ETHANOL AS AN ADDITIVE FUEL FOR DIESEL ENGINES

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Abstract. The article presents the test results obtained when using ethanol made of local lignocellulose raw materials as additive fuel for diesel engines. It studies potential methods of mixture formation and ratios of different fuel-air mixtures. The results are evaluated by comparing the output parameters and indicator indexes gained by the motor-method. The article presents maximum consumption of ethanol as additive fuel required for the diesel engine to operate and points out the changes in effective indexes arising from the use of air-fuel mixture. The authors of the article provide an innovative solution for using a dual feeding system: main fuel-supply system, which ensures the injection of base fuel, and auxiliary fuel-supply system, which ensures management of various ethanol-fuel mixtures according to the load mode of the engine. This solution ensures good engine starting and operation in a wide range of operating-speed. The article provides test methods suitable for using ethanol as fuel and the test results achieved.

Keywords: ethanol as an additive fuel, quantitative and qualitative fuel supply systems, engine cylinder pressure characteristics, engine output values and testing characteristics.

Introduction

At present there is a wide classification of alternative fuels used in internal combustion engines [1]. The most common additive fuel for a piston engine is ethanol, which is used as a standalone fuel, but also as an additive in other types of fuel [2; 3]. Wide use of ethanol in diesel engines is hindered by its physical-chemical properties and the nature of the Diesel cycle [4]. This article considers adding ethanol mixture to diesel fuel and studies its impact on the engine input and output parameters. Different fuel mixtures are simultaneously administered to the test engine by using qualitative and quantitative methods. In the first case diesel fuel is delivered to the engine by pilot injection in order to start up the engine and control the transient mode. In the second case the required quantity of ethanol is directed into the cylinder of the engine by means of an auxiliary device via the inlet manifold. The purpose of the study was to find the optimum ratio of ethanol and diesel fuel mixture, which allows satisfactory engine operation in the overload area of the test plan. The Diesel engine D-120 (No 64176) was chosen as the test engine due to the following: 1) small tractors with this engine are still used in various industries; 2) the air-cooled diesel engine D-120 is cheap and reliable; 3) it is easy to install sensors for measuring indicator indexes.

Materials and methods

Test engine equipment and measurement devices. In order to measure the indicator indexes and output parameters of the diesel engine D-120 in laboratory environment, the engine test stand Dynas3-LI250 was used, assembled with the auxiliary and measurement devices shown in Fig. 1.

Preparation of test engine. The following tasks were performed to prepare the engine D-120 for stand testing: 1) adjusting the timing gear; 2) replacing the defective elements of the fuel-supply system; 3) specifying the engine stroke points by using an indicator device; 4) optimising the static fuel delivery angle; 5) performing the in-depth testing cycle of the fuel-supply system. The output parameters were calculated on the basis of the following methods. The pump fuel delivery $V_{f.fp}$ ($mm^3 \cdot stroke^{-1}$) was determined by the formula:

$$V_{f.fp} = \frac{10^3 \cdot \sum_1^4 V_i}{n_c}, \quad (1)$$

where V_i – capacity of section i, $cm^3 \cdot min^{-1}$;
n_c – total number of cycles.

The relative variation $\sigma_{f.fp}$ (%) calculated by the formula:

$$\sigma_{f.fp} = \frac{2(V_{i.\max} - V_{i.\min})}{V_{i.\max} + V_{i.\min}} \cdot 100 \quad , \tag{2}$$

where $V_{i.max}$ and $V_{i.min}$ – maximum and minimum capacity of the section i, $cm^3 \cdot min^{-1}$.

The fuel consumption $B_{f.fp}$ ($kg \cdot h^{-1}$) was determined by the formula:

$$B_{f.fp} = 60 \cdot 10^{-6} \cdot \sum_{1}^{4} V_i \rho_f \tag{3}$$

where ρ_f – fuel density $kg \cdot m^{-3}$.

