

The influence of Animal Fat Methyl Ester (AME) on the indicator diagrams and heat release parameters in diesel engine cylinder

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Abstract: This paper presents the analysis of the indicator diagrams and heat release diagrams 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. This publication is the next part of the paper: “The influence of Animal Fats Methyl Ester (AME) on diesel engine work parameters”, in which base energy parameters of diesel engine and composition of exhaust gases were analysed.

Some of the analysed parameters were read directly from the measurement systems (e.g. indicator diagrams) but the rest of them had to be calculated (e.g. heat release parameters). The calculation of rate of heat release ($\delta Q/d\alpha$) was based on the well-known mathematical model (AVL Institute).

1. The introduction

The author's previous paper in this series of publications, entitled: “The influence of Animal Fat Methyl Ester (AME) on diesel engine work parameters”, presents a comparison of energy parameters and exhaust gas composition of a diesel engine fuelled by standard diesel fuel (DF) or Animals Fat Methyl Ester (AME). The test results presented in that article 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°C,
2. fuel consumption G_p [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 η_{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 NO_x in exhaust gases (about 4%).



However, it should be remembered that the composition of diesel engine exhaust gases is a function of many changes and depends, among others, directly 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, predisposition 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 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 release, as a function of 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 gases.

2. Methodology of diesel engine tests

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

Table 1. 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, $\phi = 0.35$ [mm], type D1LMK 14/2

