The influence of Animal Fat Methyl Ester (AME) on diesel engine work parameters

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Abstract: This paper presents the analysis of the base energy parameters and composition of exhaust gases for one-cylinder test diesel engine SB 3.1. fuelled by standard diesel fuel (DF) and Animal Fat Methyl Ester (AME). Animal Fat Methyl Ester (AME) is the result of using waste pork fat. A lot of publications analyze the use of fish fat methyl ester (CFME) and chicken fat methyl esters (CFME) but in Polish conditions we have a lot of pork fat waste. All of measurement was carried out on the some engine speed – 1600 rpm (speed of maximum engine torque) and various engine loads. Some of the analysed parameters were read directly from the laboratory measurement systems (e.g. fuel consumption) and the rest of them had been calculated (e.g. total efficiency of engine). Before the engine tests, the basic physical parameters of the used fuels were determined in the fuel laboratory: dynamic viscosity as a function of fuel temperature, distillation curve, combustion heat and calorific value. The calorific value of the used AMF fuel is 37,4 MJ/kg (42,6 MJ/kg for DF). As a result of the AME fuel viscosity analysis, it was found that in the fuel system of the internal combustion engine this fuel should be heated to the temperature 65^{o}C. Hourly AMF fuel consumption is about 9% higher than for standard diesel fuel (DF). The overall efficiency of the engine, taking into account the calorific value of the fuel and the fuel heating energy, is lower by about 7% for the AMF-powered engine than for DF fuelled engine. In the case of an AMF-powered engine, a higher NO_x concentration and a lower smoke opacity than for a DF-powered engine are obtained. For more accurate cause and effect analysis, the indicator diagrams and the rate of heat release in the cylinder of the combustion engine fuelled by the tested fuels (AMF and DF) were measured, which includes the second article: The influence of Animals Fat Methyl Ester (AME) on the indicator diagrams and heat release parameters in diesel engine cylinder.

1. The introduction

The idea of using vegetable oils as a fuel for diesel engines is almost as old as the combustion engines themselves. Rudolf Diesel patented such a fuel already in 1892, and presented his diesel engine (later called Diesel engine) powered by peanut oil in 1900 at the World Exhibition in Paris [25]. For nearly a hundred consecutive years, plant fuels (vegetable oils and their derivatives) had not been widely implemented, among others due to the much higher price of diesel oil.

The return to the concept of Rudolf Diesel, and thus to the use of plant fuels, occurred only in the 1980s, that is after oil crises, which additionally changed the priorities of constructors of internal combustion engines, from structures ensuring the highest power output, to the construction of engines reducing the consumption of petroleum-derived fuels. In the Polish conditions, good economic conditions are obtained from rape cultivation and this plant can be considered as the main source of

plant fuels for diesel engines. Natural rapeseed oil has among others viscosity and much lower volatility than diesel oil, which significantly hampers its use as a fuel for serial diesel engines.
Therefore, the commonly accepted solution to reduce the excessively high viscosity of natural vegetable oil consists of the chemical processing of rapeseed oil into the form of fatty acid methyl esters. Then, a fuel is obtained which can be regarded as interchangeable with diesel fuel with limited restrictions because its physical properties are very close to the standard diesel fuel. Such fuel, commonly referred to as biodiesel, is labelled in the Western literature as RME (Rapeseed Methyl Ester - RME) or generally FAME (Fatty Acid Methyl Esters).
It should be assumed that for 30 years of research both Polish and foreign research centres, this fuel is quite thoroughly researched, and conclusions regarding the use of RME, especially as mixtures with conventional diesel fuel, are in line. Since the addition of 5% RME to the diesel fuel, the standard has been technically possible and accepted by engine manufacturers, in accordance with the European Union directive, this operation is obligatorily applied by oil refineries.
It turns out, however, that not only vegetable oils, after the transesterification process, can be burned in the cylinder of the internal combustion engine. The transesterification reaction is analogous to vegetable and animal fats. This is important because in the national economy of various countries (also in the Polish conditions) a large amount of animal fat must be utilised by incinerators - fig.1. It is a process requiring energy inputs as well as an obvious loss of fuel oil.

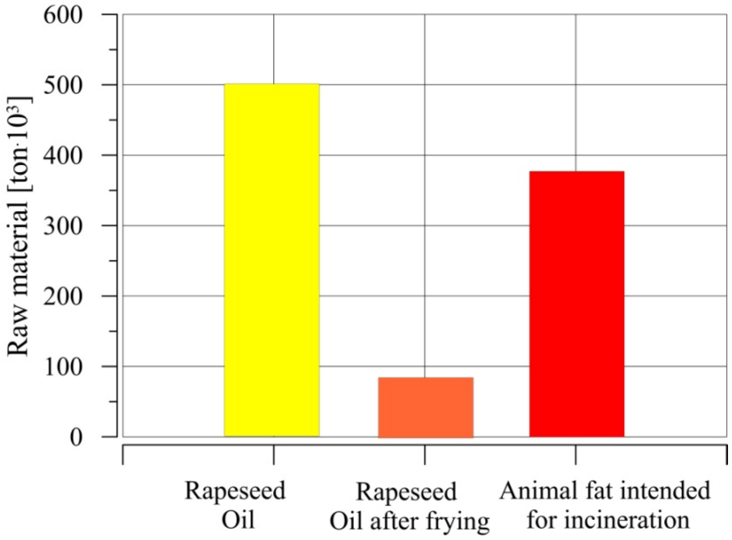

Figure 1. Potential raw materials for the production of bio fuels in Poland (2016 year) [1]

