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The Study of the Biofuel-Operated Diesel Engine with Heating

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Abstract- To reduce the concentration of hydrocarbon compounds, carbon monoxide, and nitrogen oxides in exhaust gases and to increase the completeness of combustion when using biofuel, it is proposed to use heating of biofuel. On the basis of experimental studies, the optimal heating range of biofuel – from 115 to 120 °C. They are obtained the values of hourly and specific fuel consumption, carbon monoxide emissions, hydrocarbon compounds and nitrogen oxides depending on the engine load when working on diesel fuel of petroleum origin, biofuel without heating and with heating. It is established that when using biofuel without heating, depending on the engine load, the fuel consumption is in the range of 17.67 to 27.77% when compared to the performance of diesel fuel of petroleum origin. The use of biofuel with temperature 120 °C immediately before injection into the engine cylinders reduces the consumption of biofuel from 2.78 to 9.34% depending on the engine load. When using biofuel, emissions of hydrocarbons and oxides of nitrogen do not differ significantly from the emissions while engine operation with diesel fuel of petroleum origin, however, the emissions of carbon monoxide are reduced almost twice. The use of heating of biofuel immediately before injection into the engine cylinders is reduced fuel consumption that indicates a more complete combustion of high-molecular compounds of biofuel.

Keywords Preheating, diesel engine, exhaust gases, kinematic viscosity, fuel consumption.

1. Introduction

Lack of energy resources, unstable fuel prices, and global environmental problems encourage the use of renewable energy sources [1]. One of the directions of providing regenerative fuel for diesel internal combustion engines is the use of biofuel (methyl esters of fatty acids). Biofuel is derived from vegetable oils and animal fats in their properties similar to diesel fuel of petroleum origin [2, 3]. Physical and chemical properties allow using biofuel with minimal changes in the design and settings of the diesel engine [4].

Biofuel due to a significant amount of saturated fatty acids has higher rates of kinematic viscosity [5], a higher temperature of turbidity and solidification when compared to diesel fuel of petroleum origin [6, 7]. At a fuel temperature of less than 10 °C, it is possible the formation of insoluble precipitates in the fuel, which leads to clogging of fuel filters and tubes [8, 9]. Problems associated with the filtration and supply of biofuel can be solved by using crystallization filtration with a loss of about 9% of the fuel mass [10] or preheating biofuel in the fuel tank up to 35 °C [11]. To reduce the kinematic viscosity, it is proposed mixing of biofuel with diesel fuel of petroleum origin or solvent-based high-molecular alcohols, modification of fatty acid biofuel and the use of chemical additives [12, 13]. The possibility of reducing the kinematic viscosity by adding various solvents to the biofuel [14] was investigated, but there was found no effective solvent that would reduce the kinematic viscosity of the biofuel to the level of diesel fuel of petroleum origin with a minimum concentration.

It is observed a slight increase in fuel consumption and a decrease in the power of the diesel engine when using biofuel obtained from various types of oils as motor fuel [15]. It is recommended to use mixtures with a biofuel content from 5 to 10%, since the use of a mixture with a higher concentration of biofuel requires in-depth studies and improvement of diesel internal combustion engines.

The main disadvantages of biofuel based on vegetable oil [16, 17, 18] include high values of turbidity and loss of mobility of fuel, high kinematic viscosity, higher fuel consumption, increased emissions of nitrogen oxides. It is recommended to use a mixture of biofuel with fuel of petroleum origin, the content of biofuel in which does not exceed 20%. It is also noted the need to modify diesel engines under the properties of biofuel based on fatty acids of plant and animal origin.

According to the work [19], in order to increase the completeness of fuel combustion in the internal combustion engines, it is proved the use of fuel mixture with the content of ethanol in the range from 20 to 30% in diesel fuel of an petroleum origin or biofuel. To optimize the characteristics of the fuel mixture, a computer simulation of the fuel mixture heating process in a spiral heat exchanger by exhaust gases is proposed and performed. The possibility of fuel heating up to 130º C was considered in the simulation, but the authors did not take into account the influence of this temperature on the long-term operation of the fuel system elements.

Studying the influence of the heating temperature of the fuel mixture of oil fuel with the content of 40% of biofuel based on pinnata [20], the heating of biofuel by the exhaust gases of the engine before its supply to the fuel pump was used. As a result of heating the fuel mixture from 60 to 110º C, the specific fuel consumption and emissions of hydrocarbon compounds (C_nH_m), carbon monoxide (CO) and smoke were reduced; besides, there was observed some increase in emissions of nitrogen oxides (NO_X). Reduction of fuel consumption and concentration of C_nH_m and CO in exhaust gases, the authors associate with a decrease in the kinematic viscosity of the fuel. However, the authors did not substantiate the optimal heating temperature of the fuel mixture, which can be at a temperature greater than 110º C and did not consider the operation of the fuel equipment at these temperature modes of fuel mixture heating.

The use of fuel mixtures does not solve the problems associated with the use of diesel fuel of petroleum origin. As the analysis shows, the use of mixtures of biofuel and diesel fuel of petroleum origin does not effectively reduce the kinematic viscosity. Increasing the combustion efficiency of such mixtures is possible through the use of heating fuel.

