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THE IMPACT OF THE SHARE OF BIOGAS IN A SUPPLY DOSE ON LOAD PARAMETERS IN THE COMBUSTION CHAMBER OF A DUAL-FUEL COMPRESSION-IGNITION ENGINE

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Abstract

The need to increase the share of renewable fuels in the general energy balance necessitates the search for new possibilities of their use. One such fuel is biogas, which is generated both as a result of natural processes occurring, e.g. in landfills, and can also be obtained from various biological materials in biogas plants. Because of its properties, biogas may be used to power spark-ignition engines. At the same time, in numerous scientific centres attempts are underway at using biogas to power compression-ignition engines. Due to the relatively high autoignition temperature of methane, which is the main component of biogas, it is necessary to use dual-fuel supply systems in CI engines. Providing fuel gas to such an engine in the form of biogas, which can have a varying chemical composition, considerably changes the conditions of combustion in the engine compartment, which affects both the performance of the engine as well as the emission of toxic compounds into the atmosphere.

The present paper discusses the impact of supplying an engine with fuel gas, as well as of the composition of biogas, on the ratios describing the load in the combustion chamber of a dual-fuel compression-ignition engine. The calculations were conducted for a four-cylinder forced induction engine, assuming that the volume of the drawn gas and air mixture equals the volume of the drawn air during mono-fuel operation.

Keywords: *biogas, gas and air mixture, λ ratio, compression-ignition engine*

1. Introduction

In recent years, more emphasis has been put on the increase in the share of renewable energy in the general energy balance. Particular attention is paid to second-generation renewable fuels, which can be produced from various kinds of waste of plant and animal origin. An important feature of this type of fuel is the use of agricultural products for non-food purposes, or of inedible by-products for its production, due to which the creation of such fuels does not compete with the production of food [1, 2, 5, 9].

One such fuel is biogas, which is generated spontaneously as a result of natural processes occurring, e.g. in landfills, and can also be created from organic materials in biogas plants.

The biogas produced in this manner contains considerable amounts of methane (40-75%), the main combustible component, as well as incombustible carbon dioxide (25-55%), which is a filler. Additionally, depending on its origin, biogas may contain minor shares of other components, such as hydrogen, carbon monoxide, nitrogen and oxygen, as well as trace amounts of hydrogen sulphide and other chemical compounds [1, 2, 5, 7, 9, 11].

The most important advantage of biogas-type fuel is first of all the relatively short time of its renewability in nature [7, 9]. The carbon dioxide introduced into the atmosphere as a result of the combustion of biogas is usually of plant or animal origin, and assuming its consumption by plants in the following growing cycle, the process of using such fuel becomes an element of the natural circulation of carbon in nature, and generally lasts no longer than one year.

Due to its properties, biogas is primarily used as fuel for SI engines. This method of supplying power with biogas is usually used to power stationary engines propelling power generators, as well as in agricultural biogas plants, wastewater treatment plants and landfills [3, 6-10].

Another application of fuel gases such as biogas is using them to power compression-ignition engines. Due to the high autoignition temperature of methane, the main combustible component of biogas, it is not possible to obtain the conditions necessary for its autoignition in a combustion chamber. A dual-fuel power supply is therefore utilised in order to enable the use of this type of fuel in CI engines. It involves supplying the engine with fuel gas along with air during filling, injecting a small dose of liquid fuel near the end of the compression stroke, which is meant to trigger the ignition of fuel gas 7, 9, 10, 11]

This type of supply is currently used primarily in the case of large stationary internal combustion engines. Attempts are also underway to use this type of engine to propel farm tractors. The VALTRA Company has designed a tractor with the Common Rail injection system, in which about 80% of energy is acquired from fuel gas [12].

2. Parameters describing the load in the cylinder of a dual-fuel CI engine

During the operation of a dual-fuel compression-ignition engine, in its chamber there is a mixture of gas and air, into which a small dose of liquid fuel is injected. In addition, in the case of fuels such as biogas, with diversified chemical compositions, the chemical composition of biogas may change, which affects the parameters characterising the gas and air mixture.