For this reason, this publication presents examples of the effects of using Animal Fat Methyl Esters (AME) as an intrinsic fuel for a diesel engine. This (first) article presents selected AME properties and analyzes the impact of such fuel (in comparison to conventional diesel fuel) on the energy parameters and composition of diesel engine exhaust in laboratory dynamometers. In order to better understand the differences in the combustion process of both fuels (conventional diesel fuel DF and AME), in the second article the indicator diagrams and the rate of heat release in the cylinder of the engine fed with the tested fuels were analyzed..

2. The producing process of methyl esters of animal fats (AME)

The first stage in the process of fuel production is the preparation of animal fat (18.7kg) in liquid form. In order to change its state, it is heated until all the fat is dissolved. The next step is to prepare a catalytic mixture of alcohol and catalyst. The catalytic mixture is prepared by stirring methanol (CH_3OH 1.5 L) with sodium hydroxide (NaOH 55 g).

During the initial methanol reaction with the catalyst an intermediate complex is obtained: CH_3ONa sodium methoxide. The scheme for the formation of sodium methoxide catalyzing transesterification reactions is presented below:

$$NaOH + CH_3OH = CH_3ONa + H_2O$$

The last stage of fuel production is transesterification. Animal fat in liquid form is introduced into the reactor in which it is heated to 60°C. When the fat reaches the appropriate temperature, a catalytic mixture is added and at this point the transesterification process is carried out by mixing in the reactor. Initially, the process is carried out at a temperature of 60°C after a period of 30 minutes, the mixture is heated up to 80°C again, in which the final process also lasts 30 minutes. After the transesterification process is completed, the mixing process is switched off and the mixture stays in it for one hour to carry out sedimentation, i.e. the deposition of heavier fractions (glycerol) precipitated from the solution at the bottom of the reactor. After completing the sedimentation process, the fuel is discharged from the reactor into separate tanks, followed by the by-product, i.e. glycerine.

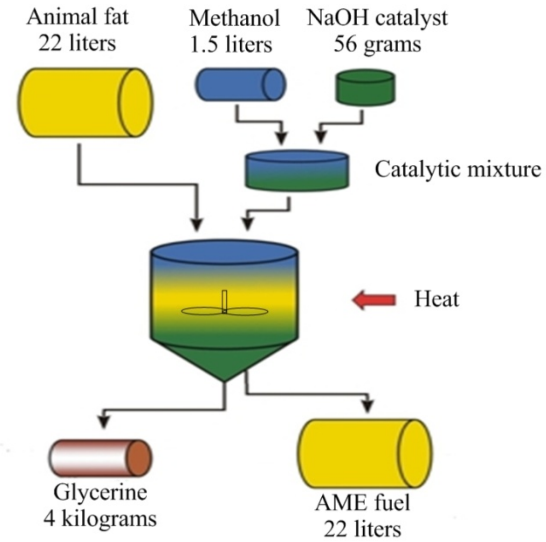

Figure 2. Diagram of the production process of methyl esters of animal fats (AME)

The fuel prepared in this way was used in research to supply the diesel engine in laboratory conditions as a self-contained fuel (100%), without using any other refining additives and without mixing it with the diesel fuel standard. AME fuel was produced at the Laboratory of the Agricultural University in Krakow by Dr Grzegorz Wcisło.

3. Specified properties of methyl esters of animal fats (AME)

3.1. Dynamic viscosity

The measurement of dynamic viscosity was carried out using the ReolabQC rheometer of the German company Anton Paar GmbH. The device measures among others dynamic viscosity, surface tension, shear forces, shear rate, shear stress, etc. To determine the effect of temperature on the above parameters of the test, the stand has been additionally equipped with a thermostatic bathtub from Grant. The results of the tests are shown in Fig.3.