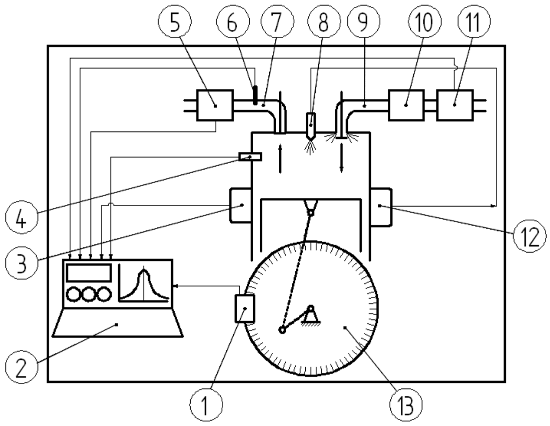

Fig. 1. **Diesel engine D-120 and placement of its measurement and auxiliary devices:** 1 – sensor of the crankshaft movement angle and sensor of rotational speed; 2 – engine control remote with AVL Indimodul device; 3 – engine unit for pressure and temperature sensors; 4 – pressure sensor Kissler 701A; 5 – opacimeter BAE 350-FIN; 6 – exhaust gases temperature sensor; 7 – exhaust manifold; 8 – injector; 9 – inlet manifold;10 – carburettor; 11 – air consumption meter SuperFlow 6-1490; 12 – diesel fuel-supply equipment with control system Horiba ATS LFM 2003; 13 – graduated scale.

In order to determine the optimum of the static fuel delivery angle (hereinafter – $\alpha_{st.opt}$), a set of the adjustment characteristics was performed with standard diesel fuel regarding the values of 7…28 crankshaft movement degrees before the top dead centre (hereinafter – ckm degrees (˚) BTDC). In the course of testing the engine indicator indexes were registered (Fig. 2). $\alpha_{st.opt}$ was determined by comparing the adjustment characteristics and indicator indexes.

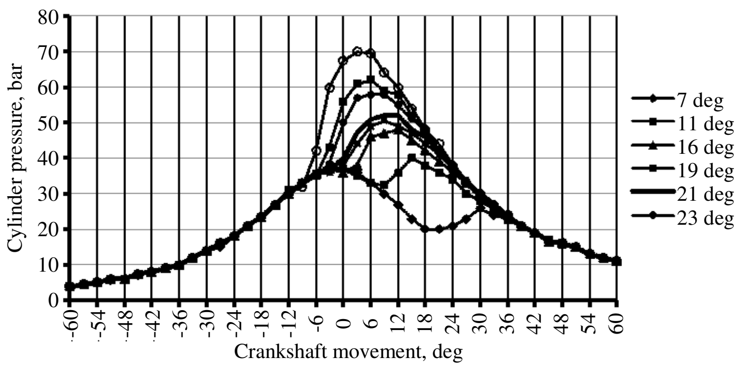

Fig. 2. **Diesel engine D-120 indicator diagram in mode $n_{e.nom}$ = 1800 rpm**

Methods for testing suitability of alternative fuels. There is not much research on the use of ethanol mixtures. The combined use of mixtures and diesel fuel in diesel engines has not been studied either. Due to their insolubility in air-fuel mixture, the changes in the engine output parameters cannot be determined by using only the classical test characteristics [5]. Thus, this study used special characteristics, explanations of which are provided below. The selection of the suitable test mode required engine characteristics with multiple parameters. In order to use ethanol in fuel mixture it is necessary to know the quantity of the base fuel. This was determined by adjustment characteristics of the in-line fuel-injection pump. Test results are provided in Table 1.

Choosing additive fuel for diesel engine. In the course of the study a series of tests were performed with 60 %, 70 %, 80 % and 96 % purity of ethanol. The purpose was to determine: 1) the dependence of consumption of ethanol with different purity on the opening ratio of the main metering jet; 2) the minimum purity level of ethanol that ensures normal operation of the diesel engine. The tests measured the basic engine output parameters, relevant indicator diagrams and exhaust composition. The test conditions were the following: n_e = const; T_e = const, varied ethanol consumption and position of governor lever. The test results are presented in Fig. 3 and Fig. 4.

