reduced fuel consumption by ensuring environment-friendly operation.

Keywords: *combustion engine, thermodynamics, methane*

Ocena parametrów termodynamicznych procesu spalania w silniku zasilanym paliwem o małej zawartości metanu

Streszczenie: Eksploatacji złóż węgla kamiennego towarzyszy wydobywanie się metanu, który może stanowić paliwo do tłokowych silników spalinowych. Metan występuje w mieszaninie z innymi gazami i stanowi tzw. gaz kopalniany o zróżnicowanym składzie chemicznym. Różnice w składzie oraz możliwość spalania mieszanek ubogich jest przedmiotem rozważań w niniejszej pracy, gdzie autorzy skupili swoją uwagę na wybranych parametrach termodynamicznych i wskaźnikach pracy silnika spalinowego. Ocenę dokonano na wirtualnym silniku, będącym kompilacją silników rzeczywistych, wykazując konieczność stosowania technik wspomagających jak: doładowanie, zmienne fazy rozrządu czy zmienny stopień sprężania. Zapewniają one mimo ograniczeń energetycznych związanych z ubogimi w metan złożami gazu kopalnianego utrzymanie na pożądanym poziomie mocy paliwowej, a przez zmniejszone zużycie paliwa zagwarantowanie proekologicznej eksploatacji.

Słowa kluczowe: *silnik spalinowy, termodynamika, metan*

1. Introduction

In Poland, as well as around the world, there are significant deposits of natural gas with low methane content, which cause difficulties with its use in industry, households and transport. These gas deposits are found in both active mines and excluded from work, where for safety reasons must be constantly cleaned. Clean up, the removal of methane, is realized in two ways:

- by methane recovery that is using methane as energetic gas,
- by direct methane disposal through ventilation to the atmosphere.

The first of these methods involves the capture and use of methane gas for energy. It is about 20% of the residual gas. The remaining 80% are losses. However, there are mines [3, 5, 6], where the proportions are the other 40/60 and the modernization of methane recovery process is still improved.

According to the Ministry of Economy [3, 6, 7, 25] in the Polish mining industry is leaving a total of over 800 million m^3 of methane per year. With simple calculation shows that about 640 million m^3 are losses that could be utilized in the form of electricity, heat or cold in air conditioning. All of these forms of energy could be used directly in the mines (place of gas production) and that means a significant reduction of further losses and transmission costs and, in some cases, give energy self-sufficiency.

In addition, methane thrown into the atmosphere by the ventilation enhances greenhouse effect around 21 times stronger than carbon dioxide, which much more attention is paid to research on global warming [3].

In the future, the amount of methane in coal mines will continue increase due to the increase of mining depth, as evidenced by the amount of methane per one tonne of coal, which in 2012 increased by 50% compared to 2001 and is currently 11 m^3 [7, 25].

The increase in depth of the mining seams to strong variations in terms of the methane content of 0.2 to 1.0% [7].

As a result of the methane recovery is obtained mine gas with different chemical composition depends on the nature of the deposit.

For the gas derived from the current operating - Coal Seam Methane (CSM), methane is measured at a level of 25 to 60%. In turn, the gas extraction from the closed mine - Abandoned Mines Methane (AMM) can be identified between 60 and 80% of CH_4. The remaining components of mine gas are: nitrogen (from 4 to 40%) and carbon dioxide (from 1 to 15%). Oxygen can be also measured in amounts of 7 to 17% as well as carbon monoxide - from 0.1 to 0.4%. Trace amounts are: hydrogen, helium, hydrogen sulphide, hydrogen chloride, hydrogen fluoride, ammonia and the longer-chain hydrocarbons [3].

The most common form of application of mine gas (with methane of course) is to be a fuel for an internal combustion engine, which very often is a part of generator sets and cogeneration or threegeneration systems [2, 5, 6, 7, 25].

Gas engines found in solutions for coal mining applications operate in two states of the air-fuel mixture: stoichiometric ($\lambda = 1$) or lean ($\lambda = 1.6$ to 2.2) [3, 5, 7, 15, 23, 24]. The most common are engine companies of the MAN, Deutz, Caterpillar - MWM or complete sets of threegeneration - Austrian company Jenbacher. These units consist of 4 to 20 cylinders in row or V-systems, with different fuel power from 100 to 10,000 kW charged in one or two-steps. These engines are operated at revolutions from 1000 to 2500 rpm, with compression ratios from 10 to 13.