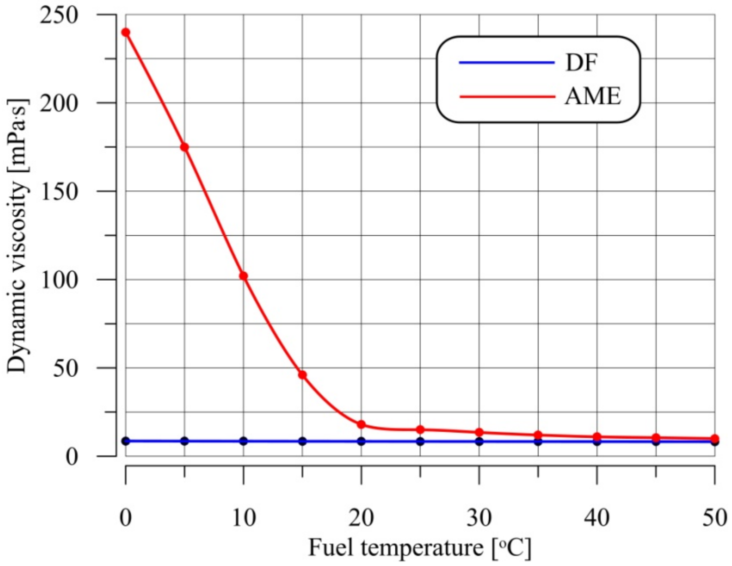

Figure 3. The influence of fuel temperature on the dynamic viscosity

The data contained in Figure 3. clearly indicate that from the point of view of dynamic viscosity, AME fuel cannot be used as stand-alone fuel without heating up to min. 50°C. In engine tests carried out by the author in the laboratory of the Cracow University of Technology, AME fuel was thermostatically heated to a temperature of 65°C.

3.2. Distillation curve

The distillation curve for engine fuels used (diesel fuel standard and methyl esters of animal fats) is shown in Figure 4. The graph shows that the distillation curve for animal fat methyl esters (AME) is above the distillation curve of diesel oil. This means that animal fat methyl esters need higher temperatures to evaporate to a degree similar to the diesel fuel standard. This suggests that with higher loads of the diesel engine, the negative differences in the combustion process of AME and the diesel fuel standard, probably due to the different properties of these fuels, are likely to decrease.

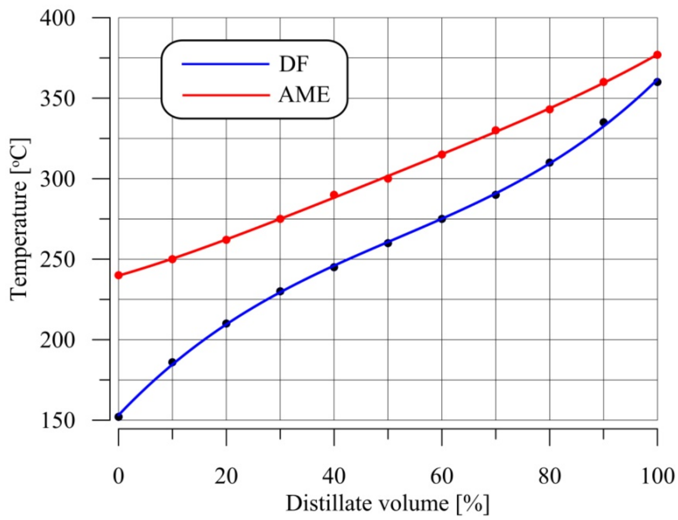

Fig.4. The Distillation curve for standard diesel fuel (DF) i methyl esters of animal fats (AME)

3.3. Combustion heat and calorific value

For the needs of the study, the heat and calorific value of the produced AME fuel and the diesel fuel standard used in engine tests at the Cracow University of Technology were determined. Both the heat of combustion and the calorific value of fuel were determined based on the PN-86 / C-04062 standard currently in force in Poland. According to the aforementioned standard, the determination of the heat of combustion is made in a calorimeter, in which a fuel sample is burned in a calorimetric bomb.
The values of heat and calorific value for fuel DF and AFM are given in table 1.

Tab.1. Combustion heat and calorific value for diesel fuel and methyl esters of animal fats

Fuel	Combustion heat [MJ/kg]	**Calorific value [MJ/kg]**
Standard Diesel Fuel **(DF)**	49,37	**42,6**
Methyl esters of animal fats **(AME)**	42,65	**37,4**

4. Methodology of diesel engine tests

4.1. Technical parameters of the internal combustion engine used in the tests

Table 2. Technical characteristics of the SB3.1 diesel engine

1	Combustion system	direct fuel injection into the toroidal combustion chamber in the bottom of the piston
2	Ignition type	self-ignition
3	Air supply	naturally aspirated
3	Fuel supply	inline injection pump
3	Timing gear	SOHC, 2 valves per cylinder
3	Number of cylinders	1
3	Diameter of the cylinder	127 [mm]
4	Piston stroke	146 [mm]
5	Engine stroke volume	1850 [cm^3]
6	Max engine power *)	23 [kW] at 2200 [rpm]
7	Max engine torque *)	110 Nm at 1600 [rpm]
8	Direction of crankshaft rotation	Left
9	Lubrication	circulation under pressure
10	Cooling	the water pump
11	Geometric start of fuel pumping	27 [deg b. TDC]
12	Static pressure of the injector opening	17 [MPa]
13	Injection pump	piston, type P56-01A
14	Injection pump speed controller	multiphase, type R 14V-20-110/12M
15	Injector	hydraulic, type W1B-01
16	Sprayer	4-hole, φ = 0.35[mm], type D1LMK 14/2