Adjusted ethanol load characteristic for diesel engine. Ethanol load characteristic for the engine D-120 was performed under the condition where: 1) engine mode was $n_{e.nom}$ = 1800 rpm; 2) fuel mixture consisted of 96 % ethanol and diesel fuel; 3) diesel fuel consumption ($B_{f.df}$) was kept minimal and constant; 4) load was regulated according to the ethanol consumption; 5) ethanol consumption was regulated by opening of the main metering jet. During the test the engine output parameters and indicator indexes were measured (Table 2).

Improved ethanol load characteristic for diesel engine. The test conditions for this load characteristic were the following: 1) engine mode was $n_{e.nom}$ = 1800 rpm; 2) fuel mixture consisted of 96 % ethanol and diesel fuel; 3) diesel fuel consumption ($B_{f.df}$) was varied; 4) engine torque was T_e = const; 5) ethanol consumption was regulated by opening of the main metering jet; 6) increase of the engine torque caused by addition of ethanol was compensated by reducing the diesel fuel consumption. The test measured engine output parameters (Table 3) and indicator indexes.

Mixture formation characteristic for diesel engine. Characteristics were performed under conditions where: 1) engine mode was $n_{e.Temax}$ = 1,300 rpm; 2) 60 % ethanol mixture was used as additive fuel; 3) position of the control rack was constant; 4) consumption of ethanol ($B_{f.et}$) and T_e varied. The tests were performed with three control rack positions, where the average values of consumption of diesel fuel were: B_{f1} = 1.16 kg·h^{-1}; B_{f2} = 1.69 kg·h^{-1}; B_{f3} = 2.40 kg·h^{-1}. The test measured engine indicator indexes, output parameters (Fig. 5) and exhaust emission composition.

Results and discussion

Test results of in-line fuel-injection pump (Table 1). The fuel-injection pump was subject to a set of governor and adjustment characteristics. The purpose was to determine the capacities of fuel delivered by the fuel-injection pump at different speed modes. The control rack of the fuel-injection pump was controlled by a micrometer. Based on the information shown in Table 1, the tests allow determining the capacity of pilot injection required for controlling the engine operation.

Results of preparing diesel engine for test. The angle of $\alpha_{st.opt}$ of the diesel engine was determined by comparing the engine indicator indexes and adjustment characteristic (Fig. 2). The test results of adjustment characteristics were the following: 1) up to six degrees change in the α_{st} towards both directions of the TDC has approximately the same impact on the change in the engine output parameters: effective power was reduced by P_e = 0.6 kW and specific fuel consumption increased by b_e = 18 g· (kWh)$^{-1}$; 2) α_{st} = 28° BTDC increases the rigidity of the engine operation significantly; 3) in case of α_{st} 32° the testing had to stop, because operational rigidity became dangerous for the engine.

Measurement of engine indicator indexes in mode ($n_{e.nom}$ = 1800 rpm) allows exact adjustment of the fuel-supply system setup. The analysis of indicator indexes showed that: 1) in case of turning the α_{st} by seven degrees later (α_{st} = 14°) and earlier (α_{st} = 28°) from the optimum angle ($\alpha_{st.opt}$), the parameters of the engine combustion process acquired the following values: $p_{z.max}$ = 43 bar, $\alpha_{pz.max}$ = 14°, and $p_{z.max}$ = 70 bar, $\alpha_{pz.max}$ = 4°, respectively; 2) the results of the ratio value $\Delta p/\Delta\alpha$ by different static fuel delivery angle, where Δp – the change in the final pressure of combustion process and $\Delta\alpha$ – the change in the crankshaft movement angle characterises the rigidity of the engine operation, were the following: 2.1) $\Delta p/\Delta\alpha$ ($\alpha_{st.28deg}$) = 2.7 bar·deg^{-1}; 2.2) $\Delta p/\Delta\alpha$ ($\alpha_{st.23deg}$) = 1.5 bar·deg^{-1}; 2.3) $\Delta p/\Delta\alpha$ ($\alpha_{st.21deg}$) = 1.0 bar·deg^{-1}; 2.4) $\Delta p/\Delta\alpha$ ($\alpha_{st.19deg}$) = 0.3 bar·deg^{-1}; 2.5) $\Delta p/\Delta\alpha$ ($\alpha_{st.14deg}$) = 0.1 bar·deg^{-1}.

