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ANALYSIS OF THE EFFECT OF THE CHEMICAL COMPOSITION OF LOW CALORIFIC GASEOUS FUELS ON WORKLOAD CONCENTRATION IN AN ENGINE'S COMBUSTION CHAMBER

Sławomir WIERZBICKI

University of Warmia and Mazury in Olsztyn
ul. Słoneczna 46A, 10-710 Olsztyn, Poland
tel. +48 89 5245222, fax. +48 89 5245150
e-mail: slawekw@uwm.edu.pl

Abstract

Low calorific gaseous fuels are becoming increasingly used as alternative fuels for feeding power equipment of all kinds, including combustion engines. The increased interest in these fuels results, above all, from support for the development of this type of power engineering by governmental and international institutions, aiming to increase the renewable energy share in the overall energy balance. Fuels of this type are obtained by processing different kinds of biomass and natural raw materials and can also be recovered from natural processes occurring in nature. Due to the diverse technologies for obtaining these fuels, their chemical composition is variable, which significantly affects the efficiency of their use as fuels for combustion engines. When engines are fed with gaseous fuels, combustion chamber filling conditions change considerably due to the much higher gaseous fuel volume compared to liquid fuels, which significantly affects the engine's performance.

This paper presents the effect of individual combustible components contained in different low calorific gaseous fuels on changes in the degree of engine combustion chamber air filling and on the calorific value of the produced combustible air-gaseous fuel mixture.

Keywords: *environmental protection, low calorific gaseous fuels, calorific value, excess air coefficient, combustible mixture*

Introduction

Growing social awareness and concern for the environment and the increasingly stricter standards for reducing greenhouse gas and toxic compound atmospheric emission limits have prompted a search for new alternative energy sources [1, 6]. Another important factor causing an increased interest in renewable energy sources is the need to increase the share of energy produced from alternative energy sources as required by EU legislation. It is also worth stressing that the heightened interest in alternative fuels is favoured by shrinking resources of fossil fuels, particularly petroleum [4, 5, 6].

Low calorific gaseous fuels of different types are potential energy sources which can be obtained by processing different kinds of biological products and can also form spontaneously as a result of natural processes occurring, among others, in dumping sites, sewage treatment plants and animal farms [1, 4, 5].

The composition of such fuels is not constant and is closely dependent not only on the raw materials from which they are produced but also on the technology for their production and treatment. The combustible compounds making up fuels of this type include, above all, methane

(CH_4), carbon monoxide (CO) and hydrogen (H_2). The basic properties of the listed combustible components of gaseous fuels are presented in Table 1.

The percentage of individual components in gaseous fuels is not constant and, as has been mentioned, is conditioned by many factors. The main low calorific gaseous fuels most often used currently include [1, 2, 5, 7, 8, 9]:

- agricultural biogas – obtained by methane fermentation of plant raw materials or animal excrement;
- biogas from sewage treatment plants – gas recovered in sewage treatment plants in sewage and water treatment;
- landfill gases – forming by decomposition of organic substances contained in municipal waste after disposal;
- fossil gases – gases obtained in hard coal mine demethanization;
- synthesis gases (syngas) – obtained in gasification of solid fuels, petroleum refining residues, steam methane reforming or partial methane oxidation with oxygen.

Table 2 presents the percentages of individual combustible components in the most common low calorific gaseous fuels.

Table 1. Basic properties of combustible components of low calorific gaseous fuels

Gas	Calorific value [MJ/m^3]	Standard density [kg/m^3]	Air demand [m^3/m^3]	Self-ignition temperature [K]
Hydrogen (H_2)	10,78	0,0899	2,38	807
Carbon monoxide (CO)	12,6	1,25	2,38	881
Methane (CH_4)	35,89	0,717	9,54	923
Ethane (C_2H_6)	63,77	1,34	16,7	793
Propane (C_3H_8)	91,28	1,97	23,8	783
Butane (C_4H_{10})	122,6	2,33	31	692

Table 2. Volumetric content of individual components in gaseous fuels [2, 4, 6, 8]