2.2. Laboratory used in the tests

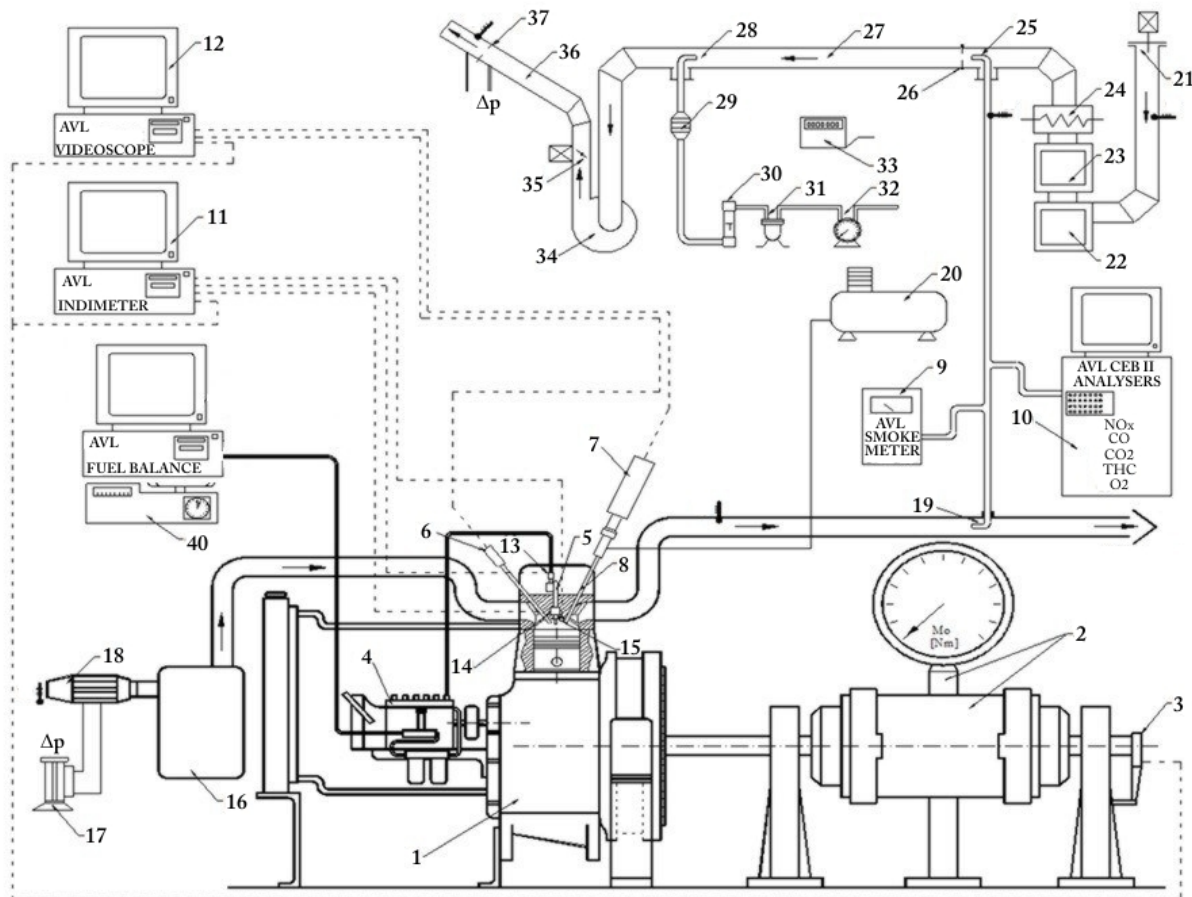


Figure 1. Diagram of the test bench

Applied in the measurement the bench emission laboratory of diesel engines, shown schematically in Fig.1., 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 1., is to be found e.g. in the author's publications [5].

3. Analysis of engine operation parameters

In order to better understand the injection and combustion processes for fuels used in the research, measurement of fast-changing fuel pressure before the injector, pressure of the working medium in the engine cylinder and displacement of injector needle as a function of the crank angle of the test engine crankshaft were carried out. Fig. 2 shows this situation for engine speed of maximum torque (1600 rpm), 50% of full load (60Nm) and an engine fuelled by conventional diesel (DF) or methyl ester of animal fat (AME). This graph is quite difficult to analyse, but it also allows the determination of a number of parameters that definitely facilitate the comparative analysis of the inside-cylinder phenomena of the engine fuelled by DF or AME fuel. These parameters include e.g.: start of fuel pumping, start of fuel injection (defined as the start of the injector needle lift), dynamic injector opening pressure, maximum fuel pressure, start of fuel self-ignition, self-ignition delay, maximum combustion pressure, rate of combustion pressure increase etc. Values of these parameters, determined for a representative engine work point (1600 rpm and 60 Nm) fuelled with DF and AME fuel, allow

for a fuller understanding of the influence of analytical fuels on energy parameters and exhaust composition, presented in the first article of this series.

From Fig.2. it results that the maximum fuel pressure (measured with a piezoelectric sensor before the injector) is significantly higher for the case of feeding the engine with AME fuel than with the DF fuel. This is shown in detail in the bar graph - fig. 3, which shows that the maximum fuel pressure (p_{pmax}) is 710 bar for DF fuel and 880 bar for AME fuel (at the same engine work point). The higher fuel pressure in the engine supply system for AME fuel than for DF fuel is obviously due to the higher viscosity of this fuel [6] (even though it was heated to 65 °C) than the DF fuel. Unfortunately, this has an effect, among others to increase the velocity of AME fuel outflow from the injector during the self-ignition delay period τ_s . The accumulation of more fuel in the combustion chamber at the moment of self-ignition usually leads to a higher combustion dynamics, an increase in the maximum combustion temperature and, for this reason, to an increase in the NO_x concentration in the exhaust gases.

In the first article in this series, concerning the effect of AME fuel on energy parameters and engine exhaust, the author stated higher NO_x concentration for the AME fuel case than for the engine's fuel with the standard DF fuel.

Both the start of the pumping (α_{pt}) and the start of the fuel injection (α_{pw}), determined on the basis of the extended indicator diagram (fig.2), shown in the bar charts - fig.4 and fig.5 - clearly show that the AME fuel it is characterized by a slightly earlier start of injection, which results from the earlier start of this fuel pumping compared to DF fuel. This is due to the higher fuel pressure in the injection system (fig. 3) for AME fuel (than DF).

The earlier start of fuel injection involves injection of fuel into the engine cylinder in which there is less compressed air pressure (the piston is lower than TDC). The low pressure of compressed air is associated with a lower temperature, so the conditions for auto-ignition are worse than at the later start of fuel injection.

This usually leads (for the same type of fuel) to extending the time (the angle of rotation of the engine crankshaft) between the start of injection α_{pw} and the start of the self-ignition α_{ps} . This time is called the self-ignition delay period τ_s .