The final work process of the diesel engine was regulated by the following parameters: 1) maximum pressure of the combustion process, $p_{z.max}$ = 52 bar; 2) peak value of the maximum pressure located on $\alpha_{pz.max}$ = 10° after the top dead centre (hereinafter – ATDC) and the optimum static fuel delivery angle $\alpha_{st.opt}$ = 21° BTDC.

Table 1

The effect of camshaft rotational speed and position of control rack to pump fuel delivery

Camshaft speed, rpm	Position of control rack, mm and corresponding pump fuel delivery, $mm^3 \cdot cycle^{-1}$								
	0	1	2	3	4	5	6	7	8
400	0	6.3	17.5	25.0	37.5	50.0	65.0	85.0	105.0
500	0	6.0	18.0	31.0	40.0	54.0	67.0	84.0	101.0
600	0	8.0	19.7	34.1	44.3	57.0	72.1	86	102.7
650	0	9.0	20.6	35.6	46.5	58.5	74.6	87	103.5
700	0	10.0	21.4	37.1	48.6	60.0	77.1	87.9	104.3
800	0	12.2	23.9	37.5	49.0	60.9	76.4	88.4	105
900	0	14.4	23.3	37.8	49.4	61.7	75.6	88.9	105.6
970	1.6	12.9	23.2	38.1	50.5	60.8	73.2	88.7	106.2

The results after choosing additive fuel for diesel engine. The tests involved load characteristics with purity of ethanol 60 %, 70 %, 80 %, and 96 %. The ethanol was added to the diesel fuel. Firstly, the dependence of the consumption of ethanol on carburettor adjustments was determined. The test results were the following (Fig. 3): 1) the higher the purity of ethanol, the higher the consumption; 2) consumption of ethanol depends on the crankshaft rotational speed. Secondly, minimum purity of ethanol required for efficient operation and ensured work resource of the diesel engine was determined. During the tests the indicator indexes of the engine and exhaust emission composition were measured. The impact of ethanol with different composition on the engine output parameters is shown in Fig. 4. The diagram initial point DF refers to the test mode, where the engine runs on base fuel, and zero test mode with open main metering jet. The test results led to the following conclusions: 1) the higher the purity of ethanol, the higher the efficiency of the engine; 2) when using 60 % ethanol the efficiency of the engine is ca 10 % lower than in case of using 70 %, 80 %, and 96 % ethanol; 3) using ethanol as motor fuel reduces the efficiency of the engine by up to 30 % in comparison with diesel fuel.

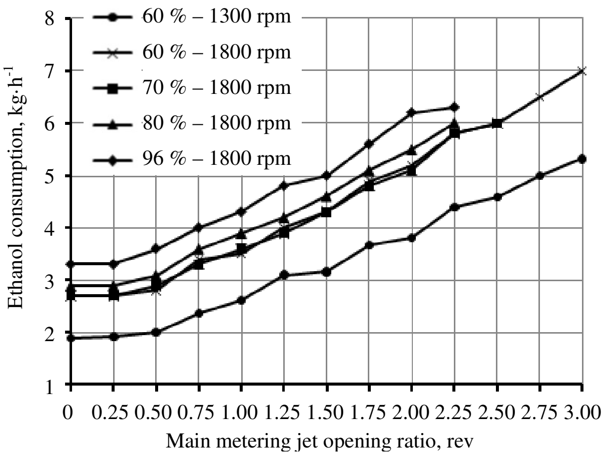

Fig. 3**. Ethanol consumption depending on main metering jet opening ratio by different purity of ethanol and crankshaft rotational speed**