Gaseous fuel	H_2 [%]	CO [%]	CH_4 [%]	CO_2 [%]	N_2 [%]	O_2 [%]
Agricultural biogas	-	-	45-75	25-55	0-5	0-3
Biogas from sewage treatment plants	-	-	57-62	33-38	3-8	0-1
Landfill gas	0-15	-	37-67	24-40	10-25	0-45
Mine gases	-	-	40-80	8-15	20-40	0-10
Synthesis gases	3-0-70	0-60	0-10	5-30	0-2	-

Because of the quite large differences possible in the chemical composition of such gaseous fuels, the combustion conditions for such fuel in the engine change significantly, which causes significant changes in the obtainable engine power, the amount of heat carried away by the engine's cooling system and heat carried away by exhaust gas.

Characteristic parameters of the fuel-air mixture

The power obtained from a combustion engine depends primarily on the calorific value and the amount of fuel burnt in the combustion chamber. The amount of burnable fuel is conditioned by the amount of oxygen available in the engine chamber, which is necessary for burning combustible components contained in the fuel. The vast majority of the oxygen supplied to the engine's combustion chamber comes from the air and only a small part of oxygen can be supplied with fuel (for oxygen-containing fuels).

Therefore, the power obtainable by the engine is limited by the amount of air (oxygen) induced into the combustion chamber needed for complete fuel combustion. For liquid fuels, the theoretical amount of induced oxygen results from its content in the air and the maximum combustion chamber volume. In this case, the volume of supplied liquid fuel is minute and can be ignored practically without error. In reality, the induced fresh air volume depends on the engine filling efficiency, which is most affected by the structure of ducts feeding fresh load to the combustion chamber, the efficiency of cleaning exhaust gas residues from the previous work cycle of the combustion chamber, engine speed as well as the temperature in the combustion chamber during the suction stroke. In real combustion engines, cylinder filling efficiency ranges from 0.7–0.85 and decreases with rising engine speed, due to shortening suction stroke length.

While for liquid fuels the volume of fuel fed to the combustion chamber can be ignored, for gaseous fuels, containing not only combustible compounds but also substantial percentages of non-combustible compounds such as carbon dioxide (CO_2) and nitrogen (N_2), the volume of fuel fed to the engine chamber is considerable (except for solutions with gas injection directly into the combustion chamber). Therefore, this significantly reduces the volume of air induced into the combustion chamber for fuel combustion which, in turn, changes the engine performance.

As mentioned before, low calorific gaseous fuels contain three basic combustible components: methane (CH_4), hydrogen (H_2) and carbon monoxide (CO). Assuming that the whole amount of fed fuel is burnt, the occurring combustion reactions for these compounds can be written as:

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{1}$$

$$2H_2 + O_2 = 2H_2O \tag{2}$$

$$2CO + O_2 = 2CO_2 \tag{3}$$

Considering that 21% of oxygen is in the air by volume, it can be stated that the theoretical amount of air needed for the combustion of a fuel which is a mixture of these three gases is:

$$L_t = \frac{1}{0{,}21}\left[0{,}5\left(H_2 + CO\right) + 2CH_4\right] \ [\mathrm{m}^3 \text{ air / } \mathrm{m}^3 \text{ gaseous fuel}] \tag{4}$$

For gaseous fuels containing oxygen, this amount of oxygen should be taken into account, therefore, the above formula assumes the form:

$$L_t = \frac{1}{0{,}21}\left[0{,}5\left(H_2 + CO\right) + 2CH_4 - O_2\right] \ [\mathrm{m}^3 \text{ air / } \mathrm{m}^3 \text{ gaseous fuel}] \tag{5}$$

To determine the volume of air induced into the combustion chamber with the air-gas mixture, the degree of combustion chamber air filling γ_{air} can be defined. With the assumption that the cylinder filling efficiency is $\eta_v = 1$, the exhaust gas removal from the combustion chamber is complete and an air-gas mixture has formed outside the combustion chamber, this ratio can be written as:

$$\gamma_{air} = \frac{V_{air}}{V_{ch}} = \frac{V_{ch} - V_{fuel}}{V_{ch}} \tag{6}$$

where:

V_{air} – air volume in the air-gas mixture;

V_{ch} – combustion chamber volume;

V_{fuel} – gaseous fuel volume.