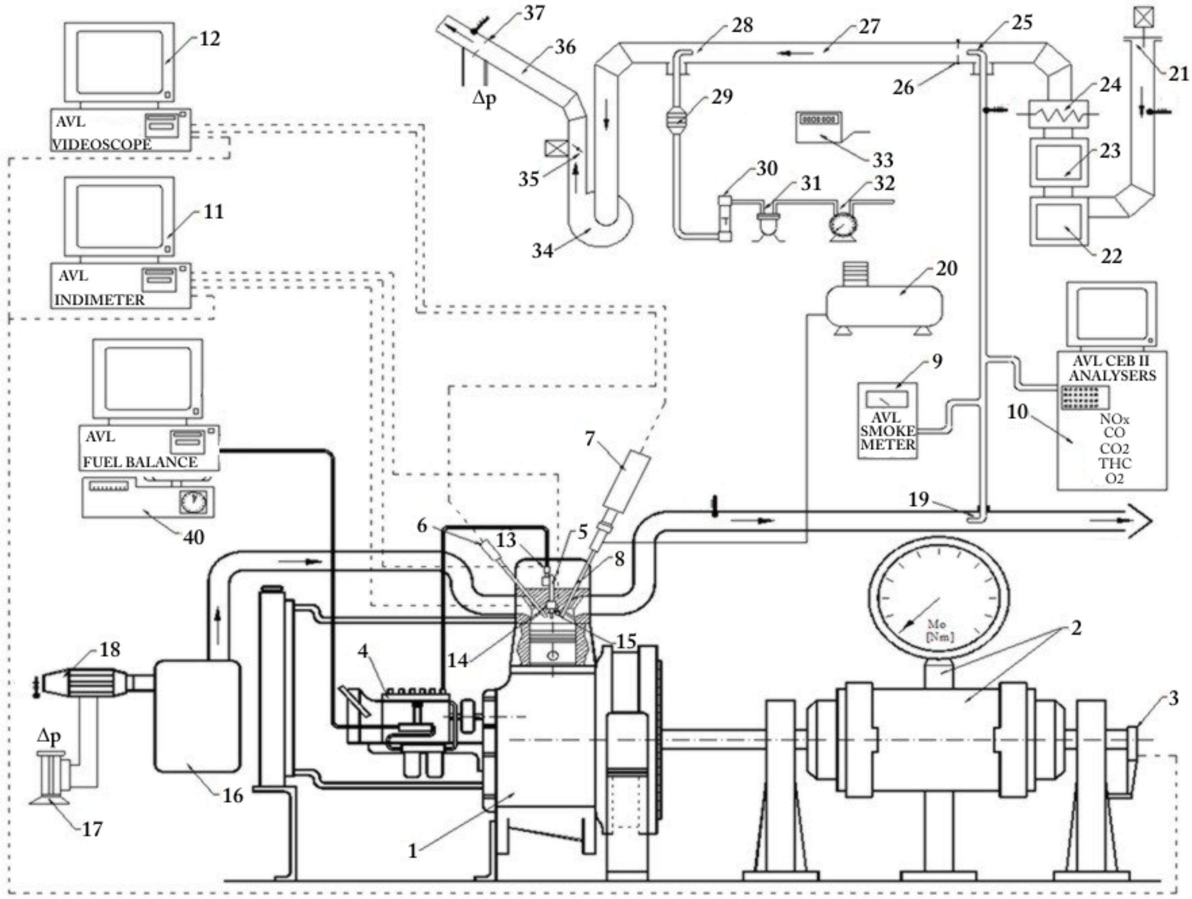

Figure 5. Diagram of the test bench

Applied in the measurement the bench emission laboratory of diesel engines, shown schematically in Fig. 5., it consists of typical measurement modules characteristic for the laboratory of internal combustion engines and will not be described in detail due to the limitation of the volume of this publication. Description of individual elements of the laboratory, shown in Figure 5. are to be found e.g. in the author's publications [5].

