ASPECTS OF THE BUTANOL USE IN THE COMPRESION IGNITION ENGINE OF THE AUTOMOTIVE

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The consumption increase of the petroleum, depletion of the natural resources and all more drastic emission Euro regulations will conduct to the increase of the fossil fuels price, which will determine automotive engineers to find the alternative fuels solutions for complete respectively replace the conventional fuels, one of these being the use of thr alcohol. Of all alcohols used for the fueling compression ignition engines, butanol is expected to be the most promising alternative fuel due to its properties. The need to use butanol at diesel engine comes from the desire to reduce smoke emissions and nitrogen oxides without significant engine's changes from the construction view point, which increase the total production cost of the engine.

Keywords: diesel, butanol, soot, NO_x.

1. Introduction

From the category of alternative fuels, alcohols have the most reliable prospects of use, because these can easily adapt at engine's requirements, have great opportunities for production, storage and distribution.

Research teams from universities and big companies are involved in ample theoretical and experimental researches on using butanol as fuel for a compression ignition engine, some methods of fueling being investigated. The paper presents some aspects of the use of butanol through the blends method for a compression ignition engine of the automobile.

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The properties of butanol

Butanol belongs from the primary alcohols class alongside methanol and ethanol. This results from the replacement of a hydrogen atom from a hydrocarbon, with a group OH. Butanol (butyl alcohol) is made up of three methyl groups and one group OH (fig. 1).

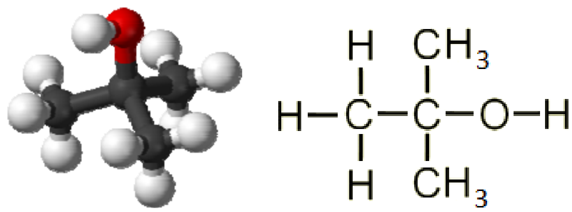

Fig. 1. The chemical structure of butanol, [1]

The main properties of the diesel fuel as compared to those of butanol are shown in the table 1.

Table 1

The properties of the butanol as compared to those of diesel fuel, [2], [3], [11]

Nr. crt.	Parameter		Butanol	Diesel fuel
1	Chemical formula		C_4H_9OH	$\approx C_{16}H_{34}$
2	Boiling temperature (1.013 bar) [°C]		82.8	180 ... 360
3	Auto ignition temperature [°C]		340	≈250
4	Flash temperature [°C]		34	50 ... 140
5	Flame temperature [°C]		2220	2054
6	Heat of vaporization [kJ/kg]		595	270
7	Specific heat at 20 °C (1.013 bar) [kJ/kg·K]		2.3	1.9
8	Lower Heating Value [kJ/kg]		32560	41855
9	Cetane number		<18	45 ... 55
10	Density at 20 °C [kg/m^3]		810	820 ... 860
11	Dynamic viscosity at 20 °C (1.013 bar) [mPa·s]		2.95	1.6 ... 6.8
12	Gravimetric composition [%]	C	64.86	≈ 86
		H	13.5	≈ 12
		O	21.64	2
13	Fuel / air ratio [kg air/kg comb.]		11.1	14.5

Butanol has worsened auto ignition properties due to very low butanol's cetane number compared to that of diesel fuel, thus resulting in an increasing of the auto ignition delay. Various measures are taken to counteract this effect, one of them consisting in adding of additives with various reactions accelerators, called organic nitrates, in order to increase the cetane number so that the auto ignition delay of butanol decreases close to that of diesel fuel.

The Lower Heating Value (LHV) of butanol is lower by ~1.28 times compared to that of diesel fuel. The mechanical work actually produced by an engine and Brake Specific Fuel Consumption (BSFC) is influenced by the calorific power of the used fuel. This Lower Heating Value is ideal to be as high as possible. The LHV is decreasing by reducing the carbon's content and by increasing the concentration of oxygen in the hydrocarbon, which leads to a butanol consumption increase. In addition, lower density of butanol imposes the volume increase of butanol dose per cycle, eventually the necessity to increase storage capacity at the vehicle board.

Butanol has a higher laminar combustion speed compared to diesel fuel due to the high oxygen content at molecular level. In paper [4] studies on butanol combustion process are presented, highlighting the combustion speed and flame temperature of the butanol. It has been found that laminar flame speed of butanol has a maximum value around 0.50 m/s at an air excess coefficient of 1.1. Similar measurements on the combustion process such as, for example, the flame speed, the flame temperature have been achieved in paper [5], where the maximum flame speed is about 3.4 m/s at an air excess coefficient of 1.1 (p_0 = 100 kPa, T_0 = 301 K) and the flame temperature is about 2200 K (p_0 = 100 kPa, T_0 = 301 K). The fact that the boiling point of butanol is lower than the temperature at the beginning of diesel fuel distillation means it will evaporate long before diesel fuel, favoring rapid combustion phase.