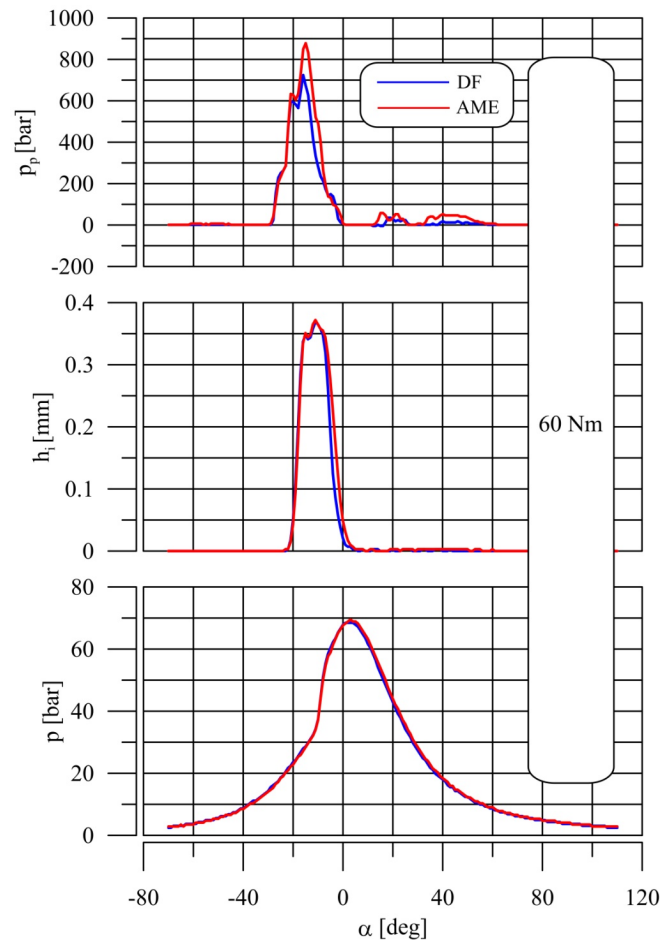


Figure 2. Fuel pressure (p_p), needle lift (h_i), pressure inside the engine cylinder (p) as a function of crank angle for standard diesel fuel (DF) and methyl ester of animal fat (AME)

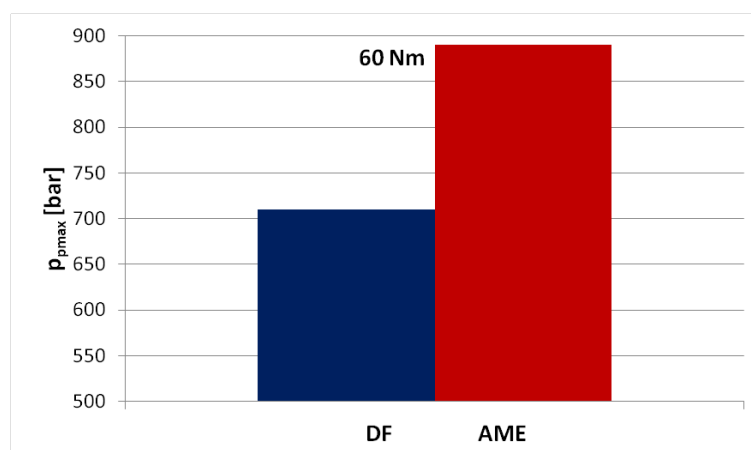


Figure 3. Max fuel pressure (before injector) of test diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

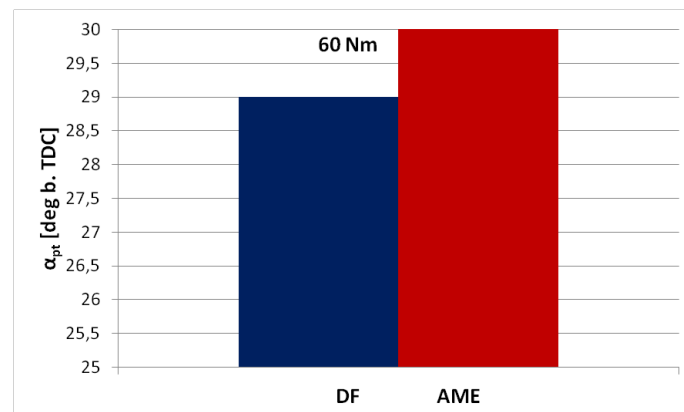


Figure 4. Start of fuel pumping (α_{pt}) for diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fats (AME)