5. Analysis of engine operation parameters

The basic parameter that initially characterizes the combustion process of various liquid fuels is the hourly Gp fuel consumption expressed in kilograms of fuel consumed during 1 hour of engine operation. The influence of the load of a motor powered with standard DF and methyl esters of animal fats AME at a constant rotational speed of 1600 rpm (speed of maximum engine torque) on fuel consumption is shown in fig.6. The nature of qualitative changes is basically the same for both fuels. Although it can be seen from the data presented in fig. 6 that the value of fuel consumption (Gp) for AME is greater in the whole load range of the engine than in the case of DF, it is difficult to accurately analyze the value. This is related to the fact that the variability of Gp values in the whole engine load range (Mo = 0-100 Nm) is much greater than the differences in Gp values resulting from the type of fuel used. In addition, it can be seen that regardless of the engine load used, the Gp values for AME are constantly higher than the Gp values for DF. For this reason, it does not matter at what load the engine will carry out a more detailed analysis of the Gp value for both DF and AME fuels used. Therefore, in order to analyse the hourly fuel consumption (Gp) values for DF and AME more accurately, decoupling from the enormous impact of the engine load on the value of this parameter (and all other parameters analysed later in this publication), the values of the considered parameters are presented at constant speed (1600 rpm) as well as constant engine load (60 Nm). This operating point of the engine used was considered representative from the point of view of the analysis of the impact of used fuels on all other parameters characterizing the operation of the engine powered by DF and AME. This operation is legitimate because it was found for each of the analyzed parameters that if it has values greater for DF than for AME, it is in the whole load range of the engine, whereas if the value of another parameter is lower for DF than for AME, then also it does not depend on the engine load. For this reason, the values of the next analysed parameters of the engine fuelled with fuel DF and parameters of the engine fuelled with AME fuel are shown in bar charts at n = 1600 rpm and Mo = 60 Nm, although in the tests they were measured over the entire engine load range (0-100 Nm).

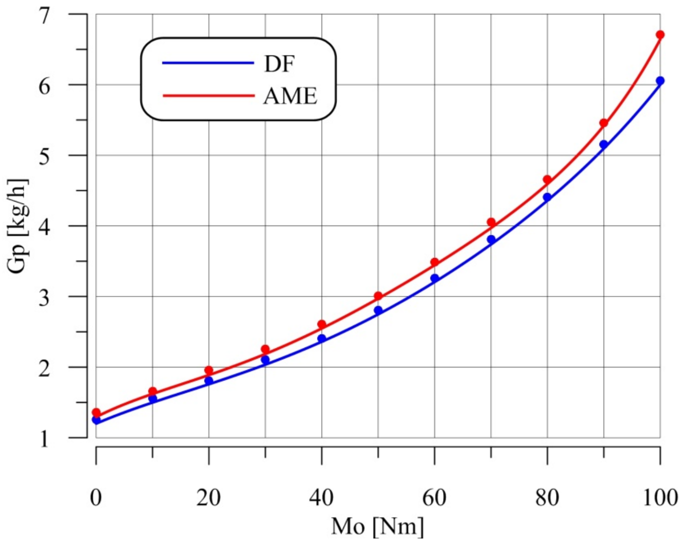

Figure 6. The influence of engine torque (Mo) on fuel consumption (Gp) for standard diesel fuel (DF) and methyl esters of animal fats (AME)

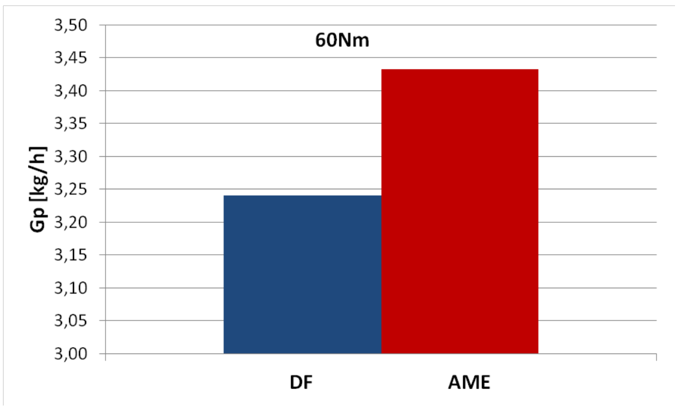

Figure 7. Fuel consumption of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

The data presented in fig. 7 shows that the hourly fuel consumption is higher by approx. 9%. However, since these fuels have different calorific value, hourly fuel consumption is not a comparative parameter (in the energetic sense). Therefore, considering the calorific value of the tested fuels (Table 1), the overall efficiency of the engine powered by DF and AME was calculated, as shown in fig.8.

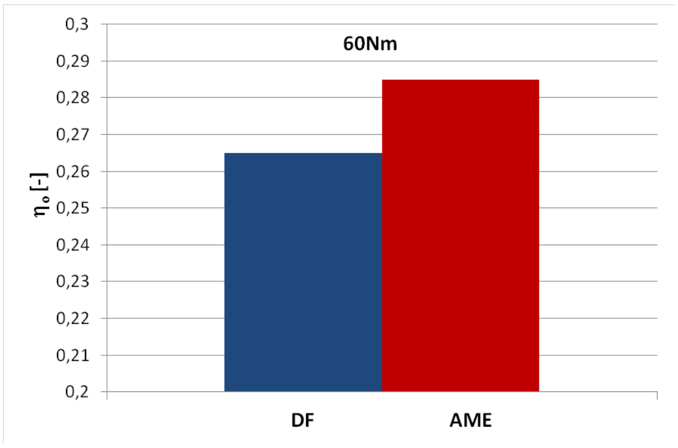

Figure 8. Total efficiency of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