Lower viscosity butanol value requires the use of additives (e.g. castor oil) to improve the lubricating properties when used either as a single fuel or double injection method.

Because the vaporization heat is higher for butanol than for diesel fuel by ~2.1 times, butanol will consume more energy than diesel fuel to evaporate, resulting in the temperature's decrease with implications for the auto ignition delay.

Theoretical quantity of combustion air for butanol is lower than for diesel fuel (11.1 kg air/kg butanol from 14.5 kg air/kg diesel fuel) which allows the increas of the fuel dose to compensate the lower calorific power (~1.28 times), with maintaining or even with a slight increase of the air excess coefficient.

The use of butanol as a single fuel for compression ignition engine creates difficulties due to its worsened auto ignition - low cetane number. More methods of fuelling can be developed, which suppose:

- Total replacement of diesel fuel (single fuel);
- Partial replacement of diesel fuel.

Among the methods that suppose total replacement of diesel fuel are:

- Controlled ignition method;

This method consists in transforming the compression ignition engine in a spark ignition engine, which requires major constructive changes to the engine.

- Direct injection method;

The method supposes injecting of butanol with additives, directly into the engine cylinder.

Methods that suppose partial replacement of diesel fuel can be:

- Blends method;

Compared to other alcohols, butanol has a good miscibility, forming a stable mixture, but we consider that the percentage of replacement of diesel fuel is around 30%, due to relatively low cetane number of the mixture.

The method involves mixing diesel fuel with butanol, the resulting mixture being injected into the engine cylinder.

- Fumigation method (diesel fuel-butanol);

It is accomplished by introducing butanol in the intake, the ignition being performed using the diesel fuel pilot injected into the cylinder.

- Double injection method.

It consists in the separate injection of the butanol and diesel fuel, the latter serving at butanol ignition. The disadvantage of this method is the need to equip the engine with two independent fueling systems.

Investigations presented in paper [6] highlights aspects related to using butanol mixed with diesel fuel (20% vol.) at various injections timing and different percentages of the exhaust gas recirculation (EGR). Thus, it was found that, without exhaust gas recirculation, the maximum cycle pressure is slightly higher when using butanol compared to using diesel fuel, the increase being ~5 bar (0% EGR, β_{inj} = 11 ^{0}RAC to PME). Also in paper [6] is presented the influence of the injection timing to the maximum pressure when using 20% of butanol compared to diesel fuel. To the same percentage of recirculate exhaust gas 50% EGR and an injection timing of 1 ^{0}RAC to PMI, the cycle pressure of butanol keeps about the same variation and maximum pressure value compared to diesel fuel.

The soot emission decreases when using 20% butanol in the mixture compared to diesel fuel, the decrease becoming even more significant without using the exhaust gas recirculation. The difference between the soot emission produced when using the diesel fuel and the soot produced when using butanol at the same percentage of exhaust gas recirculation (EGR 50 %) is about 30 mg/m^3.

Regarding NO_x emission, the authors presented in paper [6] how the injection timing influences those emissions before/after PMI. It was found that the

NO_x emissions are null up to an injection advance of ~5 ^{0}RAC with an exhaust gas recirculation of 50 %, when using 20 % of butanol mixed with diesel fuel.

In paper [7] the authors investigate the possibility of fueling the diesel engine with isobutanol with diesel fuel and n-butanol with diesel fuel mixture using the mixtures method. The mixtures used in this study are: 15% isobutanol, 30% of isobutanol, 15% n-butanol and 30% n-butanol. The results showed that the addition of diesel fuel with butanol up to 30% (isobutanol or n-butanol) may lead to the soot particles emissions decrease; moreover it was found that n-butanol produces less smoke particles as isobutanol.

A small percentage of exhaust gas recirculation (less than 25%) can significantly reduce the NO_x emission while maintaining a small increase of soot emissions without a reduction in the fuel economy.

Injection delay may decrease the NO_x emission and soot emission with a small decrease in the fuel economy. The use of butanol (both n-butanol and isobutanol), mixed with diesel fuel leads to the auto ignition delay increase and to smoke emissions reduction compared to diesel fuel.