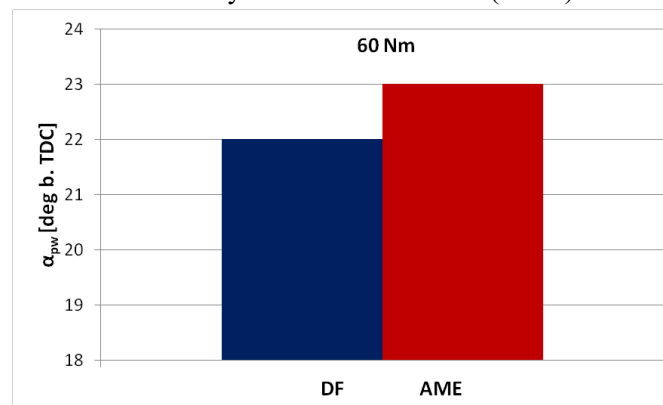


Figure 5. Start of injection (α_{pw}) for diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

The start of auto-ignition of fuel (α_{ps}) depends of course not only from the start of fuel injection (α_{pw}) but also from the natural tendency of a given species of fuel to self-ignition (this is generally defined by the parameter which is the cetane number), the temperature of the fuel-air mixture, the fuel spray spectrum, etc. Under the conditions of the presented measurements, the start of auto-ignition (α_{ps}) is basically the same for the standard fuel DF and AFM - Fig.6.

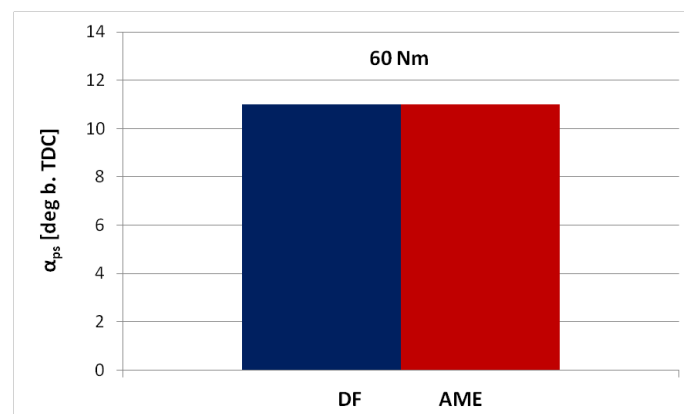


Figure 6. Start of self-combustion (α_{ps}) for diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

At the same start of auto-ignition (α_{ps}) but a slightly earlier start of injection (α_{pw}) of AME fuel, of course, a longer self-ignition delay for this fuel is obtained compared to the standard DF. This is illustrated by the data contained in Figure 7.

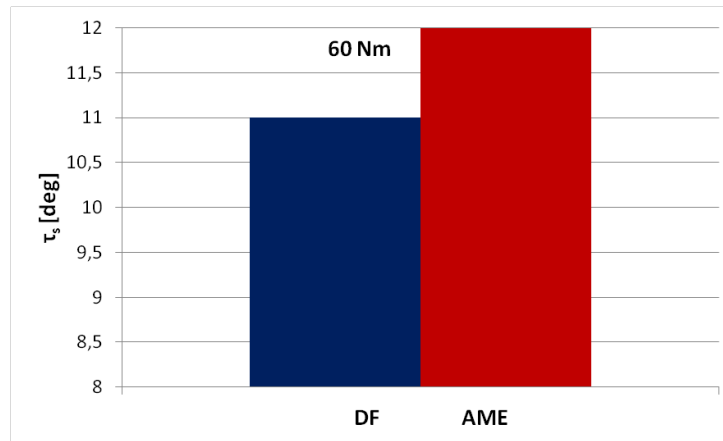


Figure 7. Delay of self-ignition (τ_s) for diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

The elongation of the auto-ignition delay τ_s (Fig. 7) in conjunction with the increase of the maximum fuel injection pressure (Fig. 3), resulting in an increase in fuel flow speed from the injector, results in more fuel stored in the engine combustion chamber at the start of combustion. It leads among others to increase the dynamics of combustion. One of the parameters that describe this phenomenon quite well is the maximum rate of combustion pressure increase $(dp/d\alpha)_{max}$.