Several air-fuel equivalence ratios are usually used for the theoretical description of the load parameters in the combustion chamber of a dual-fuel engine [6, 7, 11]:

λ_o – the air-fuel equivalence ratio for the gas and air mixture,

λ – the total (global) air-fuel equivalence ratio for the total load in the combustion chamber (gaseous and liquid fuel as well as air),

λ_{do} – the theoretical air-fuel equivalence ratio for diesel fuel (assuming that liquid fuel is the first one to be burnt),

λ_g – the hypothetical air-fuel equivalence ratio for gas, assuming that the gas is burnt only after the complete combustion of liquid fuel.

The individual ratios are defined in the following manner [6, 7, 11]:

– the air-fuel equivalence ratio for the gas and air mixture:

$$\lambda_o = \frac{\dot{V}_a}{\dot{V}_g \cdot L_{tg}}, \tag{1}$$

where:

$\dot{V}_a$ – the mass flux of air [kg],

$\dot{V}_g$ – the mass flux of fuel gas [kg],

L_{tg} – the theoretical demand for air in fuel gas,

– the total air-fuel equivalence ratio:

$$\lambda = \frac{\dot{V}_a}{\dot{V}_g \cdot L_{tg} + \dot{m}_{do} \cdot L_{tdo}}, \tag{2}$$

where:

$\dot{m}_{do}$ – the mass flux of liquid fuel [kg];

L_{tdo} – the theoretical demand for air in liquid fuel.

– the air-fuel equivalence ratio for diesel fuel:

$$\lambda_{do} = \frac{\dot{V}_a}{\dot{m}_{do} \cdot L_{tdo}}, \tag{3}$$

– the hypothetical air-fuel equivalence ratio for gas:

$$\lambda_g = \frac{\dot{V}_a - \dot{m}_{do} \cdot L_{tdo}}{\dot{V}_g \cdot L_{tg}}, \tag{4}$$

The ratios defined above do not unambiguously characterise the composition of the mixture in a dual-fuel engine. However, they do allow an understanding of the complexity of the conditions under which the combustion process occurs in this type of engine.

The total (global) air-fuel equivalence ratio describes the possibility of the total and complete combustion of both fuels. Its value should be similar to the λ ratio for a traditional CI engine, which lowers the risk of the heat overload of the engine.

The λ_o ratio describes the composition of the gas and air mixture present in the combustion chamber, assuming that the whole dose of fuel gas is supplied along with air while filling the cylinder. It can be therefore assumed that near the end of a compression stroke there is a homogeneous mixture of gas and air in the combustion chamber of the engine.

On the other hand, the value of the air-fuel equivalence ratio for diesel fuel (λ_{do}) in the combustion chamber does not define so unambiguously the conditions in which its combustion takes place. The injection of liquid fuel takes place shortly before its ignition, and the distribution of the fuel dose in the cylinder is not even (a heterogeneous mixture); additionally, with higher pilot doses the ignition may occur as early as during the injection of fuel.

The λ_g ratio describes the conditions of the gas combustion process, assuming that liquid fuel is the first one to be burnt, as a result of which the amount of available oxygen in the combustion chamber drops. The value of this ratio is particularly important in the case of small pilot doses. In such cases, during the combustion of a liquid fuel dose, only a small dose of fuel gas present within the stream is burnt, while the majority of the fuel gas dose burns when the burning of the pilot dose has already ended.

The equivalence ratios defined in this manner unambiguously describe just the properties of the combustible mixture, only in the case of fuels containing solely the combustible components. In the case of fuel gases such as biogas, which may contain considerable amounts of incombustible gases, this ratio is ambiguous since it does not take into account the share of incombustible gases in fuel gas. In such cases, it is advisable to determine the concentration of oxygen in the mixture of gas and air k_{O2}, which can be calculated using the following formula:

$$k_{O2} = \frac{V_{O2}}{V_{air} + V_g} \cdot 100\%, \tag{5}$$

where:

V_{O2} – the volume of oxygen,

V_{air} – the volume of air,

V_g – the volume of fuel gas.