The combination of the percentage of residual exhaust gas with the injection timing and the butanol concentration mixed with the diesel fuel can achieve the ignition temperature decrease and simultaneously to reduce the NO_x emission and smoke emissions with a small reduction in the fuel economy.

There is an increase in the BSFC when using of both isobutanol and n-butanol compared to diesel fuel. As well, when using n-butanol, the BSFC is slightly smaller compared to isobutanol.

Regarding the CO emission, an increase can be noticed when using the butanol compared to diesel fuel.

If we make a comparison between isobutanol and n-butanol on the CO emission, we find that n-butanol used as fuel mixed with the diesel fuel produces a slight decrease in CO emission compared to isobutanol. The explanation could be the exhaust gas temperature which is higher in the case of n-butanol compared to isobutanol.

Paper [9] shows an experimental study for investigating the influence of butanol content mixed with diesel fuel while maintaining constant the engine speed and the engine load. The percentage of exhaust gas recirculation has been modified so that the NO_x emissions are 2.0 g/kWh. Diesel fuel with various amounts of n-butanol (0%, 5%, 10% and 15% by volume) was used. The results showed that the addition of n-butanol in the diesel fuel can substantially improve the soot and CO emission without a serious impact on the Brake Specific Fuel Consumption and NO_x emission. Early pilot injection reduces the soot emissions, but leads to a dramatic increase of CO emission. Post-injection effectively reduces the soot and CO emissions.

Regardless of the fueling method, the n-butanol content increase mixed with the diesel fuel further leads to the soot reduction.

Also in paper [10] the blends method (BU5 BU10, BU15, BU20 vol.) is presented. The results of the experimental investigations have shown that the smoke's opacity, the NO_x emission and also the CO emissions were reduced, but HC emission increased when the content of the n-butanol is increasing in mixture with the diesel fuel.

Also it was registered an increase in the BSFC and in the thermal efficiency with the butanol content increase mixed with diesel fuel. Regarding the exhaust gas temperature, this decreases with butanol content increase mixed with diesel fuel.

In addition, there is an increase in the BSFC and the thermal efficiency with increasing content of n-butanol in the blends of fuels. Also, the temperature of the exhaust gas decreased with increasing content of n-butanol from the blends of fuel.

2. Experimental investigations

Experimental researches have been carried out on a diesel engine type K9K – 1.5 dci mounted on a test stand presented in figure 2. The engine's characteristics are presented in table 2.

Experimental investigations were performed using the butanol by the blends method in the following volumetric proportions: 10% butanol and 20% butanol. Experimental investigations have been carried out at full load ($\chi = 1$) and with an engine speed of 2000 rev/min. When using butanol, the fuel's dose (butanol-diesel fuel blend) is increased to restore the standard engine power, and injection timing has been optimized from the NO_x emissions point of view and implicitly of the maximum pressure limit from the cylinder.

Table 2

Design and functional characteristics of the K9K engine

Nr. crt.	Parameter	Value
1	Cylinders number	4 in line
2	Bore [mm]	76
3	Stroke [mm]	80.5
4	Compression ratio [-]	18.3
5	Maximum power [kW] / Maximum power speed [rev/min]	52 / 3900
6	Maximum Torque [Nm] / Maximum torque speed [rev/min]	156 / 2000
7	Boost pressure [bar]	1.8