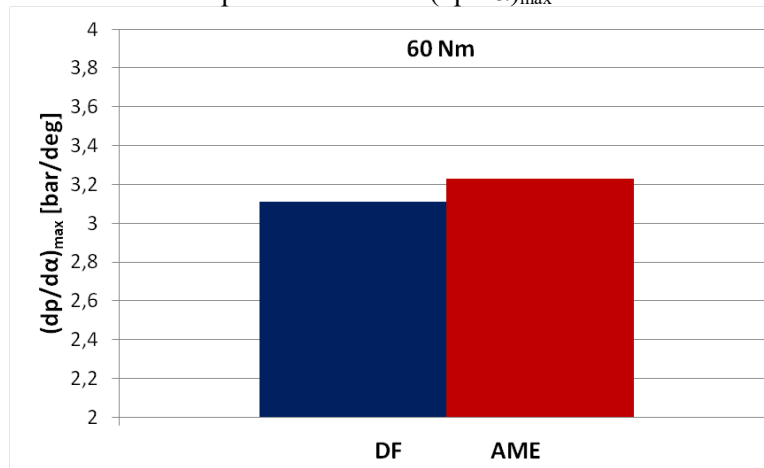


Figure 8. Maximum rate of combustion pressure for diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

The higher maximum rate of combustion pressure for diesel engine fuelled by methyl esters of animal fats (AME) than standard diesel fuel (DF) it also requires a higher combustion pressure for this fuel in the engine cylinder - fig.9

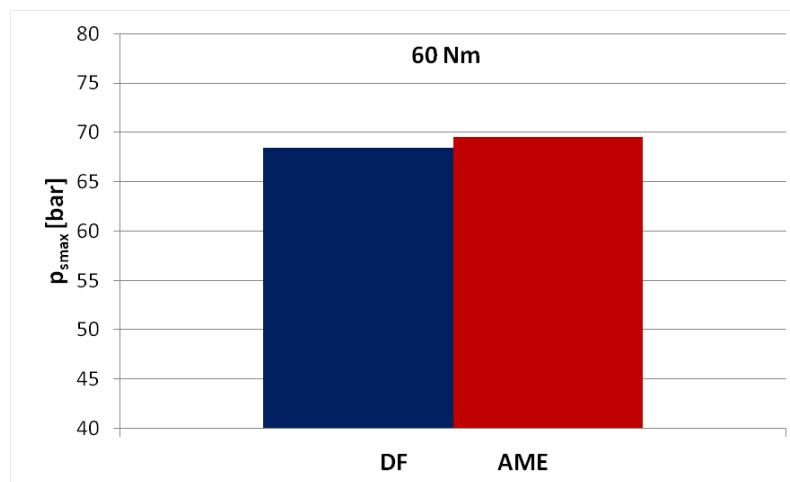


Figure 9. Maximum pressure of combustion for the diesel engine fuelled by standard diesel fuel (DF) and methyl ester of animal fat (AME)

Attention should be paid to the fact that both the maximum combustion pressure and the maximum rate of combustion pressure for the diesel engine fuelled by methyl ester of animal fats (AME) are just slightly higher than for the engine powered by DF (about 2-3%). Therefore, only a slight increase in the maximum AME fuel combustion temperature should be expected compared to DF fuel. Since the increase in the maximum combustion temperature is the main reason for the increase in NO_x concentration in the exhaust gas of the diesel engine, for this reason the increase in NO_x concentration in the exhaust gas of diesel engine fuelled by AME fuel was only 4%, compared to conventional fuel DF (the first publication of the author). The course of the parameters of the indicator diagrams does not explain why, for AME fuel, significant decreases of CO, HC and smoke concentration (up to 37%) were obtained (and thus also a decrease in PM particulate emissions probably).

For this purpose, on the basis of indicator diagrams, the rate of heat release in the cylinder of the diesel engine fuelled with DF fuel or AME fuel were calculated. Used for this purpose commonly known calculation model used, among others, by AVL Institute and presented in [7].

Fig. 10 shows the course of heat release rate in the cylinder fuelled by a standard DF fuel or fuel AME at the speed of maximum torque (1600 rpm) and 60 Nm (50% of max Torque).