Very often the motors are operated continuously for fixed parameters of the load and therefore at one point of the full load performance map [5, 6, 16, 18]. Although gas storage tanks, which act buffers pressure, these engines are exposed on extreme methane jumps. It must have an effect on the thermodynamic characteristics of the combustion process as well as the operating factors therefore, authors propose, by modelling, to determine changes that occur in the combustion chamber for different methane content in the gas-air mixture and to determine the effects of the application of support systems, such as different levels of charge, variable compression ratio and variable valve timing [1, 10, 11, 12].

2. Methane as an engine fuel

. Methane is an energy factor for all mine gases, so attention is paid to it for all considerations both adiabatic combustion process as well as real ones. In Table 1 summarizes the characteristics of the methane as compared to other fuels.

Analysing the data in Table 1, it should be noted the low densities of natural gas and methane. They ensure homogenous air-fuel mixture and thus provide the possibilities of operating at lean mixtures and higher engine speeds. The use of lean mixtures is also apparent from the fact of a wide range of combustibility (5-15%). This advantage results in an easy starting engine - even with a low ambient temperature.

Table 1 Chosen parameters of selected gaseous fuels and gasoline [2, 14]

Fuels	Density kg/m^3 at T=20^{o}C	Calo-rific values MJ/kg	Motor Octane Nr	Combustibility limit, % vol. gas in the air		Flash point ^{o}C
				Lower	top	
Gasoline	720-750	43	81-88	1,16	7	480-550
Methane	0,6680	50	140	5,00	15	654
Natural gas	0,71-0,80	38-49	115-130	5,00	15	540-650
Mixture of 50% propane 50% butane	-	46,1	95	1,80	9	500
Hydrogen	0,0840	120	70	4,00	77	585

Another advantage is the lower value of methane combustion temperature which reduces the thermal load of the combustion chamber and provides lower emissions of nitrogen oxides [8, 9, 13, 14, 16, 17]. The disadvantage of lean mixture is reduced engine power. The high octane number for methane indicates high knock resistance and this makes it possible to use a relatively high compression ratios (10 to 13). It is also provides by high flesh point. The possibility of using high compression ratios can partially compensate for the loss of power resulting from the application of lean burn [20, 21].

In mining conditions, as mentioned in the introduction, the gas recovered in the drainage process has different characteristics than those described in Table 1, because it is not a pure methane or natural gas. Depending on origin the composition of the gas is different - Table 2.

Table 2. Chemical composition (%) of mine gas, depending on the origin [3]

Component	CSM	AMM
CH_4	25-60	60-80
N_2	4-40	5-32
CO_2	1-6	8-15
O_2	7-17	0
CO	0,1-0,4	0

CSM - Coal Seam Methane
AMM - Abandoned Mines Methane

In turn, table 3 contains the data for the fuel gas, which unfortunately, gives the lack of evidence of suitability to internal combustion engines because it do not meet the standard PN-C-04750: 2002 - about the classification, marking and the requirements for gaseous fuels.

Table 3 Characteristics of methane gas
in one of the mines of JSW [25]

Component / parameter	Value
CH_4, %	50,89
N_2, %	40,39
CO_2, %	1,37
O_2, %	7,35
CO, %	0,0008
Calorific value, MJ/m^3	18,1
Density of the nat. standard, kg/m^3	1,002
Molecular weight, kg/kmol	22,41
Wobbe Index, MJ/m^3	20,56

JSW – Jastrzębska Spółka Węglowa (Coal Joint-stock Company)

The above example indicates a strong variation of composition of mine nitrogen-rich gas. It confirms the belief of the necessity of deep study of the combustion process and thermodynamic parameters as well as operating indicators of internal combustion engines.

3. Results

Modelling [1, 11, 13, 14, 15, 19, 22] adopted the virtual gas engine, whose parameters have average values of the engines found in reality. The tables and graphs demonstrating the results of the analysis, which rated the chosen indicators for the gas fuel supply with different calorific values and with different levels of methane. The results included in the relative terms, relating them to the values for pure methane fuelled engine (100%), which was burnt in a stoichiometric mixture ($\lambda = 1$).