Effect of gaseous fuel composition on the degree of combustion chamber air filling and the calorific value of the mixture

The variable composition of gaseous fuels significantly affects both the degree of combustion chamber air filling and the calorific value of the produced combustible mixture. Fig. 1 presents changes in the degree of engine combustion chamber air filling for basic combustible components of gaseous fuels as a function of the excess air coefficient λ. The presented changes clearly show that for feeding with gaseous fuels the volume of induced air is much lower than when the engine is fed with liquid fuels. For a stoichiometric mixture (λ = 1), the volume of air induced into the combustion chamber is 10% lower for feeding with methane and 30% lower for feeding with hydrogen or carbon monoxide. Fig. 2 presents changes in the calorific value of the combustible mixture produced from individual gaseous fuel components depending on λ. For comparison, this figure also contains changes in the calorific value of propane (C_3H_8) and butane (C_4H_{10}), the main LPG components.

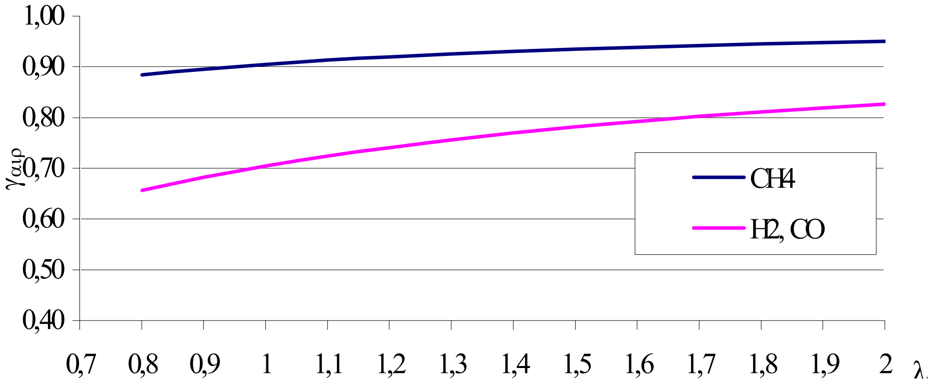

Fig. 1. Degree of combustion chamber air filling for feeding with CH_4, H_2 and CO as a function of λ

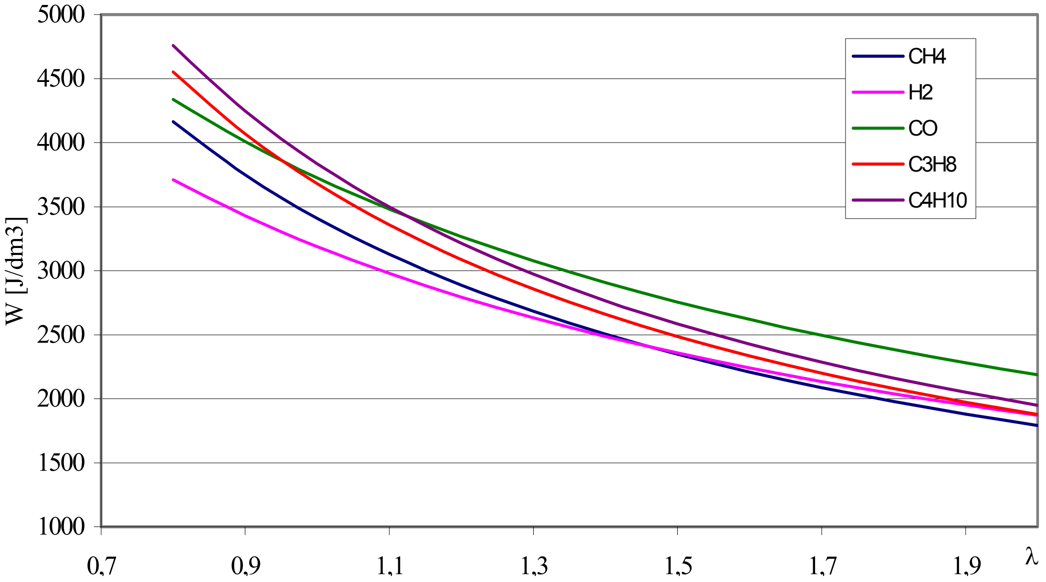

Fig. 2. Change in the calorific value of the air-gas mixture depending on λ for different gaseous fuel components