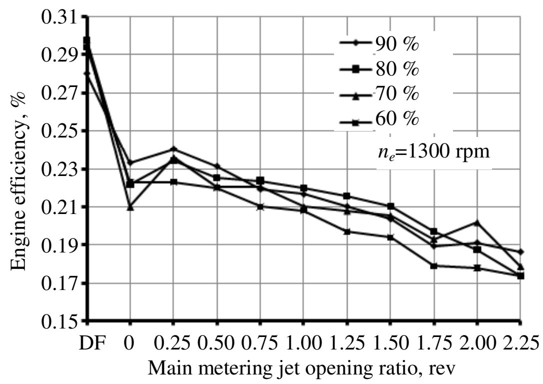

Fig. 4. **Dependence of engine efficiency on purity of ethanol and opening ratio of main metering jet**

Test results for diesel engine, adjusted to ethanol load characteristic. It appears from the test data, that the diesel engine runs up to 4.1 $kg \cdot h^{-1}$ when adding 96 % ethanol to the fuel mixture without causing deterioration of the engine output parameters and significant increase in the temperature of exhaust gases. In case of increase in consumption of ethanol ($B_{f.et}$) by 0.5 $kg \cdot h^{-1}$ from the initial value, the combustion process may be delayed on average by two cmk degrees. The engine ran in a stable manner until the consumption of ethanol $B_{f.et}$ = 4.8 $kg \cdot h^{-1}$. When the consumption of ethanol is increased, the $\Delta p/\Delta\alpha$ and T_e will exceed their preset values. Addition of larger consumption of ethanol becomes dangerous for the technical condition of the engine. The rigidity of the engine work process increases up to $\Delta p/\Delta\alpha$ = 2 bar·deg^{-1}.

Table 2

Adjusted ethanol load characteristic for diesel engine

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
$B_{f.df,}$ kg·h^{-1}	2.1	2.2	2.5	2.5	2.6	2.3	2.4
$B_{f.et}$, kg·h^{-1}	3.3	3.3	3.6	4.1	4.2	4.8	5.1
$\sum B_f$, kg·h^{-1}	5.4	5.5	6.1	6.6	6.8	7.1	7.5
T_e , Nm	73	75	94	102	104	112	116
λ_a	2.34	2.26	2.01	1.89	1.79	1.76	1.62
t_{egt}, ºC	<200	<200	220	230	260	280	280

Diesel engine test results based on improved ethanol load characteristic. Test results in Table 3 indicate that the reduction of the position of the governor lever (GL) from 100.0 % to 84.7 % will lead to the reduction of the quantity of pilot injection twice, i.e. 1.2 kg·h^{-1}.

Table 3

Improved ethanol load characteristic for diesel engine

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
$B_{f.df,}$ kg·h^{-1}	5.0	2.4	2.4	2.3	2.2	2.0	1.8	1.2	1.2
$B_{f.et}$, kg·h^{-1}	0	3.3	3.3	3.6	4.2	4.5	4.8	5.7	6.3
$\sum B_f$, kg·h^{-1}	5.0	5.7	5.7	5.9	6.4	6.5	6.6	6.9	7.5
T_e, Nm	90	90	90	90	90	90	90	90	90
λ_a	2.40	2.21	2.20	2.14	1.93	1.82	1.80	1.81	1.59
GL, %	100	88.4	87.9	87.9	87.4	86.4	86.2	84.7	84.7

A low value of excess-air ratio indicates good quality of the combustion process and low level of opacities in exhaust gases. The analysis of the indicator indexes shows that upon adding 96 % ethanol up to 4.3 kg·h^{-1}, the indexes of the combustion process show the following changes: $p_{z.max}$ is reduced by up to six bar and $\alpha_{pz.max}$ is delayed by up to six ckm degrees. When adding 96 % ethanol 4.8 kg·h^{-1} and more, the diesel engine operation process becomes inefficient.