Assuming that the volume of oxygen in the air is constant and amounts to 21%, and that fuel gas contains no oxygen, the above formula takes the following form:

$$k_{O2} = 0.21 \frac{V_{air}}{V_{air} + V_g} \cdot 100\%. \tag{6}$$

3. The analysis of load parameters in the combustion chamber of a dual-fuel compression-ignition engine

In order to analyse the impact of the share of biogas in the dose powering a dual-fuel compression-ignition engine on the load parameters in a cylinder, the calculations of the ratios characterising the fuel and air mixture were performed for various compositions and shares of biogas in the supply dose.

A theoretical analysis of the composition of the load in the combustion chamber was conducted for an ADCR engine, assuming that the total volume of fuel gas and air is the same as the volume of air during mono-fuel operation. It was additionally assumed that the total calorific value of both fuels equals the calorific value of the fuel consumed during mono-fuel operation. Fig. 1 presents the courses of the changes in air and fuel consumption during mono-fuel operation for two rotational speeds of the analysed engine.

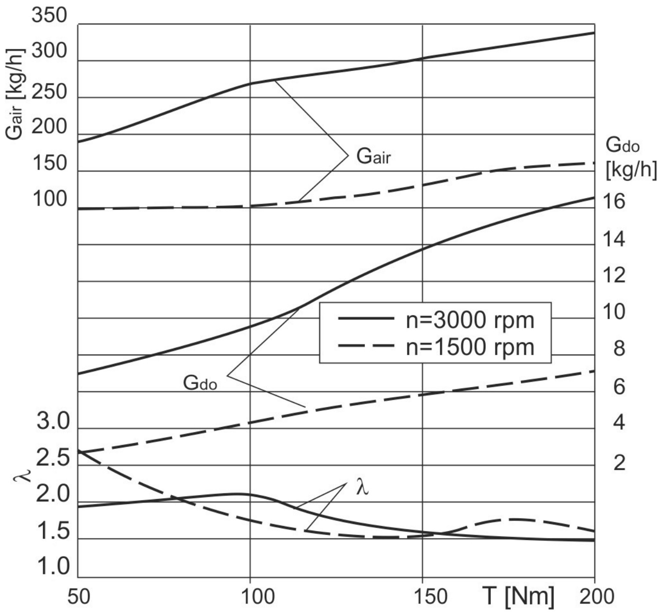

Fig. 1. A course of the change in the mass of the drawn air, the consumption of fuel and the λ ratio as a function of the engine load at n = 1500 and n = 3000 rpm for an ADCR engine

Figure 2 and. 3 present the courses of the changes in the individual ratios describing the load in the combustion chamber of a dual-fuel compression-ignition engine, with a rotational speed of 1500 rpm and loads amounting to 100 and 200 Nm. The presented courses clearly indicate that the global air-fuel equivalence ratio λ over the completely analysed range takes on values no lower than 1.4. It is also clearly visible that the value of this ratio is highly affected by the methane content of fuel gas. Fig. 4, on the other hand, presents the course of changes in the ratios characterising the load in the combustion chamber of a dual-fuel compression-ignition engine, at a rotational speed of 3000 rpm and with a load of 200 Nm. In this case, with a 90% share of fuel in the supply dose, the λ ratio ranges between 1.16 for biogas with a 50% CH_4 content and 1.25 for pure methane.

The impact of the methane content of biogas on the ratios describing the load in the combustion chamber for various engine loads is presented in Fig. 5. The presented courses indicate that the value of the total air-fuel equivalence ratio λ is lowest for maximum engine loads, and highest within the range of medium engine loads, which results from the characteristics of the turbocharger used in the engine.