Fig. 3 presents changes in the degree of combustion chamber air filling γ_{air} and changes in the calorific value of the air-gaseous fuel mixture containing only biogas (e.g. methane) depending on the percentage of CH_4 in fuel with the excess air coefficient $\lambda = 1$. It can be concluded based on changes in combustion chamber air filling that a rise in the percentage of methane in fuel significantly affects the use of the combustion chamber. For fuels with a ca. 40% methane content the degree of engine combustion chamber volume use is only 65%.

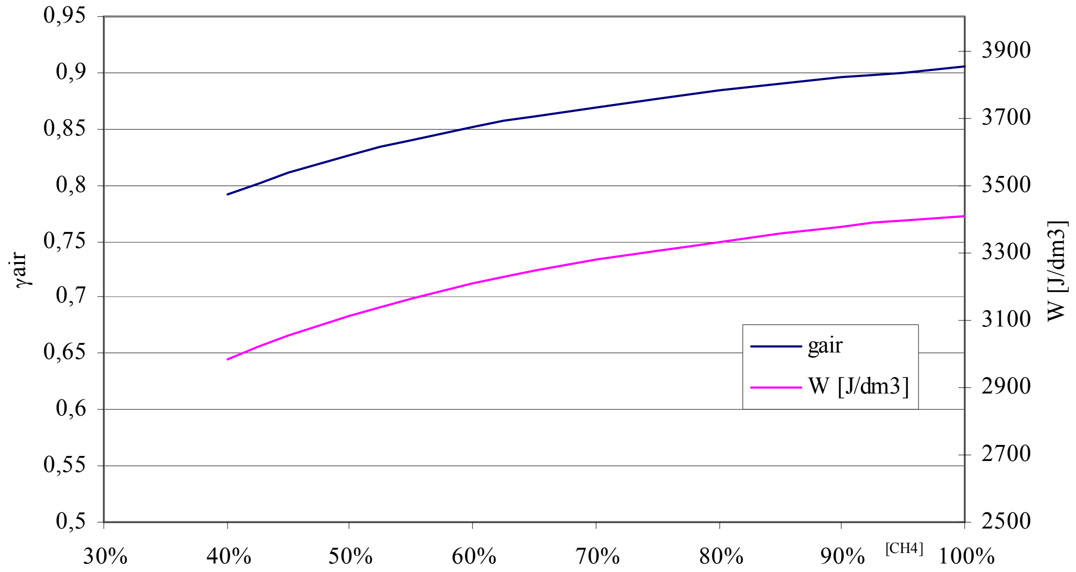

Fig. 3. Change in the degree of combustion chamber air filling and the calorific value of the air-gaseous fuel mixture for fuels with different methane percentages for $\lambda = 1$

Fig. 4 presents changes in the degree of combustion chamber air filling γ_{air} with $\lambda = 1$ for gaseous fuels containing two combustible components, e.g. landfill gases. Fig. 5 presents changes in the calorific value of the air-landfill gas combustible mixture for different concentrations of individual combustible components depending on the excess air coefficient λ.