Table 4 Relative changes in selected parameters of the combustion process and engine operating indicators for gas with a high content of nitrogen (L) and another with the rich mixture (E - $\lambda = 0.92$) of methane-rich gas (98%)

parameter	Base engine, % (47MJ/kg $\lambda = 1$)	Change_L, % (37MJ/kg, $\lambda = 1$)	Change_E, % (47 MJ/kg, $\lambda = 0,92$)
p_1	100	0,0	0
η_v	100	0,0	0
T_{max}	100	-14,7	+4,3
p_{max}	100	-14,7	+5,1
BMEP	100	-20,5	+7,1
η_m	100	-2,2	+0,6
η_o	100	-1,0	-1,5
g_e	100	+25,8	+1,5
P_e	100	-20,5	+7,1

Where : p_1 - the pressure at the end of the intake stroke, η_v - filling ratio, T_{max} - maximum temperature of thermodynamic cycle, p_{max} - maximum pressure circulation, BMEP – brake mean effective pressure, η_m - mechanical efficiency, η_o - overall efficiency, g_e - specific fuel consumption, P_e - power (from fuel).

The values of the parameters in table 4 confirm the expected results. The use of less energy fuel (the so-called group L, whose calorific value is about 21% lower than the base) results in the same level of engine power loss, resulting in an increase of specific fuel consumption by more than 25%. Lower energetic fuel results decrease of the value of the maximum pressure and adiabatic temperature by nearly 15%, which is caused by changes in the specific heat of combustion products to the unchanging coefficient of molecular transformation.

Using the same fuel as the base engine, but the enriched mixture ($\lambda = 0.92$) produces the desired effect, i.e. an increase in power, but the resulting decline in the overall efficiency of the engine and increase the maximum thermodynamic cycle parameters.

Changes in fuel parameters obviously did not cause changes in the charging process, i.e. the pressure at the end of the intake stroke or filling ratio are not changed.

In subsequent studies, it was decided to investigate the effect of different levels of methane in the mine gas on the selected parameters of the combustion process - table 5.

Table 5. Relative changes in selected parameters of the combustion process and engine operating indicators fuelled with gas of varying methane.

Parameter	Relative changes in the parameter for different methane content in the fuel,%						
	100	83	71	63	55	50	45
p_1	0	0	0	0	0	0	0
η_v	0	0	0	0	0	0	0
T_{max}	0	-8,8	-15,5	-20,9	-25,2	-28,8	-31,8
p_{max}	0	-10,1	-17,7	-23,5	-28,2	-32,0	-35,2
BMEP	0	-14,1	-24,6	-32,8	-39,3	-44,6	-48,9
η_m	0	-1,4	-2,8	-4,2	-5,4	-6,7	-7,9
η_o	0	+3,1	+5,6	+7,6	+9,4	+10,9	+12,4
g_e	0	-3,0	-5,2	-7,0	-8,5	-9,8	-11,0
P_e	0	-14,1	-24,6	-32,3	-39,3	-44,0	-48,9

Description as below table 4.

The obtained data show that, as in previous studies of gas composition changes do not affect the parameters of the charging process. However, a significant influence on other parameters is shown, in this way that with a decrease of the content of methane, the engine power and the brake mean effective pressure are lower and the reduction of the maximum values of thermodynamic parameters are also observed. At the same time, decrease specific fuel consumption resulting in increased overall efficiency – fig. 1 and 2.

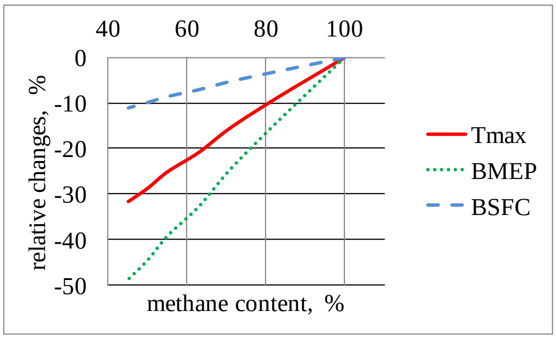

Fig. 1. Relative changes of temperature (T_{max}), brake mean effective pressure (BMEP) and specific fuel consumption (BSFC) for changes in the methane content in the fuel.