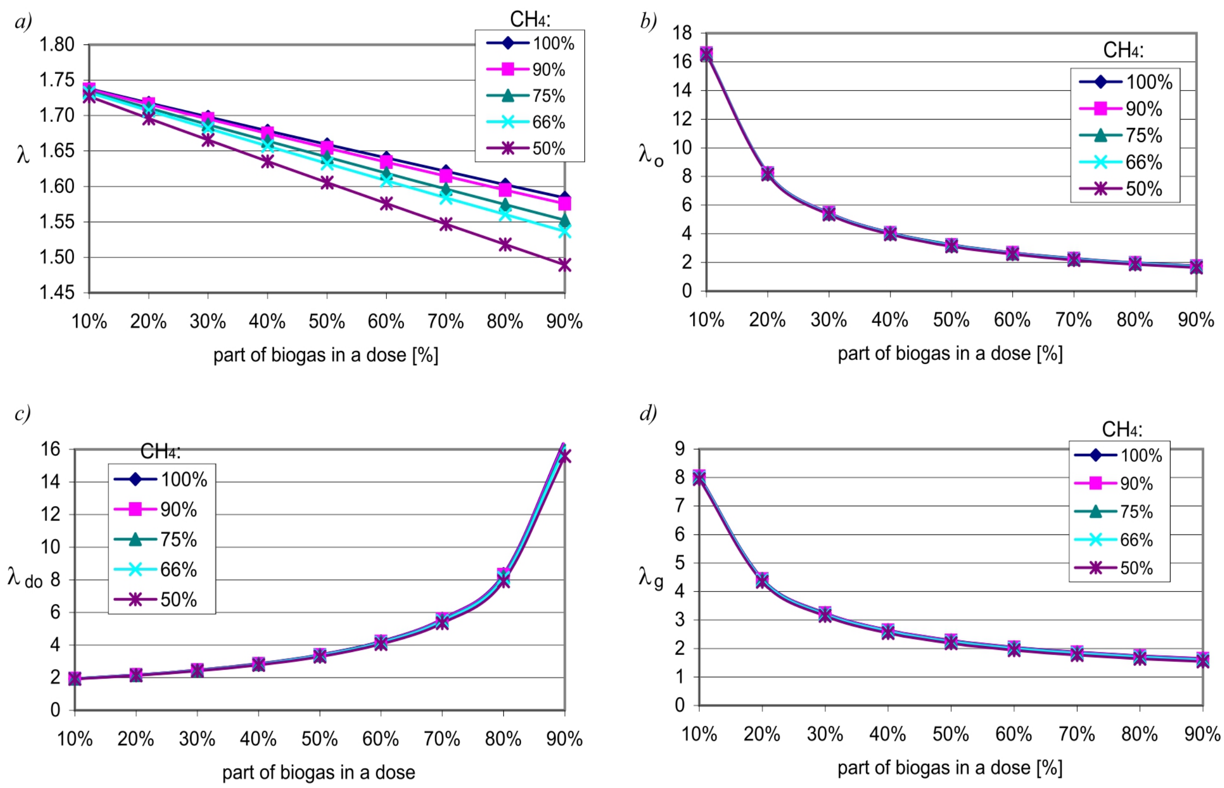

Fig. 2. The impact of the share of biogas in the dose powering the engine for fuels of varying methane content at n = 1500 rpm and T = 100 Nm on the ratios: a) λ, b) λ_o b) λ_{do} b) λ_g