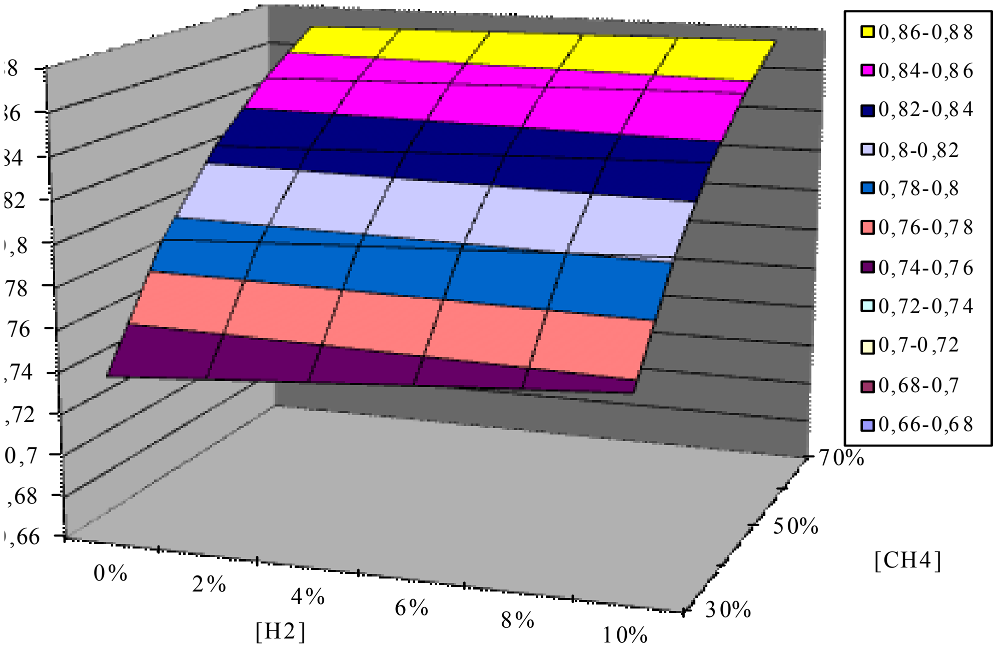

Fig. 4. Change in the degree of combustion chamber air filling for the air-combustible gas mixture with different CH_4 and H_2 percentages for $\lambda = 1$

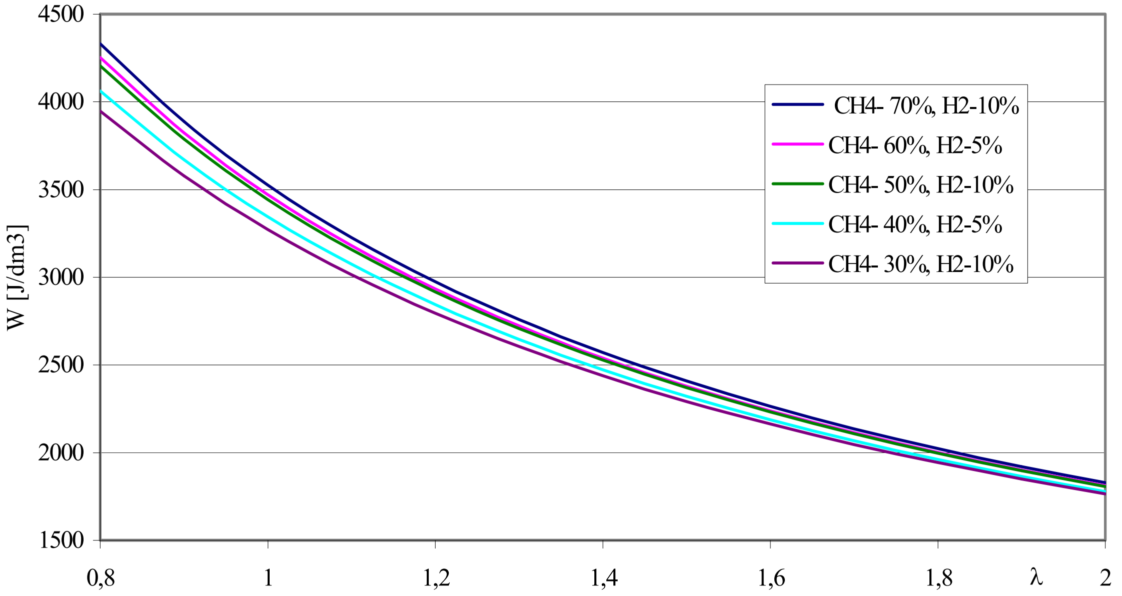

Fig. 5. Change in the calorific value of the air-landfill gas mixture depending on λ for different percentages of combustible components