The sense of total efficiency η_o, shown in fig. 8, takes into account the amount of mechanical energy obtained on the engine drive shaft in relation to the energy provided theoretically with the fuel. In this case, the overall efficiency has a slightly higher value for the AME-powered motor than for the conventional DF. However, it should be remembered that methyl esters of animal fats (AME) was electrically heated (from an external energy source) to a temperature of 65°C to reduce its viscosity. Taking into account this loss of electricity, of course, lower values of the overall efficiency of the engine fuelled with AME fuel were obtained, with fixed values for DF, which is shown in fig. 9. For this reason, the actual overall efficiency of η_o is smaller for an AME-powered motor than for a DF-powered motor of approx. 7%.

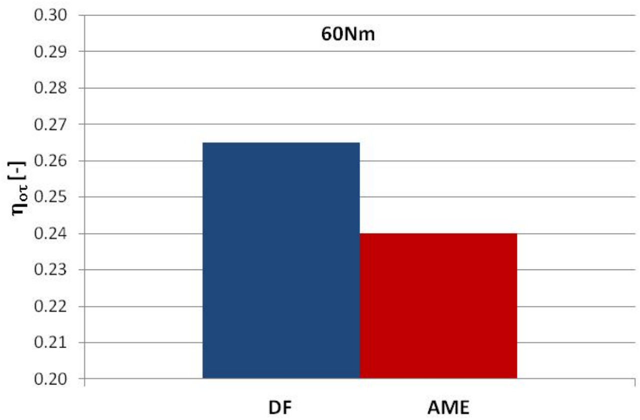

Figure 9. Total efficiency (including energy for fuel heating) of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

Despite the heating of AME fuel to 65°C, its viscosity was still higher than the standard diesel fuel. It influenced, among others for mechanical and hydraulic resistance of movement in the engine fuel supply system during the process of fuel pressing. For this reason, the value of the mechanical efficiency η_m of the engine measured in the laboratory was much lower in the case of powering the engine with the AME fuel than with the DF fuel. This is represented in fig. 10.

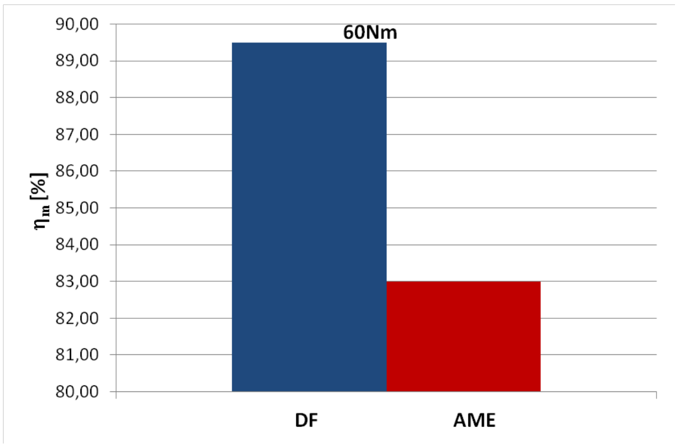

Figure 10. Mechanical efficiency of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

The values of the air excess coefficient λ measured in the laboratory for the analyzed fuels and the same engine work point, taking into account other values of the stoichiometric constant Lt for AME and DF (due to the presence of oxygen in the AME elemental composition), are shown graphically in fig. 11.

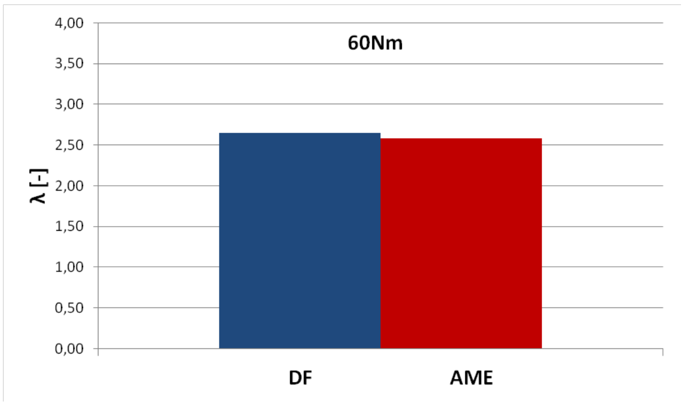

Figure 11. excess air ratio of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

Small differences in λ values for AME and DF should not have a significant impact on the engine exhaust composition. However, it should be remembered that the composition of diesel engine exhaust is a function of many changes and depends on indirectly on the composition and chemical structure of the fuel and indirectly on the physical properties of the fuel (even viscosity, surface tension, heat of evaporation, propensity to self-ignition, etc.), which affect the fuel injection process (injection start, injection characteristics), process of atomization, evaporation, self-ignition and combustion. For this reason, the article presents only the effect of the replacement AME and DF fuel on the composition and smokiness of fumes, while the next article presents the effect of these fuels on the fuel pressure measured before the injector, quick-change pressure of the working medium in the engine cylinder and the rate of heat compliance as a function the angle of rotation of the engine crankshaft. These processes and parameters determined on their basis facilitate the analysis of the impact of DF and AME fuel on the composition of diesel engine exhaust.