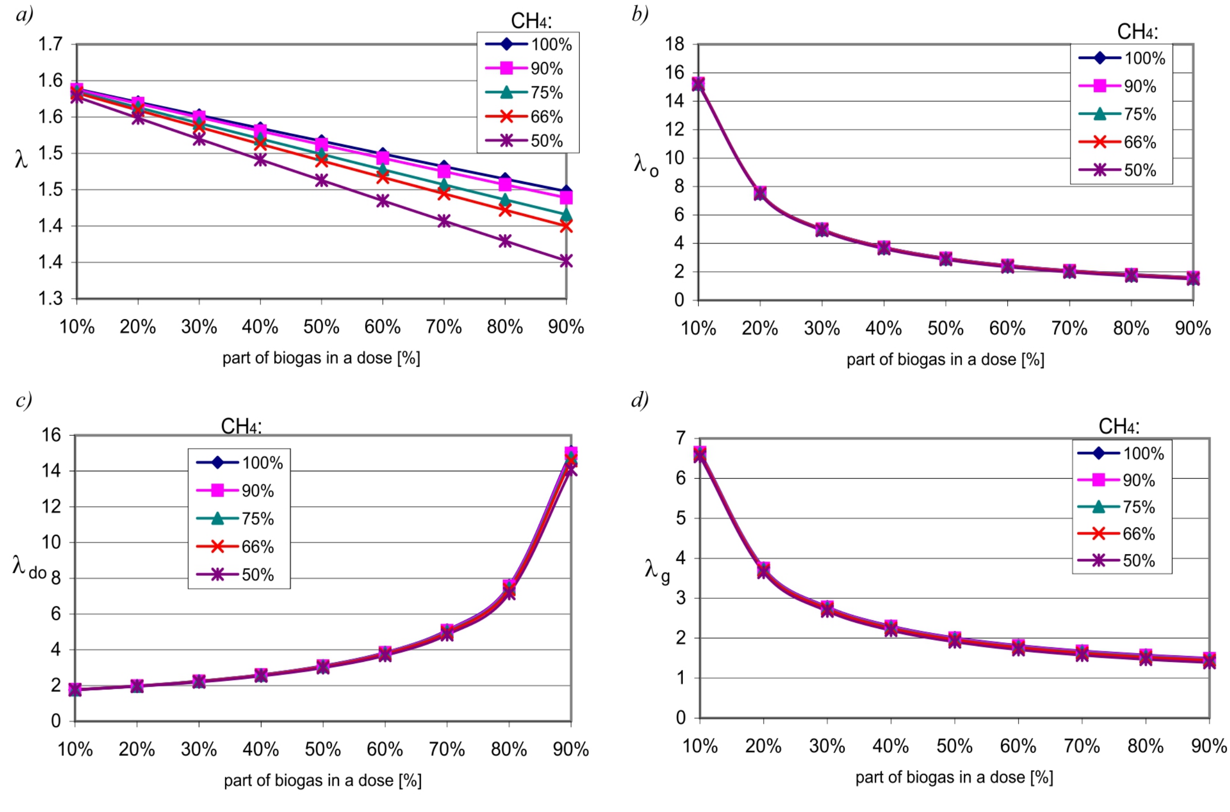

Fig. 3. The impact of the share of biogas in the dose powering the engine for fuels of varying methane content at n = 1500 rpm and T = 200 Nm on the ratios: a) λ, b) λ_o b) λ_{do} b) λ_g