For the combustion of synthesis gases, obtained by gasification of biomaterials (e.g. biomass, wood), coal gasification or steam methane reforming, oxygen contained in this fuel should also be taken into account. In fuels of this type, the oxygen volume fraction can reach even 20%, which significantly changes fuel combustion conditions. Fig. 6 presents changes in the combustion chamber air filling ratio for selected synthesis gases [3] and Fig. 7 presents changes in the calorific value of the air-synthesis gas mixture depending on the pure oxygen content in this fuel for λ = 1. The presented changes show that oxygen contained in fuel considerably increases the value of heat obtainable from the combustion of a specific portion of the produced air-gaseous fuel mixture.

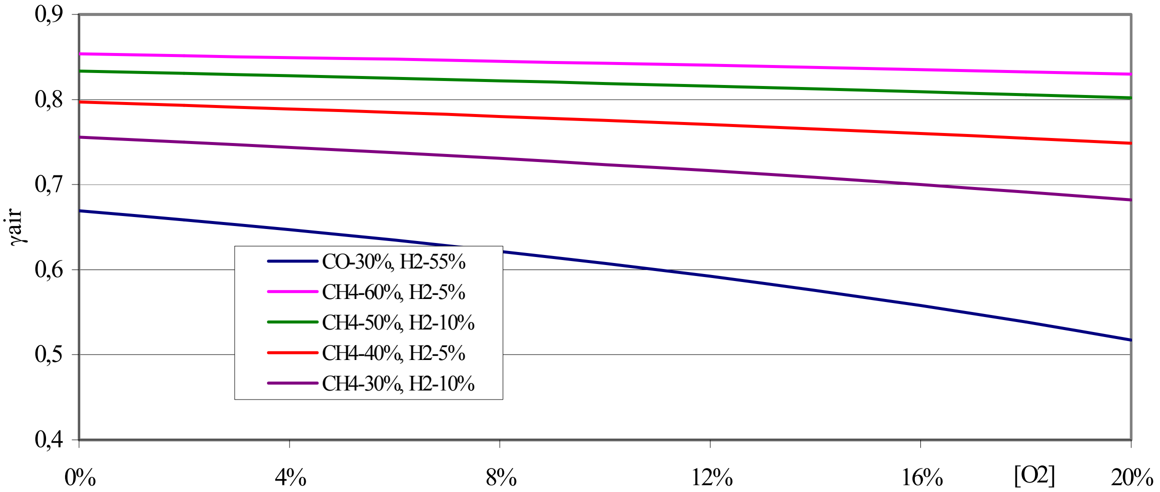

Fig. 6. Effect of the oxygen content in the synthesis gas on the value of the combustion chamber air filling ratio maintaining λ = 1