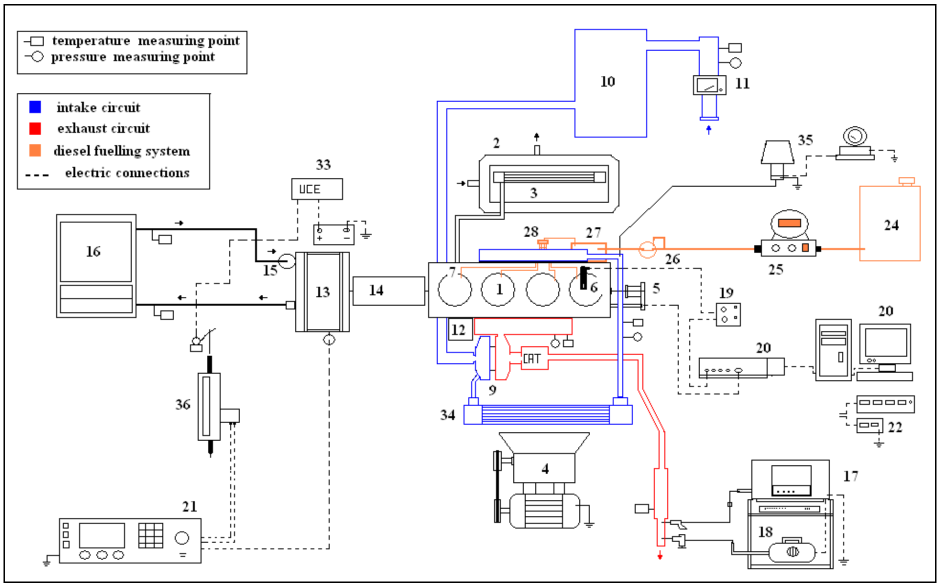

Fig. 2. Test bed scheme

1 – 1.5 dci diesel engine; 2 – engine cooling system; 3 – engine water cooler; 4 – intercooler fan; 5 – engine angular encoder; 6 – AVL piezoelectric pressure transducer; 7 – diesel fuel injector; 9 – Turbocharger; 10 – intake air drum; 11 – intake air flow meter; 12 – exhaust gas recirculation; 13 – Schenck E90 dyno; 14 – dyno-engine coupling; 15 – Schenck E 90 dyno cooling water pump; 16 – dyno cooling system; 17 – AVL Dicom 4000 gas analyzer; 18 – AVL Dicom 4000 Opacimeter; 19 – AVL charge amplifier; 20 – PC + AVL data acquisition system; 21 – Schenck E 90 dyno controller; 22 – temperatures displays: a) – exhaust gas; b) – intake air; c) – engine oil; d) – engine cooling liquid; e) – engine oil pressure; 24 – diesel fuel tank; 25 – diesel fuel mass flow meter; 26 – fuel filters; 27 – high pressure pump for common Rail; 28 – Common Rail; 33 – diesel engine ECU; 34 – intercooler; 35 – supercharge pressure measuring system; 36 – throttle (pedal) actuator

Figures 3...9 present the results of the experimental investigations carried out. Figure 3 shows the maximum pressure on cycle depending on the volumetric diesel fuel substitute ratio (x_c).

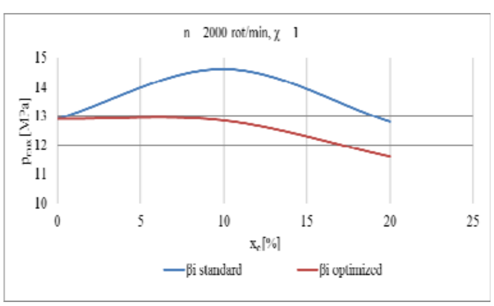

Fig. 3. Maximum pressure depending on the volumetric diesel fuel substitute ratio

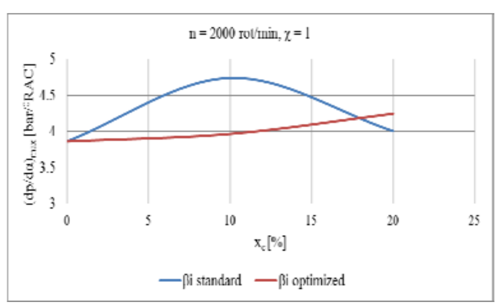

Fig. 4. The maximum pressure rate depending on the volumetric diesel fuel substitute ratio

According to the graph shown in Fig. 3, the maximum pressure in the cycle, to standard injection timing, increased at the use of butanol-diesel mixture, with 10% vol. butanol because of the increase of preformed mixture amount that burns during rapidly combustion phase. Decrease of the maximum pressure for a large percentage of diesel fuel substitution is achieved by a more intensive cooling effect due to vaporization of high amounts of butanol.

By optimizing the injection timing (the use of butanol needs the reduction injection timing to reduce the substantial NOx emissions) the maximum pressure value has been maintained till a percentage substitution of diesel fuel by 10% vol. and then decreased slightly due to amplification of the cooling effect of the vaporization of butanol.

$$COV = \frac{\sigma}{\bar{x}} \cdot 100 \qquad (1)$$

where: COV represents the cyclical variability coefficient of the maximum pressure;

σ – mean square deviation;

$\bar{x}$ – Average.

The cyclic variability coefficient of the maximum pressure by operation with the standard injection timing is: 0.92% for diesel fuel, 0.54% for BU10 and 0.88% for BU20, what indicates a high stability of the combustion process.

In terms of cyclic variability coefficient of the maximum pressure by operation with the optimized injection timing, this decreases both at BU20 (0.69%) and at BU10 (0.51) to diesel fuel.