On the basis of the analysis of studies on the heating of biofuel and diesel fuel [21], it is concluded that the heating of biofuel and its mixture with fuel of petroleum origin leads to a decrease in fuel consumption, a decrease in the diameter of fuel drops during injection, an increase in the thermal efficiency of the engine, and a reduce in emissions of C_nH_m, CO, and NO_X. The increase in the completeness of fuel combustion is due to the reduction of surface tension, viscosity and diameter of the fuel droplets injected into the engine cylinders. Heating of biofuel made from cotton oil up to 52 °C leads to almost twofold decrease of the kinematic viscosity of the biofuel, while there was a decrease in engine fuel consumption and the concentration of C_nH_m, CO, and NO_X in the exhaust gases [22].

The authors [23] considered the possibility of using heating of biofuel to increase the completeness of combustion in a diesel engine. The mathematical modeling of the heating biofuel to a temperature of 150º C and experimental studies of the heating of the biofuel up to 110º C were carried out. The studies allow arguing that pre-heating of biofuel leads to a reduction in time and increased completeness of fuel combustion. A significant disadvantage of the experimental studies is the use of "methyl butanoate ($C_5H_{10}O_2$)" as a biofuel. This compound, in comparison with other esters of fatty acids derived from vegetable oils, has a rather short carbon chain, therefore, the results of the studies cannot fully correspond to the use of biofuel containing more complex esters of fatty acids.

In the research [24], to compensate the kinematic viscosity of biofuel based on animal fats which is 1.7 times higher, it was investigated the possibility of heating the biofuel up to a temperature of 100º C. The use of heating made it possible to reduce the specific fuel consumption by 9.82%, and reduce by almost a factor of two the CO emissions, with a slight decrease in NO_X emissions when compared to the values of these emissions for diesel fuel of petroleum origin.

Studying the operation of the diesel engine on biofuel derived from cotton oil [25], it was used fuel heating in the range from 30 to 120 °C with increments of 30 °C. It was found that when heated to 90 °C, it takes place a decrease in hourly fuel consumption and reduces in the concentration of C_nH_m, CO, and NO_X in exhaust gases. The use of a higher heating temperature of biofuel led to an increase in fuel losses through the gaps of the plunger pairs of the high-pressure fuel pump and made it impossible to provide the necessary fuel supply to the engine cylinders.

On the basis of the results of [25], a certain number of researchers limited their experimental studies to the heating temperature of biofuel at the level of 80 to 90 °C.

It was studied the influence of biofuel heating up to 90 °C on the performance of a diesel engine with a capacity of 5 kW [26]. It was found that with the increase in the heating temperature of biofuel up to 80 °C, fuel consumption and emissions of C_nH_m and CO are reduced. When the biofuel is heated up to 90 °C, there is a slight increase in C_nH_m and CO emissions and smoke. In our opinion, this may be due to the beginning of active combustion of heavy fuel fractions.

Investigating the possibility of using non-food vegetable oils as a possible raw material for the production of biofuel [27], biofuel was preheated by a tubular heat exchanger using exhaust gases. The investigated heating temperature of biofuel was limited based on the parameters of the fuel pump at the level of 80º C. While increasing the heating temperature of biofuel, a decrease in fuel consumption and the concentration of C_nH_m, CO, and NO_X in the exhaust gases was obtained. It was noted the prospect of the use of biofuel pre-heating for the modernization of the engine.

To reduce the kinematic viscosity and increase the completeness of combustion of biofuel derived from the wastes after processing cashew nuts, it was used biofuel preheating up to 80 °C [28]. This made it possible to increase braking power by 20%, reduce CO emissions by 66% and C_nH_m emissions by 52% when compared to the performance of the engine without heating biofuel.

The analysis suggests that the use of biofuel preheating before injection into the engine cylinders provides an increase in the completeness of its combustion. The studies performed to date do not give the opportunity to set the optimal temperature range of heating of biofuel. On the basis of operating temperature of the high-pressure fuel pump, heating the biofuel to a temperature above 100º C requires the search for other design solutions. On the basis of the analyzed studies it is impossible to establish the final effect of biofuel heating on the environmental performance of the diesel internal combustion engine.

2. Materials and Methods

The aim of the research is to reduce the consumption of biofuel by using heating before injection into the diesel engine cylinders.

To achieve the goal, the following tasks were solved:

– to implement the method of biofuel heating, which would allow performing the biofuel heating without changing the thermal mode of the fuel high-pressure pump operation;
– to determine the optimal temperature range of biofuel heating before injection into the engine cylinders;
– to investigate the environmental performance of the diesel engine when using biofuel in comparison with the run on diesel fuel of petroleum origin.

The study was carried out using four-stroke, reciprocating, four-cylinder diesel engine with in-line vertical cylinders with direct injection volume of 0.00494 m^3 specification D-65N, of the tractor UMZ-6AKL. The fuel injection was carried out directly into the combustion chamber, which is located in the piston with the help of a nozzle F-22, which has 4 spray holes with a diameter of 0.32 mm. Braking of the engine was carried out through the power take-off shaft, with the help of the stand KI-5543-GOSNITI equipped with an electric balancing machine, a power device for determining the braking force, a liquid rheostat for changing the braking force of the balancing machine, and the tachometer of the rotor shaft of the balancing machine (fig. 1).

Fig. 1. Equipment for determining the operational characteristics of the diesel engine KI-5543-GOSNITI

Biofuel based on methyl esters of fatty acids obtained from rapeseed oil (density 879 kg/m^3 at the temperature 20 ºC and kinematic viscosity 4.78 mm^2/s at the temperature 40 ºC) and diesel fuel of petroleum origin (density 824 kg/m^3 and kinematic viscosity 4.45 mm^2/s at the temperature 20 ºC) were used as fuels in the research. The range of values of fuel properties is given in table. 1.