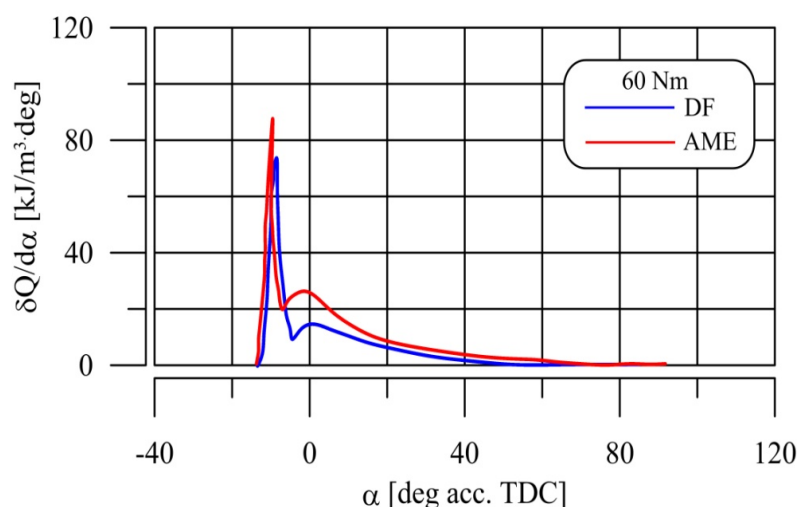


Figure 10. Rate of heat release for the diesel engine fuelled by standard diesel fuel (DF) and methyl ester of animal fat (AME)

Several parameters were determined on the basis of the rate of heat release (slightly similar to those for the indicator diagrams), which facilitate the analysis of the effect of DF and AME fuels on energy parameters and exhaust gases composition, presented in the author's first article. These parameters include: maximum rate of kinetic combustion, maximum rate of diffusion combustion and conventional combustion end. It is known from experience [6] that the course of rate of heat release rates is closely related to both the composition of exhaust gases and the overall efficiency of an internal combustion engine:

- reduction of the maximum kinetic combustion rate results in a reduction of the NO_x concentration in the engine exhaust gases,
- increasing of the maximum diffusion combustion rate leads to a reduction of smoke opacity and particulate matter PM emission,
- elongation of combustion process reduces the value of the total efficiency of the diesel engine.

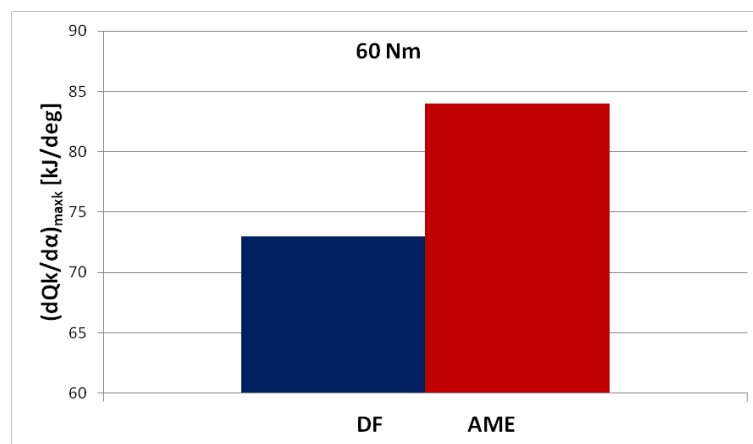


Figure 11. Max. rate of kinetic heat release $(dQ_k/d\alpha)_{\max}$ for the diesel engine fuelled by standard diesel fuel (DF) and methyl ester of animal fat (AME)

From the data contained in Figure 11, it appears that the maximum value of kinetic heat release rate $(dQ_k/d\alpha)_{\max}$ for the diesel engine fuelled by AME is higher than for standard diesel fuel (DF). It is significant that the difference in values $(dQ_k/d\alpha)_{\max}$ for DF and AME is only 15%. This explains why the NO_x concentration in the exhaust of the AME-fuelled engine is only slightly higher than for the diesel-fuelled engine.