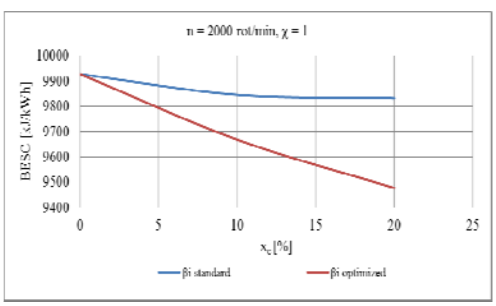

Fig. 5. The BESC depending on the volumetric diesel fuel substitute ratio

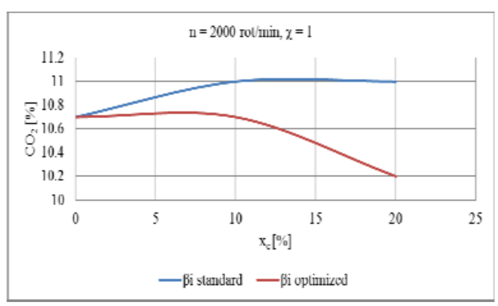

Fig. 6. The CO_2 emission depending on the volumetric diesel fuel substitute ratio

Fig. 4 shows the maximum pressure rate depending on the x_c. When using standard injection timing, the maximum pressure rate increases till $x_c \sim 10\%$ as a result of the amplification rapid combustion phase, and then decreases with the increase of the x_c as a result of amplification of the cooling effect produced on the larger amount evaporation of butanol and the combustion's period increase as a result of the period fuel injection increase. In the case of optimized injection timing the maximum pressure rate presents a slight increase with the x_c increase.

Fig. 5 shows the Brake Energy Specific Consumption (BESC) depending on the volumetric diesel fuel substitute ratio.

One observes a reduction of the BESC as volumetric diesel fuel substitute ratio increases, as a result of the amplification of the rapid combustion phase. The reduction is more pronounced for optimized injection timing.

Fig. 6 shows the variation of the CO_2 emission level by the volumetric percentage substitution of diesel fuel. It is observed that CO_2 emission increased when using butanol compared to diesel fuel for standard injection timing, variation correlated with the specific fuel consumption. When using the optimized injection timing CO_2 emission decreases when using butanol, use compared to diesel fuel, the decrease being more pronounced to the volumetric percentage substitution of diesel fuel increase as a result of the thermal efficiency increase.

Fig. 7 shows the variation of the HC emission level by the volumetric percentage substitution of diesel fuel. It has been observed that HC emission increased with the x_c increase to the use of the standard injection timing. This fact is due to decreasing evaporation speed and implicit by formation of the mixture, determined by high value of the heat vaporization.

For optimized injection timing, the HC emission increase is relatively low when x_c is increasing.

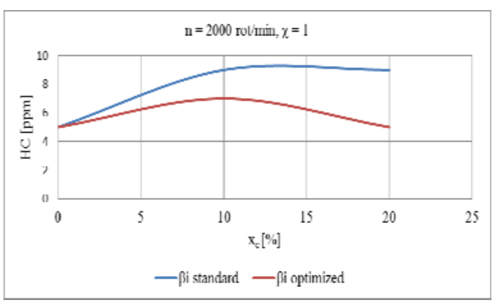

Fig. 7. The HC emission level depending on the volumetric diesel fuel substitute ratio

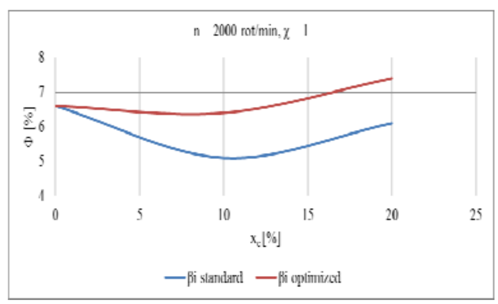

Fig. 8. Smoke opacity depending on the volumetric diesel fuel substitute ratio

Fig. 8 shows the variation of the smoke emission represented by opacity function of the volumetric percentage substitution of diesel fuel. It is observed that for a standard injection timing, the smoke opacity decreases when is using butanol compared to diesel fuel till $x_c \sim 10\%$ vol. and then presents an increase without passing the registered value, for the function with diesel fuel.

The presence of the oxygen in the butanol molecule improves the combustion, which implies a reduction in smoke emission. For the injection timing modified for limit the maximum pressure, gas opacity remains practically unchanged till x_c ~ 10%, after which registers a slight increase with the x_c increase, as a result of the combustion extension in detente through the reduction injection timing and the increase of the injection period.