Table 1. The range of values of fuel properties

Temperature, ºC	Biofuel:			Diesel fuel of petroleum origin:		
	kinematic viscosity, mm^2/s	density, kg/m^3	spraying angle of fuel, degrees	kinematic viscosity, mm^2/s	density, kg/m^3	spraying angle of fuel, degrees
20	7.76	879	21.69	4.45	824	31.05
30	5.99	871	21.8	3.38	820	31.41
40	4.78	865	22.7	2.75	812	31.23
50	3.91	857	23.56	2.34	806	31.54
60	3.3	851	24.2	2.0	799	31.22
70	2.8	844	24.75	1.71	791	31.4
80	2.42	837	26.52	1.50	785	30.33
95	1.99	824	29.01	1.35	774	31.07

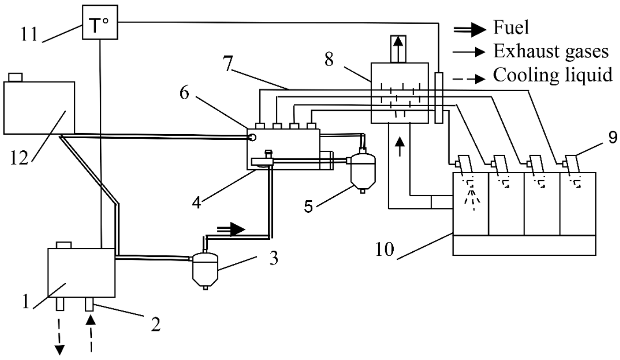
According to table 1 the kinematic viscosity of biofuels has reduced by 4 times, of diesel fuel of petroleum origin by 3 times, biofuel density by 5.6 % and density of diesel fuel of petroleum origin by 6.2 % when is heated in the temperature range from 20 °C to 95 °C. The spraying angle of the injected biofuel by the nozzle increases by 33.7 % when an increase the temperature from 10 to 95 °C. The temperature of the diesel fuel of petroleum origin does not affect the value of the spraying angle.

To determine the optimal heating temperature of the biofuel, the temperature range of biofuel heating studies was chosen in the range from 90 to 140 °C, when the engine was loaded in the range from 19 to 37 kW, which corresponds to the operating power range of the selected engine for the most common types of field work. As a criterion for assessing the effect of temperature on the performance of the engine, the value of specific and hourly fuel consumption was chosen. The experiment was performed for two studied factors using the two-factor matrix *D*-optimal Box-Behnken plan (table 2).

Table 2. Values intervals and variation levels of factors when searching for the optimum temperature for heating biofuel

Factor name	Marking	Factor levels			Variation intervals
		–1	0	+1	
Biofuel temperature before the injection, ºC	T_F	90	115	140	25
Load of the engine, kW	N_{ENG}	19	28	37	9

For biofuel heating and preservation of the fuel temperature mode of high-pressure pump system, it was implemented biofuel heating (fig. 2) [29].



1 – the biofuel tank; 2 – heat exchanger; 3 – coarse filter; 4 – booster pump; 5 – fine filter; 6 – fuel injection pump; 7 – high pressure fuel lines; 8 – heating chamber; 9 – the engine nozzles; 10 – engine; 11 – temperature control unit; 12 – diesel fuel tank.

Fig. 2. The scheme of biofuel heating system

After starting the engine, the preheating of biofuel in the fuel tank 1 is carried out by the heat of the engine coolant. After heating the biofuel to a temperature from 30 to 35 ºC, the diesel fuel tank 12 was turned off and the engine was converted on biofuel feed from tank 1. This enabled using the filtering of biofuel via coarse filter 3 and fine filter 5. Biofuel heating was carried in the range from 90 to 140 °C out in the area between the high-pressure fuel pump 6 and the injectors 9 in the high-pressure fuel lines 7 with the help of the heat of the engine exhaust gases 10 in the heating chamber 8. The temperature of biofuel was controlled directly before the nozzles by means of a temperature sensor 11, the temperature of fuel heating was controlled by changing the cross section of the flue gas bypass channel of the heating chamber 8.

Experimental studies of operational and environmental indicators of a diesel engine were also carried out. Comparative brake tests of the diesel engine D-65N were performed using diesel fuel of petroleum origin, biofuel without heating and with using heating before injection into the engine cylinders (table 3).

Table 3. Biofuel temperature before the injection and load of the engine during experimental studies of operational and environmental indicators of a diesel engine

Fuel type	Fuel temperature, ºC	Load of the engine, kW
Diesel fuel of petroleum origin	35	from 0 to 46.31
Biofuel without heating	35	from 0 to 46.13
Biofuel with heating	120	from 0 to 45.99

During research, the ambient temperature was 20 ºC, the temperature of the biofuel with the use of heating was 120 ºC and the temperature of the biofuel without heating and diesel fuel of petroleum origin was 35 ºC.

Emissions of CO, C_nH_m, and NO_X in the exhaust gases were recorded by the exhaust gases analyzer 325 FA02 (fig. 3). During the research, the temperature, humidity, atmospheric air pressure and air flow rate by the diesel engine, as well as the content of CO emissions in percentages, C_nH_m and NOx in ppm were recorded. The indications of exhaust gases analyzer were translated into the specific emissions of CO, C_nH_m and NO_X with using the standard methodology given in [30].