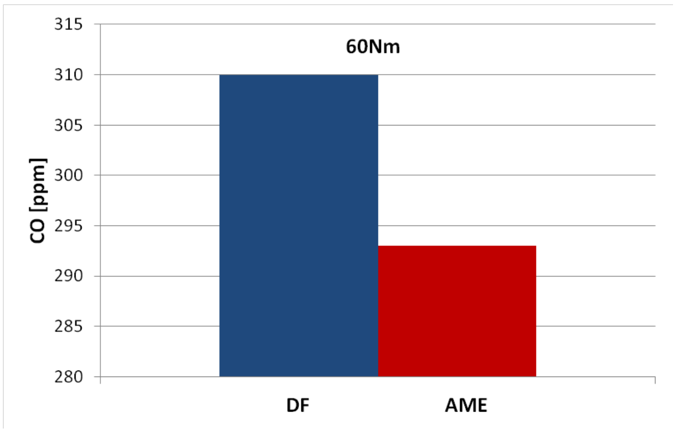

Figure 12. Carbon monoxide concentration in exhaust gases of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

Carbon monoxide is a typical product of incomplete combustion, which in the engines with spark ignition is a global effect, and in diesel engines - the local oxygen deficiency. It would seem that the combustion of AME fuel with a higher viscosity, and in connection with a much worse spray, will result in a higher concentration of carbon monoxide than the standard DF fuel. However, as presented in fig.12, this is not the case. This may be due to the fact that AME contains 10-11% oxygen in its structure. In addition, the higher viscosity of AME (compared to DF) affects both the increase in the maximum injection pressure and the start of the injection of such fuel, which in turn implies a different course of heat dissipation in the engine cylinder. The analysis of these phenomena is contained in the next article.

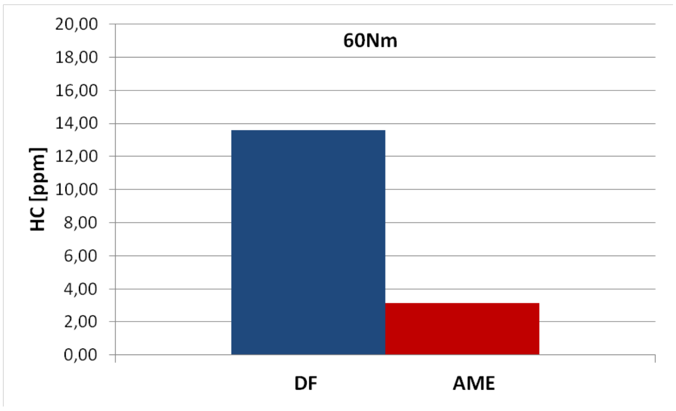

Figure 13. Total hydrocarbons concentration in exhaust gases of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

The amount of total hydrocarbons (HC) in the exhaust gas of the diesel engine powered by AME and DF is shown in fig. 13. As with CO, the HC concentration is lower in the case of AME engine exhaust than DF. However, the concentration and emission of CO and HC are not a challenge for modern diesel engines due to the high efficiency of oxidation catalytic convertors.
It is important to know that a DME-powered engine is characterized by a lower smoke opacity (fig.14) than in the case of standard DF power supply. In the first approximation, it can be assumed that also the emission of particulate matter (PM) in the exhaust of the DME-powered engine will be smaller than for the combustion engine of standard DF.

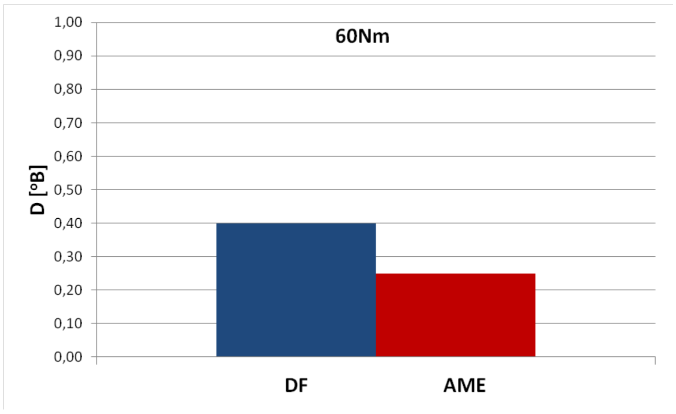

Figure 14. Smog in exhaust gases of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

Due to the reasons for the formation of NO_x molecules in the engine cylinder and the balance of the formation and burning of soot that forms the PM nucleus, most often the change of the engine's construction or regulation parameters or change in the fuel composition that leads to a reduction in PM emissions in the exhaust gases leads to an increase in NO_x concentration the exhaust gas. As the data in fig. 15 shows, this was also the case here.