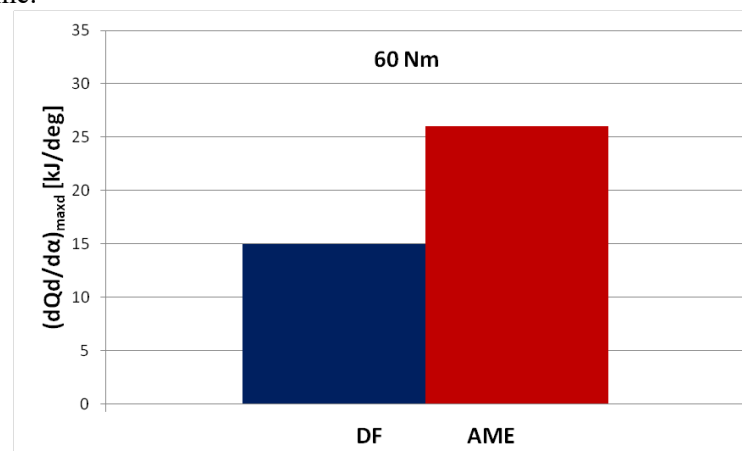


Figure 12. Max. rate of diffusion heat release $(dQ_d/d\alpha)_{\max}$ for the diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

The data contained in Figure 12 shows that the maximum value of the diffusion heat release rate $(dQ_d/d\alpha)_{\max}$ for the diesel engine is higher than for standard diesel fuel (DF) - about 73 %. The higher value of the diffusion heat release rate causes that the previously formed PM particles can be burned out, so in the general balance they are much less emitted with the exhaust gases. Therefore, in the first article concerning the effect of AME fuel on the composition of exhaust gases it was found that in the case of fuelled engine by AME fuel, there is a reduction of smoke opacity by as much as 37%. The growth phenomenon of $(dQ_d/d\alpha)_{\max}$ for the engine fuelled by AME is likely to significantly reduce PM emissions in the exhaust gases in comparison to the exhaust of engine fuelled by the standard diesel fuel (DF).

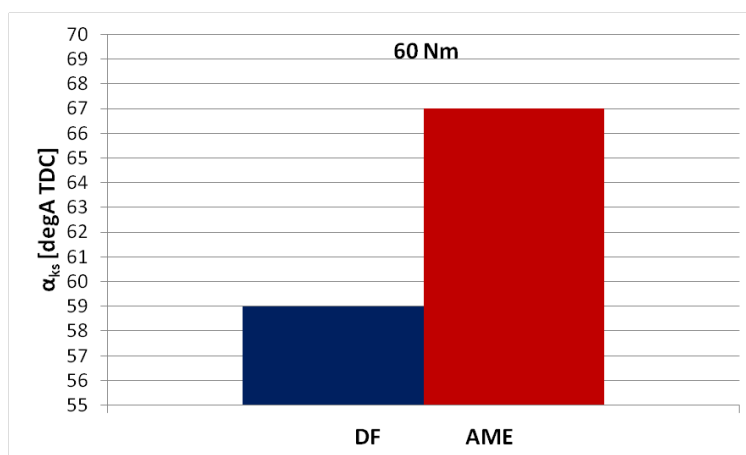


Figure 13. Contractual end of combustion process (α_{ks}) for the diesel engine fuelled by the standard diesel fuel (DF) and methyl ester of animal fat (AME)

The figure 13 shows that the AME fuel combustion process in the diesel engine cylinder ends much later than the DF fuel. This is due to various reasons, but is the main reason for the lower total efficiency of the engine, specified in the author's first article, at 26.5% for DF fuel (1600 rpm and 50% M_{\max}) and only 24% for DF fuel.

4. Conclusions

The test results presented in this article give the right to submit the following conclusions regarding the replacement of the standard diesel fuel for AME fuel (methyl ester of animal fat). The usage of AME fuel (compared to DF) causes:

1. increase of maximum fuel pressure (before the injector) by up to 25%. This results in an increase in the amount of fuel accumulated in the combustion chamber at the moment of self-ignition, especially since AME fuel has a longer self-ignition delay τ_s ,
2. increase of maximum combustion pressure and the rate of maximum combustion pressure increase (by approx. 3%),
3. increase of rate of maximum kinetic heat release $(dQ_k/d\alpha)_{\max}$ only 15%, which explains a slight increase in NO_x concentration in engine exhaust gases,
4. increase of maximum rate of diffusion heat release $(dQ_d/d\alpha)_{\max}$ about 73%, which explains the big reduction of smoke opacity of the engine powered by this fuel,
5. the later end of the combustion process α_{ks} , which explains the reduction in the total efficiency of the diesel engine fuelled by AME compared to the engine fuelled by conventional diesel fuel.

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