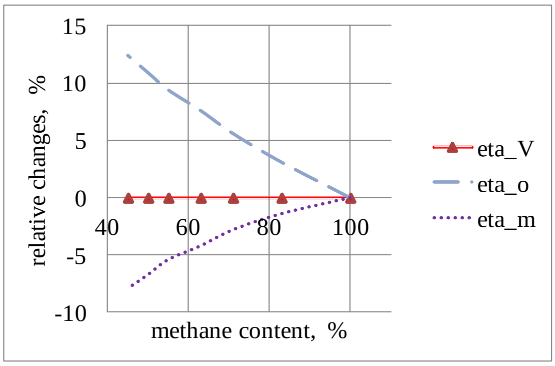

Fig. 2. Relative changes in efficiencies of: volumetric (eta_v), mechanical (eta_m) and overall (eta_o) as a relationships of changes in methane content in the fuel.

The above results are so-called net changes i.e. without other techniques support. If systems of: one or two-stage supercharging, variable valve timing and variable compression ratio are used, the engine can be operated with lean mixtures of mine gas maintaining the desired level of engine power and required electrical power of electric generator and heat power in cogeneration sets. The data are presented in table 6.

Results demonstrate the ability to maintain established levels of engine power using technologies supported combustion of lean mixtures. Due to the support of the charging process it results significant increases both the pressure at the end of intake stroke and volumetric efficiency. The treatments associated with intensive cooling loads in circuits of turbocharger and variable valve timing necessitated an increase of maximum pressure and decrease of temperature of adiabatic combustion of lean mine gas mixtures with the air.

Table 6 Relative changes in selected parameters of the combustion process and engine operating indicators fuelled with gas for different fuel-air mixtures with support of VVT technology, VCR and two-stage supercharging.

parameter	Relative changes, % for		
	$\lambda = 1$	$\lambda = 1{,}4$	$\lambda = 2{,}2$
p_1	0	23,1	46,1
η_v	0	31	57,3
T_{max}	0	-17,8	-23
p_{max}	0	1,9	9
BMEP	0	-1	5,6
η_m	0	-0,1	1,1
η_o	0	5,8	47,8
g_e	0	-5,5	-32,3
P_e	0	-1,03	-4,02

Description as below table 4.

There was a slight change in mean effective pressure which makes the engine will not be unduly loaded. A significant, positive effect of the application of assistive technology is to increase the overall efficiency of the engine and reduce fuel consumption which will result in lower emissions of carbon dioxide into the atmosphere, and thus significantly reduce the generation of greenhouse effect.

4. Conclusions

Aim of the study, which was to evaluate the thermodynamic parameters of the combustion process in the engine fuelled with gas having low methane content has been achieved. The possibilities of mine gas application with particular emphasis on its use as a fuel for internal combustion engines has been presented. Diversified mine gas composition was analysed by evaluating the thermodynamic cycle and selected engine operating indicators. It has been shown that in the absence of support of modern techniques such as one or two-stages charging, variable valve timing, variable compression ratio, the use of methane gas will result in low power and significant changes in thermodynamic parameters of cycle. Modelling has showed possibility of maintain the desired level of power despite changes in the gas composition and work on gas with methane limited. This has translated e.g. in cogeneration systems for electric power generated or heat and thus the level of gas utilization. Further work, the authors will move towards the protection of the environment through reduced emissions of carbon dioxide by downsizing technique.

Nomenclature

CSM - Coal Seam Methane,
AMM - Abandoned Mines Methane,
λ - fuel/air factor,
E - mine gas with high methane content,
L - mine gas nitrogen-rich,
p_1 - the pressure at the end of the intake stroke,
η_v (eta_v)- filling ratio,
T_{max} - maximum temperature of cycle,
p_{max} - maximum pressure circulation,
BMEP - brake mean effective pressure,
η_m (eta_m) - mechanical efficiency,
η_o (eta_o) - overall efficiency,
g_e - specific fuel consumption,
P_e - power (from fuel).
VVT - variable valve timing,
VCR – variable compression ratio,
JSW – Jastrzębska Spółka Węglowa (Coal Joint-stock Company)

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