Characteristics of the equipment used in conducting experimental studies are shown in table 4.

Measurements were performed in three-fold repetition at each change of load, and for calculations and construction of the regulatory characteristics, it was used the average value of the corresponding indicators with 5% error range.

Fig. 3. The exhaust gases analyzer 325 FA02 in the work

When using biofuel, it was carried out a change in the angle of advance of fuel injection. When switching from diesel fuel of petroleum origin to biofuel, the change in the injection advance angle is associated with differences in carburation and the delay time of ignition of the fuel mixture. When installing the fuel heating system, the length of the high-pressure fuel lines increased from 0.45 to 1.5 m, which also required adjusting the fuel injection advance angle.

Table 4. Measurement parameters, devices and equipment used in conducting experimental studies

Parameters name	Devices and equipment name	Measurement range	Measurement error,%
Biofuel temperature before the injection, ºC	Thermocouple TERA TRC–205–50M-B-3-1000-ME	from -40 to180 ºC	±0.9
Load of the engine, kW	Stand KI-5543-GOSNITI	from 0 to 55	±0.9
Value of fuel consumption, g	Scales WBD-2M	from 0 to 5	±1
CO emissions, %	Exhaust gases analyzer 325 FA02	from 0 to 2	±5
CnHm emissions, ppm		from 0 to 2000	±5
NO_X, emissions, ppm		from 0 to 5000	±5

3. Results and Discussions

As a result of the study of the influence of the biofuel heating temperature when changing the engine load, it was obtained the response surface of the specific flow rate of biofuel (fig. 4). The specific consumption of biofuel varies by parabolic function, which has the optimum – the minimum value of the response function for the studied temperature and power range is at the heating temperature of 117.4 °C and the engine load of 33.2 kW.

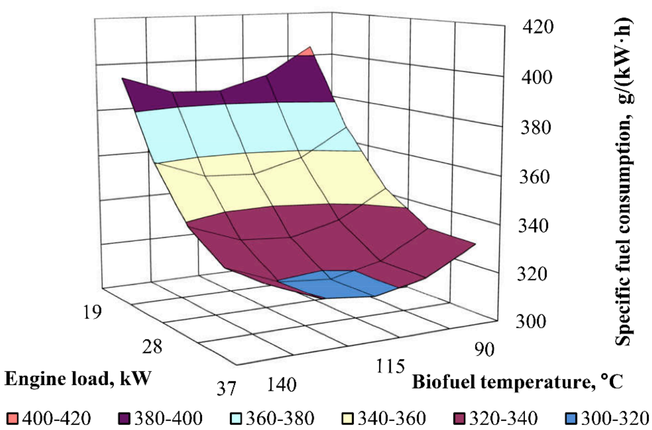


Fig. 4. The dependence of the specific consumption of diesel biofuel on the fuel temperature before the injection and load of the engine

On the basis of the experiment results, a regression equation of the dependence of the specific fuel consumption on the fuel temperature before injection and the value of the engine load was obtained:

$$g_F = 973.8 - 5.217T_F - 20.268N_{ENG} + 0.021T_F^2 + \\ + 0.281N_{ENG}^2 + 0.0067T_F N_{ENG}, \quad (1)$$

where g_F – specific fuel consumption, g/(kW·h); T_F – the biofuel temperature before the injection into the engine cylinders, °C; N_{ENG} – engine power, kW.

The regression equation of the dependence of the specific diesel biofuel consumption (1) was obtained for the experimental conditions within the limits the engine load from 19 to 37 kW and within the limits of diesel biofuel temperature from 90 to 140 ºC.

Checking of the adequacy of the regression equation to experimental data according to Fisher criterion demonstrated that the resulting regression equation can be considered adequate with 95% probability, since the calculated value of the Fisher criterion F_P=4.3263 is less than the table one F_T =4.4957. Using the regression equation (1) limited by the engine power D-65N from 19 to 37 kW, biofuel temperature from 90 to 140 ºC and properties of biofuel at which the equation is obtained. Using power values beyond the specified range will result in the deviation of the estimated values of the specific fuel consumption from the actual.

Analysis of the obtained results shows that with increasing heating temperature the specific consumption of biofuel gradually decreases and reaches its minimum value, respectively: 318 g/(kW h) with the engine load of 37 kW; 329 g/(kW h) with the engine load of 28 kW and 386 g/(kW h) with the engine load of 19 kW in the temperature range from 115 to 120 °C. It should be noted that the nature of the change in the dependence of the specific fuel consumption on the heating temperature of biofuel, with appropriate engine loads, is similar, and the value of the heating temperature of biofuel, at which the minimum consumption of biofuel is achieved, is in the range from 115 to 120 °C.

When using diesel fuel heating in the temperature range from 90 to 120 °C, it is reduced the viscosity of the fuel which is injected, as a result, the angle of spraying of biofuel increases, the range of the torch decreases, the diameter of the spray drops decreases [23], which leads to an increase in the completeness of fuel combustion and a decrease in the specific consumption of biofuel. When heating biofuel over 125 °C, it takes place a further decrease in the viscosity of the fuel and, as a consequence, an excessive decrease in the diameter of the droplets when spraying biofuel, which leads to a decrease in the range of the torch, reduce the turbulence of the fuel-air mixture in the cylinder, the formation of zones with excessive concentrations of biofuel and insufficient air. In these zones, the rate of biofuel combustion and the completeness of its combustion decreases, as a result – there is an increase in the specific consumption of biofuel.