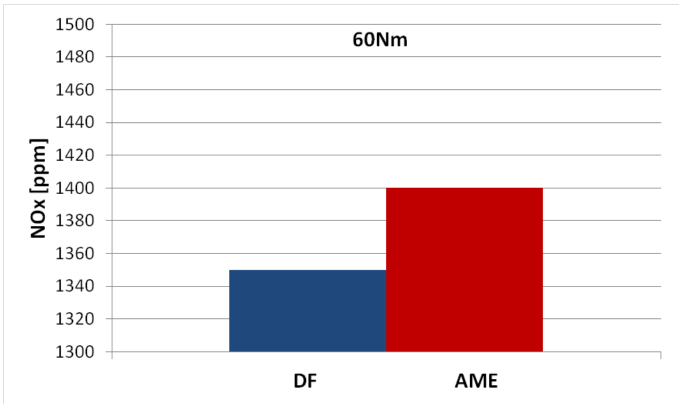

Figure 15. Nitrogen oxides concentration in exhaust gases of test diesel engine fuelled by standard diesel fuel (DF) and methyl esters of animal fats (AME)

Because the NO_x concentration in the exhaust gas of the diesel engine depends on the maximum combustion temperature, the availability of oxygen in the high temperature zones and the reaction time of nitrogen and oxygen, in practice NO_x concentration is very sensitive to the start of fuel injection and heat flow rate. In particular, this applies to the maximum kinetic combustion speed, just like PM emission is associated with the maximum diffusion combustion rate. Due to the limited volume of this publication, the analysis of these phenomena was carried out in the next article in this series.

6. Conclusions:

The test results presented in this publication, comparing the energy parameters and the composition of exhaust gases of diesel engine fuelled by standard diesel fuel (DF) or Animals Fat Methyl Ester (AME) constitute only a small part of our own research. The remaining part will be presented in the second article of this series and will allow for a fuller understanding of the observed phenomena. Irrespective of this, the test results presented here give the right to submit the following conclusions:
1. due to the very high viscosity of AME, its use, as a self-contained fuel for a diesel engine, requires heating this fuel to a temperature of 65 ^{o}C,
2. fuel consumption Gp [kg / h] is higher for AME fuel by approx. 9% than for DF fuel. This is due to both the lower calorific value of AME (compared to DF) and the deterioration of efficiency of the combustion process and mechanical efficiency,
3. the overall efficiency of the engine's ,ot, taking into account the external energy consumed for heating AME, is about 7% lower compared to the engine powered by DF,
4. interchangeable use of AME and DF decreases CO, HC and smoke concentration (up to 37%), at the expense of increasing NOx in exhaust gases (about 4%),
5. A more comprehensive understanding of the results obtained here requires the analysis of indicator diagrams and heat-delivery rates, which will be presented in the second article of this publication.

References

[1] Ferenc Z., Pikon K.:Przeglad rodzajów i ilości odpadów tłuszczowych i olejowych w Polsce. Archives of Weste Management and Enviromental Protection. ISSN 1733-4381, Vol. 2 (2005)
[2] Klecan R.: Paliwa do silników Diesla ze zużytych tłuszczów roślinnych i zwierzęcych. Archiwum gospodarki odpadami i ochrony środowiska, ISSN 1733-4381, Vol. 3 (2006), p-55-68 [2] Skrzyńska E., Matyja M.: Porównanie właściwości fizykochemicznych wybranych tłuszczów naturalnych oraz ich estrów metylowych. Chemik 2011, 923-935
[3] Cisek J.: Report on the Research Project KBN nr 8T12D 035 20 pt. "Study of the impact of the process of fuel atomisation and combustion in a diesel engine using optical and digital methods for the emission of toxic exhaust components" Cracow University of Technology. Krakow 2014
[4] Golimowski W., Golimowska R., Kliber A.: Temperature effect on kinematic viscosity of animal fats, vegetables oils and its transestryfication products.
[5] Cisek J.: The influence of non-cooled exhaust gas recirculation on the indicator diagrams and heat release parameters in diesel engine cylinder. Kongres PTNSS, Poznań 2017.
[6] Ackman R. G.: Remarks on official methods employing boron trifluoride in the preparation of methyl esters of the fatty acids of fish oils
[7] Gürü M., Koca A., Can O., Can Ç., Şahin F.: Biodiesel production from waste chicken fat based sources and evaluation with Mg based additive in a diesel engine.