Fig. 9 shows that the NO_x emission was reduced with x_c increase, the effect being more pronounced with an optimized injection timing for the larger percentages of substitution diesel fuel. The reduction of the NO_x emissions is determined by the cooling effect produced by the evaporation of butanol, and when the optimized injection timing was used (reduced to the standard) the NO_x emission was influencing in a decreasing way.

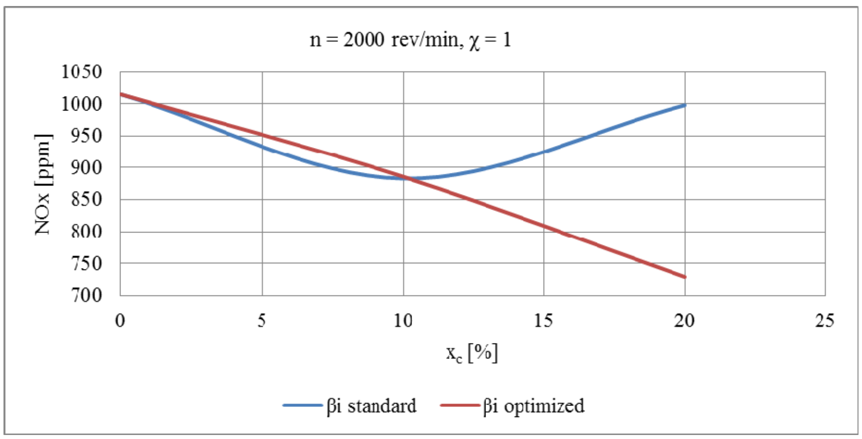

Fig. 9. The NO_x emission level depending on the volumetric diesel fuel substitute ratio

In particular, the fuel that contains a high level of oxygen (butanol) can significantly reduce the smoke emissions.

Experimental researches on the blends method were presented also in paper [8]. The mixtures used in this paper are: 8% butanol, 16% butanol and 24% butanol. Similar results concerning the smoke emission for butanol use mixed with the diesel fuel have been obtained also by the authors of [8].

Improved Brake Thermal Efficiencies (BTE) over the baseline diesel engine and low steady state NOx, HC and CO, together with inherently low PM emissions have been found when supplying the engines with methanol and ethanol. Additionally, if comparing with a similar diesel, considerable system cost advantages are expected from the engine, mostly due to its low-pressure port fuel injection (PFI) system, [12].

The break power experiences a small decrease in the case of blends which contain a percentage of maximum 10% isobutanol. On the other side, it experiences a strong decrease in the case of blends which contain a percentage of 15 and 20% isobutanol. The blend which contains a percentage of 10%

isobutanol slightly increases in terms of BTE at high engine speeds even though the highest BTE is produced by diesel fuel. If comparing to diesel fuel, the results also show that the level of CO and NO_x emission decreases with the use of the blends, while HC emissions significantly increase, [13].

In terms of the CO emission, this is negligible when using butanol in the mixture of the diesel fuel is.

3. Conclusions

Using butanol in the compression ignition engine represents a viable solution for improving the engine performances. Thus, by the increase of the percentage of butanol mixed with diesel fuel for the same power with standard engine, we can formulate the following conclusions:

- Increases the engine's economy with ~5% for BU20;
- Decreases the CO_2 emission level with ~5% for BU20;
- The NO_x emissions level is significantly reduced (with ~20% for BU20);
- The maximum gas pressure into the cylinder slightly decreases, and the variation speed of the pressure increases from the combustion period slightly increases compared to the reference engine;
- Smoke emission level increases due to the necessity to reduce injection timing and implicit the increase of the combustion during. One can continue the research aiming at obtaining the best adjustments so that the smoke emission becomes acceptable.

Using the butanol through the blends method in the compression ignition engine doesn't impose major structural changes of the engine.

In terms of affecting performance and emissions, the results reveal that the fumigation and blends methods have the same behavior. On the other side, using the fumigation method led to a better improvement compared to using blends. 20% is the best percentage for ethanol fumigation. It should be noted that the mentioned percentage results in an increase of 7.5% in BTE, 55% in CO emissions, 36% in HC emissions and in a decrease of 51% in soot mass concentration. 15% is the best percentage for ethanol-diesel fuel blends. The above mentioned percentage results in an increase of 3.6% in BTE, 43.3% in CO emissions, 34% in HC and in a decrease of 32% in soot mass concentration, [14].

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