The obtained results allow setting the optimal temperature range of biofuel heating before injection into the engine cylinders. The temperature 120 °C was selected for biofuel heating in further comparative brake tests.

On the basis of the obtained data, the comparison of hourly and specific fuel consumption of different types of fuel (table 5) is made and the graphical dependences of the change in hourly and specific fuel consumption depending on the engine load were constructed (fig. 5).

Table 5. Experimental data of the diesel engine performance using different types of fuel

Diesel fuel of petroleum origin (fuel temperature 35 °C)						
Power, kW	0	10.03	21.49	29.55	40.05	46.31
Fuel consumption per hour, kg/h	3.98	4.94	6.85	8.37	10.64	11.5
Specific fuel consumption g/(kW·h)	–	493	319	283	266	248
Biofuel without heating (biofuel temperature 35 °C)						
Power, kW	0	10.05	19.78	29.36	38.86	46.13
Fuel consumption per hour, kg/h	4.87	6.01	7.87	9.78	12.65	13.68
Specific fuel consumption g/(kW·h)	–	598	398	333	326	297
Overruns when compared to diesel fuel of petroleum origin,%	22.36	21.30	24.77	17.67	22.56	19.76
Overruns when compared to diesel biofuel with heating,%	6.33	6.22	9.34	2.78	6.54	6.07
Biofuel with heating (biofuel temperature 120 °C)						
Power, kW	0	10.01	19.71	29.24	38.68	45.99
Fuel consumption per hour, kg/h	4.58	5.63	7.18	9.47	11.82	12.9
Specific fuel consumption g/(kW·h)	–	563	364	324	306	280
Overruns when compared to diesel fuel of petroleum origin,%	15.08	14.20	14.10	14.49	15.04	12.90
Specific fuel consumption according (1), g/(kW·h)	–	483.58	375.69	321.28	317.71	349.35
Deviation specific fuel consumption according (1) and data table 5, %	–	-16.45	3.11	-0.85	3.69	19.85

The possibility of applying a regression equation (1) for calculating the engine indicators with the use of biofuel heating in the load range from 19 to 37 kW is confirmed by the experimental values of the specific fuel consumption (table 5).

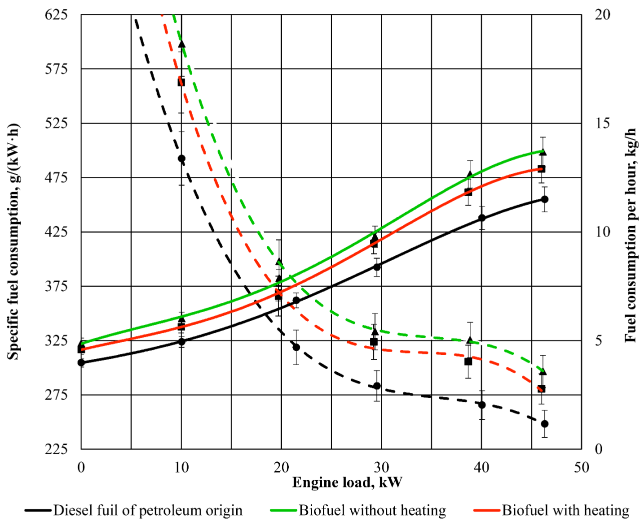


Fig. 5. Specific fuel consumption (dashed lines) and hourly fuel consumption (solid lines) depending on the engine load

The analysis shows that the engine operated on biofuel develops almost the same power as the one operated on diesel fuel of petroleum origin, but has worse indicators of hourly and specific fuel consumption. In comparison with diesel fuel of petroleum origin, when using biofuel, there is an increase in specific fuel consumption by the amount from 17.67 to 24.77% depending on the engine load. The increase in the consumption of biofuel without heating, when compared to the diesel fuel of petroleum origin, is associated with less heat of combustion and lower combustion completeness. The use of biofuel heating before injection into the cylinder allows achieving the reduction in overruns by an amount from 2.78 to almost 9.34%, depending on the load of the engine. When using heating of biofuel in comparison with diesel fuel of petroleum origin, the overspending of biofuel is in the range from 12.9 to 15 %.

The difference between the data according to the regression equation (1) and the experimental data of the specific fuel consumption in the load range from 19 to 37 kW does not exceed 4 %. The difference between the data according to the regression equation (1) and the experimental data of the specific fuel consumption for the load 10.01 and 45.99 kW due to the fact that the data of power values are beyond the range for which the regression equation was obtained (1).

It was provided the analysis of emissions of C_nH_m, CO, and NO_X in diesel engine using different types of fuel (table 6) depending on the engine load (fig. 6).

In the main operating load range of the engine it is observed a decrease in C_nH_m emissions when working on biofuel when compared to operating on diesel fuel of petroleum origin.

The reduction of CO emissions while using biofuel in comparison with diesel fuel of petroleum origin is explained by the presence of free oxygen in the structure of the biofuel molecule, which contributes to its more complete oxidation. The increase in C_nH_m emissions at low and maximum load is associated with unfavorable mixing and combustion conditions, which is particularly characteristic of biofuel, which has a high density and kinematic viscosity. Biofuel requires higher temperature in the cylinder and time for evaporation. When using biofuel heating, there is an increase in CO emissions in almost the entire range except the maximum power. When biofuels are heated, CO emissions are slightly reduced at maximum engine load.