Results of mixture formation characteristic for diesel engine (Figure 5). The test results were the following: 1) minimum average consumption of diesel fuel, which ensures operation of the engine in mode $n_{e.Temax}$ was B_{f1} = 1.16 kg·h^{-1}; 2) engine operation became unstable when adding 60 % ethanol when exceeding $B_{f.et}$ = 3.2 kg·h^{-1} (diesel and ethanol fuel ratio 1:2.8); 3) in case of these fuel ratios the maximum engine torque achieved was $T_{e.max}$ = 33 Nm; 4) when increasing the consumption of pilot injection up to B_{f2} = 1.69 kg·h^{-1} and up to B_{f3} = 2.4 kg·h^{-1}, the fuels ratios decreased to 1:2.6 and 1: 1.9 and the torque increases up to T_e = 78 Nm and T_e = 117 Nm, respectively.

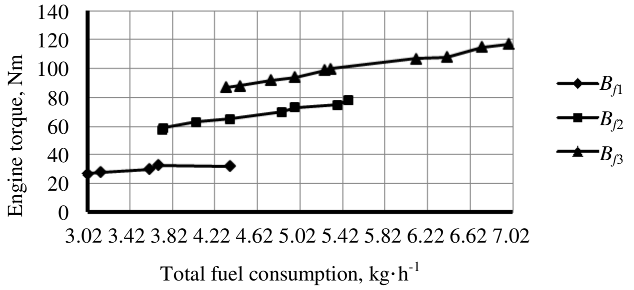

Fig. 5. **Dependence of engine torque on total fuel consumption of ethanol in case of different consumption of pilot injections, where: B_{f1} = 1.16 kg·h^{-1}, B_{f2} = 1.69 kg·h^{-1}, B_{f3} = 2.4 kg·h^{-1}**

Results of comparison of pilot injections. When testing the diesel fuel-supply system on the test stand without the engine, the pump fuel delivery is determined by formula (1). The calculation of the capacity of pilot injection, i.e., pump fuel delivery $V_{f.en}$ during the engine testing performed in the same mode is based on the following formula:

$$V_{f.en} = \frac{10^8 \cdot B_{f.en}}{(6 \cdot i_l \cdot n_{cam} \cdot \rho_f)}, \quad (4)$$

where $B_{f.en}$ – engine fuel consumption, kg·h^{-1};
i_l – number of sections of fuel-injection pump;
n_{cam} – camshaft rotational speed of fuel-injection pump, rpm;
ρ_f – fuel density, kg·m^{-3}.

Theoretically the formulas (1) and (4) should, in case of prescribed test mode, yield similar pump fuel delivery values. In reality, however, the following relation occurs between the fuel-injection pump and pump fuel delivery values gained from the engine testing:

$$V_{f.fp} = k \cdot V_{f.en}, \quad (5)$$

where k – is a factor which takes into account the reduction in the value of the pump fuel delivery depending on the engine test mode. The value of the factor k depends on the engine rotational speed, load mode and stability of the crankshaft rotational speed. The value of the factor for diesel engine D-120 remains within the range of k = 1.1…1.3.

Conclusions

1. In order to adjust the engine work with ethanol it is sufficient to use an additional carburettor device.
2. The engine works satisfactorily with 96 % ethanol as additive fuel at consumption up to $B_{f.et}$ = 4.8 kg·h^{-1},
3. When using 96 % ethanol as additive fuel the rigidity of the engine operation increases up to 2 bar·deg^{-1} and the combustion process is delayed by up to 10 crankshaft movement degrees.
4. When using 96 % ethanol as additive fuel the diesel/ethanol ratio may increase up to 1:4.
5. The higher the purity of ethanol, the higher the efficiency of the engine.
6. Addition of ethanol leads to linear reduction of the efficiency of the engine.
7. Engine operation is satisfactory in maximum load mode upon pilot injection with 60 % ethanol additive fuel up to 4.5 kg·h^{-1}.
8. When using 60 % ethanol the efficiency of the engine is ca 10 % lower than in case of 96 % ethanol.
9. When using ethanol as additive motor fuel the efficiency of the engine is reduced by up to 30 % in comparison to diesel fuel.

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