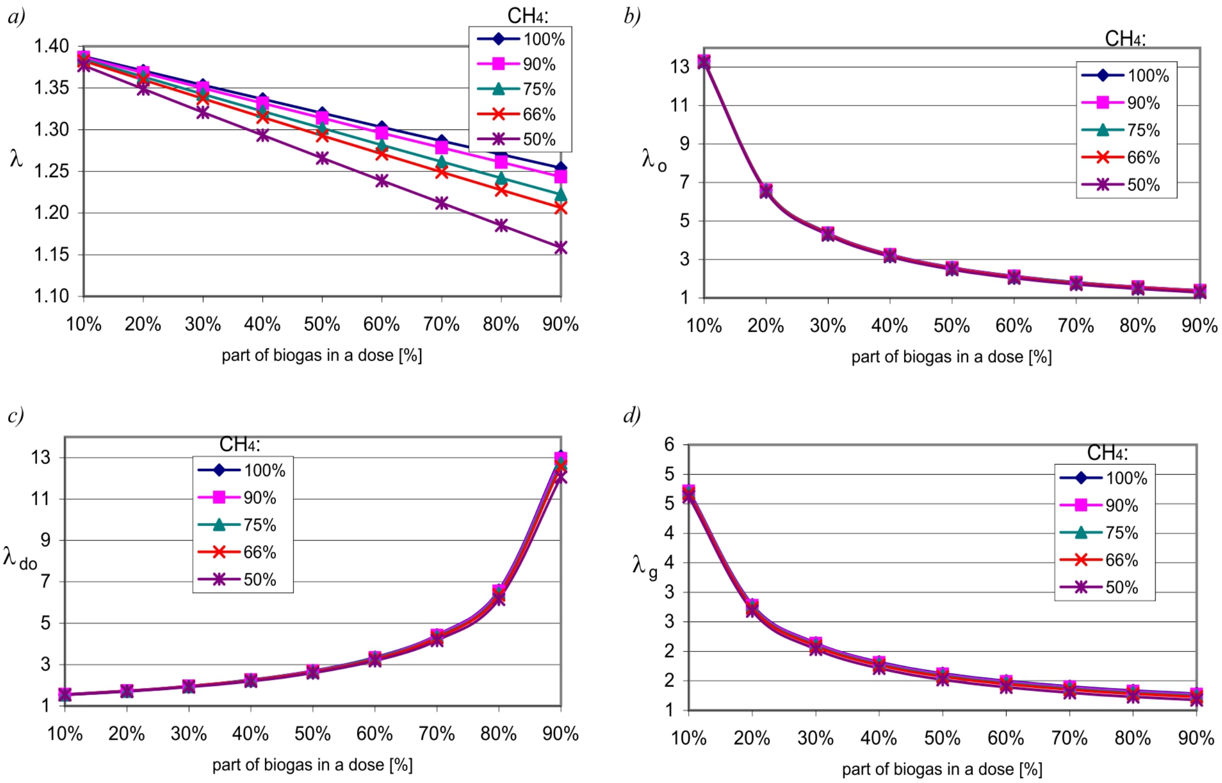

Fig. 4. The impact of the share of biogas in the dose powering the engine for fuels of varying methane content at n = 3000 rpm and T = 200 Nm on the ratios: a) λ, b) λ_o b) λ_{do} b) λ_g