C_nH_m emissions are almost the same and do not differ significantly depending on the type of fuel used. The use of heating of biofuel leads to an increase in CO emissions. Quite uncharacteristic is the mode of operation at maximum load characterized by a sharp increase in C_nH_m emissions for biofuel compared with emissions from diesel fuel of petroleum origin.

Table 6. Experimental data on diesel engine emissions using different types of fuel

Diesel fuel of petroleum origin (fuel temperature 35 °C)					
Engine load, kW	10.03	21.49	29.55	40.05	46.31
CO emissions, g/(kW·h)	21.16	10.46	10.06	13.05	13.33
C_nH_m emissions, g/(kW·h)	0.54	0.21	0.17	0.16	0.18
NO_X, emissions, g/(kW·h)	6.76	6.18	5.84	6.63	8.68
Biofuel without heating (biofuel temperature 35 °C)					
Engine load, kW	10.05	19.78	29.36	38.86	46.13
CO emissions, g/(kW·h)	21.72	7.09	4.91	3.8	23.2
Changes in CO emissions when compared to diesel fuel of petroleum origin, %	2.64	-32.22	-51.19	-70.88	74.04
C_nH_m emissions, g/(kW·h)	0.59	0.19	0.12	0.12	0.42
Changes in C_nH_m emissions when compared to diesel fuel of petroleum origin, %	9.26	-9.52	-29.41	-25.00	133.33
NO_X emissions, g/(kW·h)	7.15	6.29	6.21	6.3	7.77
Changes in NO_X emissions when compared to diesel fuel of petroleum origin, %	5.77	1.78	6.34	-4.98	-10.48
Biofuel with heating (biofuel temperature 120 °C)					
Engine load, kW	10.01	19.71	29.24	38.68	45.99
CO emissions, g/(kW·h)	22.98	7.73	5.93	4.72	15.42
Changes in CO emissions when compared to diesel fuel of petroleum origin, %	8.60	-26.10	-41.05	-63.83	15.68
Changes in CO emissions when compared to biofuel without heating, %	5.80	9.03	20.77	24.21	-33.53
C_nH_m emissions, g/(kW·h)	0.56	0.3	0.14	0.15	0.22
Changes in C_nH_m emissions when compared to diesel fuel of petroleum origin, %	3.70	42.86	-17.65	-6.25	22.22
Changes in C_nH_m emissions when compared to biofuel without heating, %	-5.09	57.90	16.67	25.00	-47.62
NO_X emissions, g/(kW·h)	6.39	6.52	6.36	6.52	9.37
Changes in NO_X emissions when compared to diesel fuel of petroleum origin, %	-5.48	5.50	8.91	-1.66	7.95
Changes in NO_X emissions when compared to biofuel without heating, %	-10.63	3.66	2.42	3.49	20.59

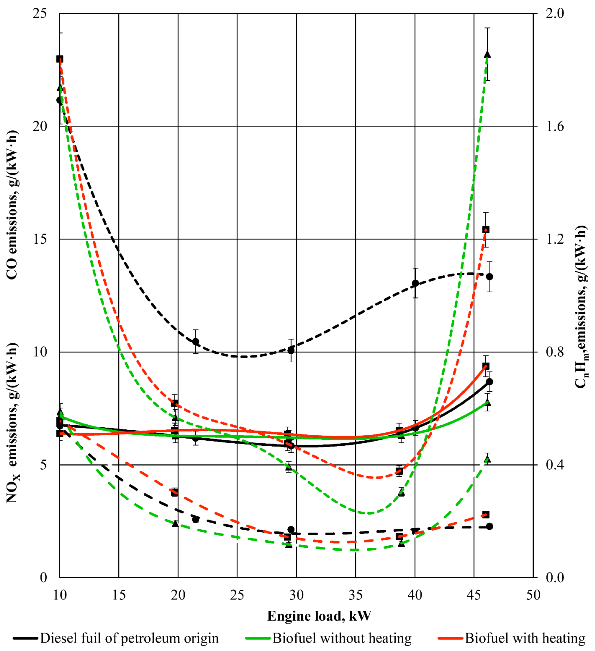


Fig. 6. The concentration of emissions in the exhaust gases of the diesel engine when using different fuel types (solid lines – NO_X emissions; dotted lines – C_nH_m emissions; dash-dotted lines – CO emissions

A sharp increase of emissions of CO and C_nH_m in the maximum power of the engine when using biofuel without heating due to insufficient quality of atomization and mixture formation (drops of biofuel in the cut are bigger than of the diesel fuel of petroleum origin, because of the higher value of the kinematic viscosity), which on the background of the maximum cyclic supply of biofuel leads to an increase in the number of zones with insufficient amount of oxygen around the fuel droplets which is injected into the cylinders.

In the absence of oxygen, the molecules of biofuel, having a larger molecular chain, do not have time to undergo complete destruction and oxidation and, as a result, it takes place a decrease in the fuel combustion completeness, and increase of emissions of CO and C_nH_m.

The use of heating of biofuel increases the efficiency of mixture formation and combustion of biofuel, which is confirmed by a decrease in specific fuel consumption and an increase in emissions of CO and C_nH_m. Low emissions of CO and C_nH_m at maximum load are associated with better spraying and mixing during heating of biofuel.