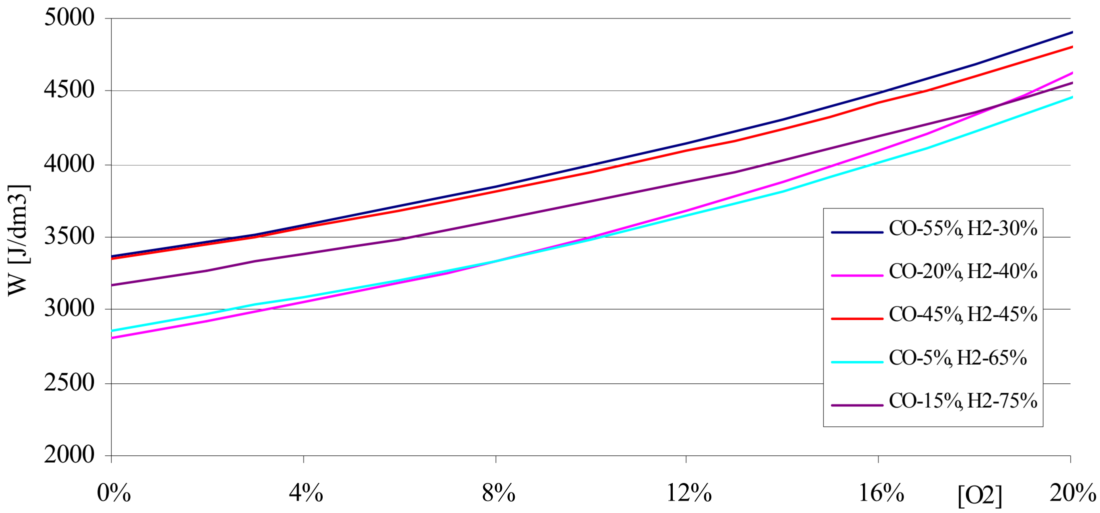

Fig. 7. Effect of the oxygen content in the synthesis gas on the calorific value of the combustible mixture for λ = 1

Conclusions

In summarizing the results on the effect of the composition of low calorific gaseous fuels on combustion chamber air filling and the calorific value of the obtained air-gaseous fuel mixture with the combustible mixture formed outside the combustion chamber, it must be concluded that:

- feeding the engine with gaseous fuels significantly reduces combustion chamber fresh air filling, which limits the burnable amount of fuel. When the engine is fed with pure methane with λ = 1, the combustion chamber volume fillable by air decreases by around 10%. When the engine is fed with pure carbon monoxide or methane, the volume of induced air under the same conditions decreases by 30%. This reduces the amount of burnable fuel, which limits the amount of heat released in the combustion chamber;
- when the engine is fed with low calorific fuels containing ballast compounds besides combustible components, the amount of heat obtainable in the combustion chamber is still lower, which causes a further decrease not only in the obtainable engine power, but also causes increased losses of heat absorbed by gases not participating in the combustion reaction;
- for fuels containing oxygen, e.g. synthesis gases, the oxygen contained in fuel increases the calorific value of the formed combustible mixture along with an increasing oxygen percentage in the fuel;
- it should, however, be stressed that despite the above limitations, low calorific gaseous fuels positively affect the share of renewable fuels in the overall energy balance. It is also important to stress that the use of these fuels for energy purposes reduces the emission of methane released spontaneously from, among others, dumping sites, which is ca. 25 times more harmful to the ozone layer than carbon dioxide [3].

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References

[1] Cebula J.: *Biogas purification by sorption techniques*. ACEE Journal, 2/2009.

[2] Dubiński J.: *Produkcja paliw ciekłych i gazowych z węgla - szanse i perspektywy*, Wiadomości Górnicze, 2007. Vol. 58, nr 5 str. 273-278

[3] Fahey D. W.: *Twenty questions and answers about the ozone layer*. United Nations Environment Programme. Ozone Secretariat, 2002, Q.12.

[4] Piskowska-Wasiak J.: *Uzdatnianie gazów pochodzenia biologicznego w celu wytwarzania biopaliw i biokomponentów*. Nafta – Gaz. 2013, R. 69, nr 3 241-255.

[5] Piętak A.: *Paliwa dla silników spalinowych*. Czysta Energia, 2011, nr 3, str. 21-24.

[6] Skorek J., Kalina J.: *Gazowe układy kogeneracyjne*. WNT, Warszawa, 2005.

[7] Usidus J., Kryłowicz A. Chrzanowski K.: *Budowa elektrowni, elektrogazowni i gazowni biometanowych w skali przemysłowej*. Spektrum. 2010, nr 9-10.

[8] Wandrasz J. W., Wandrasz A. J.: *Paliwa formowane. Biopaliwa i paliwa z odpadów w procesach termicznych*. Wydawnictwo Seidel-Przywecki, 2006.

[9] Żyła M., Kreiner K.: *Wykorzystanie energii ze złóż naturalnych paliw węglowych*. Gospodarka Surowcami Mineralnymi. 2007, t. 23, z. 3, str. 257-264.