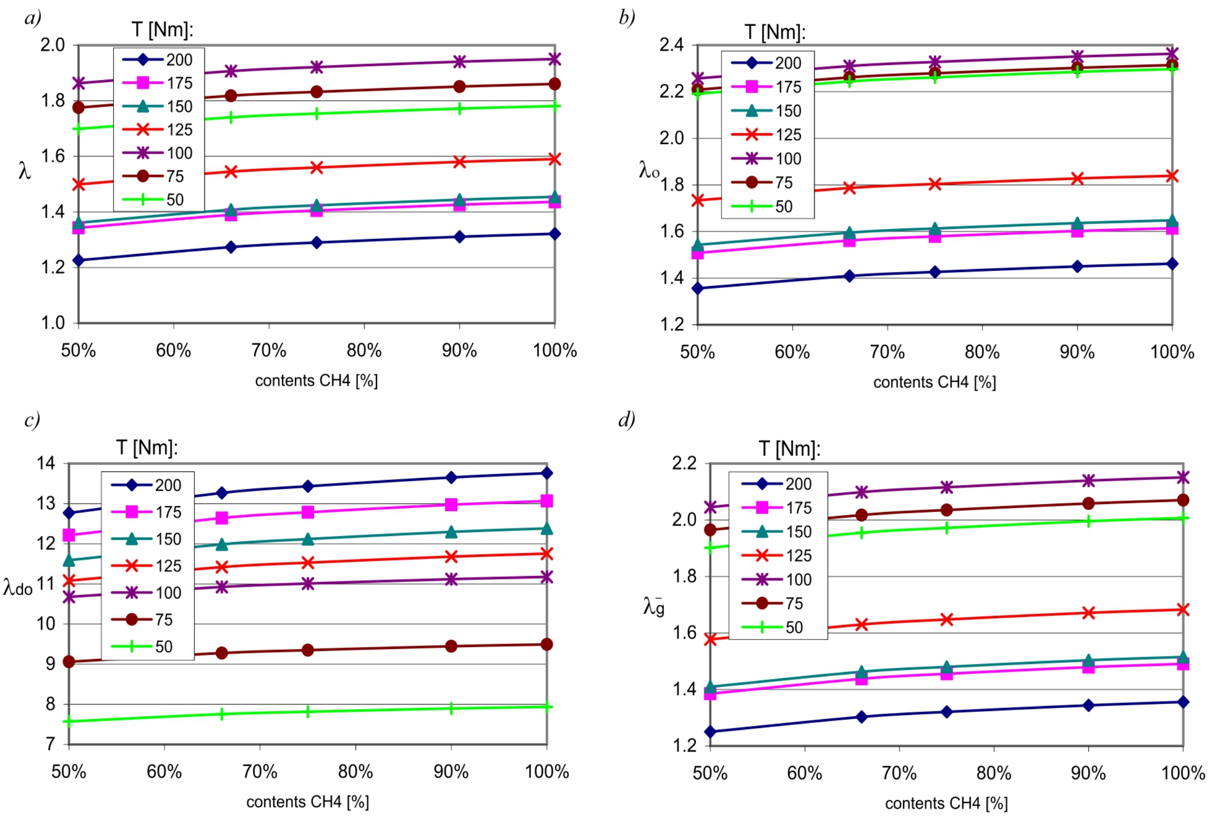

Fig. 5. The impact of the concentration of methane in biogas on the ratios characterising the mixture at n = 3000 rpm with a 10% share of liquid fuel for various engine loads: a) λ, b) λ_o b) λ_{do} b) λ_g

Figure 6 presents the course of the changes in the concentration of oxygen in the gas and air mixture, depending on the air-fuel equivalence ratio for biogas of varying methane content.

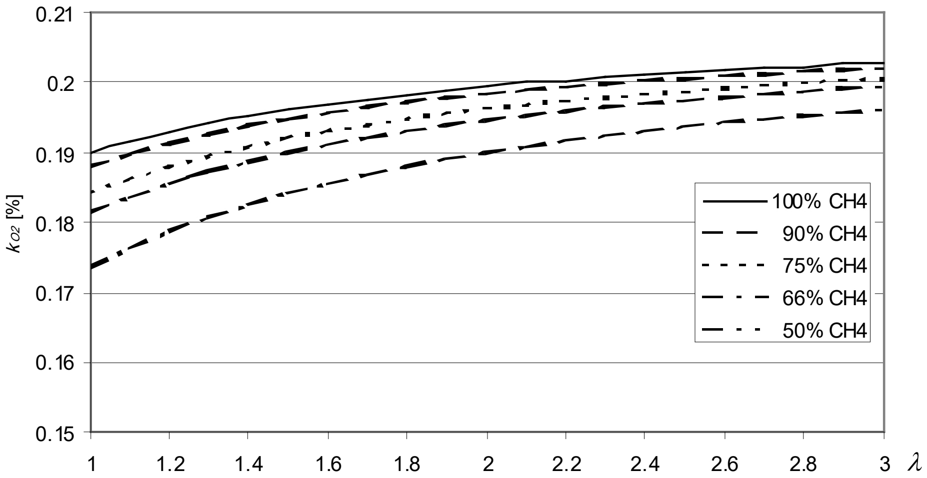

Fig. 6. The changes in the concentration of oxygen in the gas and air mixture for various shares of methane in biogas depending on the λ ratio

4. Summary

The presented analysis of the impact of supplying power by means of fuel gas of varying chemical composition on the parameters characterising the load in a cylinder of a dual-fuel compression-ignition engine allows the formulation of the following conclusions:

- the values of the ratios describing the load in the combustion chamber depend on both the engine load and the chemical composition of fuel;
- the amount of fuel gas in the combustion chamber increases along with the increasing engine load, which leads to higher concentrations of methane, therefore diminishing the λ_o ratio. This favours an improvement in the conditions of burning the gas and air mixture, considering that the composition of the gas and air mixture approaches the lower ignition point of methane;
- the values of the ratios describing the composition of the load in the compartment of a dual-fuel engine are also significantly affected by the composition of fuel gas;
- in the case of forced induction engines, the composition of the mixture may be controlled by the regulation of the level of forced induction in the engine.

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