The NO_X mission values vary almost identically and differ slightly from one fuel to another. Slightly higher NO_X emissions for heated biofuel are associated with an increase in the temperature of the local combustion zones due to an increase in the completeness of its combustion, which in turn contributes to the formation intensification.

4. Conclusion

The optimum temperature range of biofuel heating before injection into the engine cylinders is in the range from 115 to 120 °C; at the heating temperatures of 120 °C, in depending on the loading of the engine, the amount of over-consumption of biofuel in comparison with diesel fuel of petroleum origin is from 12.9 to 15.09 %.

When using biofuel in comparison with diesel fuel of petroleum origin, there is an increase in fuel consumption and a decrease in CO emissions. When the engine is loaded in the range from 20 to 40 kW, the concentration of CO in the exhaust gases, when operating on biofuel, is twice less than when operating on diesel fuel of petroleum origin. C_nH_m and NO_X emissions from different fuel types do not differ significantly.

When biofuel is heated to the temperature 120 °C, the degree of dispersion and mixture formation increases, resulting in an increase of fuel high-molecular carbohydrates combustion completeness. The use of heating of biofuel increases the combustion completeness; as a result, there is a decrease in the consumption of biofuel by an amount of 2.78 to 9.34 % depending on the load, with an insignificant increase in the concentration of C_nH_m, CO, and NO_X in exhaust gases.

References

[1] A. Harrouz, M. Abbes, I. Colak, and K. Kayisli, “Smart grid and renewable energy in Algeria”, 2017, IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2017.819123, San Diego, pp. 1166-1171, 5-8 Novembe 2017. (Conference Paper)

[2] A. T. Quitain, S. Katoh, M. Sasaki and M. Goto, "Rapid facile biofuel synthesis by microwave irradiation," 2012, IEEE International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2012.6477438, Nagasaki, pp. 1-4., 11-14 Novembe 2012. (Conference Paper)

[3] E. K. Çoban, C. Gençoğlu, D. Kirman, O. Pinar, D. Kazan and A. A. Sayar, "Assessment of the effects of medium composition on growth, lipid accumulation and lipid profile of Chlorella vulgaris as a biodiesel feedstock," 2015, IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Doi: 10.1109/ICRERA.2015.7418521, Palermo, pp. 793-796, 22-25 Novembe 2015. (Conference Paper)

[4] A. Agarwal, J Gupta, A. Dhar, “Potential and challenges for large-scale application of biodiesel in automotive sector”, Progress in Energy and Combustion Science, vol. 61, pp. 113-149, July 2017; doi:10.1016 / j.pecs.2017.03.002. (Article)

[5] S. Dewang, Suriani, S. Hadriani, Diana, E.S. Lestari, and Bannu, “Viscosity and calorie measurements of biodiesel production from Callophyllum”, Iphyllum L using catalyst and time variations for stirring in tansesterfication process, 2017, IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA), DOI: 10.1109/ICRERA.2017.8191157, San Diego, pp. 734-738, 5-8 Novembe 2017. (Conference Paper)

[6] E. Alptekin, M. Canakci, “Characterization of the key fuel properties of methyl ester-diesel fuel blends”, Fuel, vol. 88 (1), pp. 75-80, January 2009, https://doi.org/10.1016/j.fuel.2008.05.023. (Article)

[7] R. Dunn, (2009), “Effects of minor constituents on cold flow properties and performance of biodiesel”, Progress in Energy and Combustion Science, vol. 35 (6), pp. 481–489, December 2009, https://doi.org/10.1016/j.pecs.2009.07.002. (Article)

[8] Sandhya K. Vijayan, Mary Naveena Victor, Abinandan Sudharsanam, Velappan Kandukalpatti Chinnaraj, Vedaraman Nagarajan, “Winterization studies of different vegetable oil biodiesel”, Bioresource Technology Reports, vol 1, pp. 50-55, March 2018, https://doi.org/10.1016/j.biteb.2018.02.005. (Article)

[9] M. Ramos, C. Fernandez, A. Casas, L. Rodriguez, A. Perez, “Influence of fatty acid composition of raw materials on biodiesel properties”, Bioresource Technology, vol. 100(1), pp. 261–268, January 2009, https://doi.org/10.1016/j.biortech.2008.06.039. (Article)

[10] Á. Pérez, A. Casas A., C. Fernández, M. Ramos, L. Rodríguez, “Winterization of peanut biodiesel to improve the cold flow properties”, Bioresource Technology, vol. 101(19), pp. 7375-7381, October 2010, https://doi.org/10.1016/j.biortech.2010.04.063. (Article)

[11] G. Golub, V. Chuba, O. Kepko, “Research on temperature preparation of diesel biofuel in an energy vehicle fuel tank”, INMATEH - Agricultural Engineering, vol. 56 (3), pp. 101-108, December 2018. (Article)

[12] G. Dwivedi, P. Verma, M. Sharma, “Impact of oil and biodiesel on engine operation in cold climatic condition”, Journal of Materials and Environmental Science, vol. 7 (12), pp. 4540-4555, 2016. (Article)

[13] G. Dwivedi, P. Verma, M. Sharma, “Experimental investigation of metals and antioxidants on oxidation stability and cold flow properties of pongamia biodiesel and its blends”, International Journal of Renewable Energy Research, vol. 7 (1), pp. 26-33, 2017 (Article)

[14] R. Misra, M. Murthy, “Blending of additives with biodiesels to improve the cold flow properties, combustion and emission performance in a compression ignition engine - A review”, Renewable and Sustainable Energy Reviews, vol. 15 (5), pp. 2413-2422, June 2011, doi:10.1016/j.rser.2011.02.023. (Article)

[15] Maawa W.N., Mamat R., Najafi G, Ali O. Majeed, Aziz A., "Engine performance and emission of compression ignition engine fuelled with emulsified biodiesel-water", 2015 3rd International Conference of Mechanical Engineering Research, Paper presented at the IOP Conference Series: Materials Science and Engineering, vol. 100 (1), December 2015, doi:10.1088/1757-899X/100/1/012061. (Conference Paper)

[16] P. Tamilselvan, N. Nallusamy, S. Rajkumar,"A comprehensive review on performance, combustion and emission characteristics of biodiesel fuelled diesel engines", Renewable and Sustainable Energy Reviews, vol. 79, pp. 1134-1159, November 2017, doi:10.1016/j.rser.2017.05.176. (Article)

[17] G. Dwivedi, M. Sharma "Cold flow behaviour of biodiesel-A review", International Journal of Renewable Energy Research, 3 (4), pp. 827-836, January 2013. (Article)

[18] R. Arslan and Y. Ulusoy, "Utilization of waste cooking oil as an alternative fuel for Turkey", 2016, IEEE International Conference on Renewable Energy Research and Applications (ICRERA), doi: 10.1109/ICRERA.2016.7884526, Birmingham, pp. 149-152 , 20-23 November 2016.(Conference Paper)

[19] B. Ashok, K. Nantha Gopal, T. Rajagopal, S. Alagiasingam, S. Appu, A. Murugan, "Design and analysis of a fuel preheating device for evaluation of ethanol based biofuel blends in a diesel engine application", SAE International Journal of Engines, vol. 10 (1), pp. 39-45, January 2017, doi:10.4271/2017-26-0073. (Article)

[20] P. Dinesha, P. Mohanan, "Experimental Investigation on the Performance and Emission Characteristics of Diesel Engine using Preheated Pongamia Methyl Ester as Fuel", International Journal of Advances in Engineering & Technology; Bareilly, Vol. 5 (1), pp. 591-600, November 2012. (Article)

[21] Mustaffa N., Khalid A., Sies M.F., Zakaria H., Manshoor B., "Preheated biodiesel derived from vegetable oil on performance and emissions of diesel engines: A review", 2014 4th International Conference on Mechanical and Manufacturing Engineering, Applied Mechanics and Materials, 465-466, pp. 285-290, January 2014, DOI: 10.4028/www.scientific.net/AMM.465-466.285. (Conference Paper)

[22] V. Joshua Jaya Prasad, V. Rambabu, "Combustion and performance analysis of direct injection, compression ignition engine fuel with preheated neat cotton seed methyl ester", Biofuels, vol. 6 (3-4), pp. 137-145, July 2015, DOI:10.1080/17597269.2015.1065588. (Article)

[23] Y. Ren, X.-G. Li, "Numerical study on the combustion and emission characteristics in a direct-injection diesel engine with preheated biodiesel fuel", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 225 (4), pp. 531-543, 2011, DOI: 10.1177/09544070JAUTO1593. (Article)

[24] H. Bayrakceken, "The effects of using preheated animal tallow biodiesel on engine performance and emissions in a diesel engine", Energy Education Science and Technology Part A: Energy Science and Research, vol. 28 (1), pp. 133-142, October 2011. (Article)

[25] M. Karabektas, G. Ergen, M. Hosoz, "The effects of preheated cottonseed oil methyl ester on the performance and exhaust emissions of a diesel engine", Applied Thermal Engineering, vol. 28 (17-18), pp. 2136-2143, December 2008, doi:10.1016/j.applthermaleng.2007.12.016. (Article)

[26] Khandal S., Honawad V.A., Nagesh S., Banapurmath N., "Effective utilization of waste heat from engine exhaust gas for preheating the fuel to enhance the performance of diesel engine", 2018 International Conference on Advances Manufacturing, Materials and Energy Engineering, Paper presented at the IOP Conference Series: Materials Science and Engineering, 376(1), pp. 1-15, June 2018, doi:10.1088/1757-899X/376/1/012090. (Conference Paper)

[27] M. Ramakrishnan, T. Rathinam, K. Viswanathan, "Comparative studies on the performance and emissions of a direct injection diesel engine fueled with neem oil and pumpkin seed oil biodiesel with and without fuel preheater", Environmental Science and Pollution Research, vol. 25 (5), pp. 4621-4631, December 2017, doi:10.1007/s11356-017-0838-9. (Article)

[28] S. Vedharaj, R. Vallinayagam, W. Yang, S. Chou, K. Chua, P. Lee, "Performance emission and economic analysis of preheated CNSL biodiesel as an alternate fuel for a diesel engine", International Journal of Green Energy, vol. 12 (4), pp. 359-367, November 2014. DOI: 10.1080/15435075.2013.841162. (Article)

[29] G. Golub, M. Trehub, V. Chuba, M. Pavlenko "Fuel heating system for diesel internal combustion engine". Patent No. 116375. Ukraine, 2018. (Patent)

[30] ГОСТ 17.2.2.05-97. Protection of Nature. Atmosphere. Standards and methods for determining emissions of harmful substances from exhaust gases of diesel engines, tractors and self-propelled agricultural machinery. (Standards and Reports)