EFFECTS OF BIOETHANOL ULTRASONIC GENERATED AEROSOLS APPLICATION ON DIESEL ENGINE PERFORMANCES

by

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In this paper the effects of an experimental bioethanol fumigation application using an experimental ultrasound device on performance and emissions of a single cylinder Diesel engine have been experimentally investigated. Engine performance and pollutant emissions variations were considered for three different types of fuels (biodiesel, biodiesel-bioethanol blend and biodiesel-fumigated bioethanol). Reductions in brake specific fuel consumption and NO_x *pollutant emissions are correlated with the use of ultrasonic fumigation of bioethanol fuel, comparative to use of biodiesel-bioethanol blend.*

Considering the fuel consumption as Diesel engine's main performance parameter, the proposed bioethanol's fumigation method, offers the possibility to use more efficient renewable biofuels (bioethanol), with immediate effects on environmental protection.

Key words: *biodiesel, bioethanol, pollutant emissions, ultrasound, Diesel engines*

Introduction

The extensive use of Diesel engines as a power source for transportation, agriculture, industry, and construction owes much to their well-defined advantages, when compared to other internal combustion engines. Diesel engines have a better thermal efficiency, torque, and fuel economy [1-2].

According to [3], the global CO_2 equivalent of greenhouse gas emissions *budget* is less than 750 Gt before reaching the 2 °C global warming limit. In order to achieve the desired limits of pollution alternative energy sources must be considered. Because the transport industry is a major contributor to global warming a lot of effort is put into developing environmental-friendly vehicles. As a means to impact the whole vehicle park, research and development projects must also include fuels. This paper focuses on the superior use of bioethanol as renewable energy source for Diesel engines running in dual-fuel mode, using a novel fumigation technique.

Kujawski and Zielinski [4], Dincer [5], and Nag [6] shown that the renewable characteristics of biofuels can partly replace fossil fuels, and may help reduce green-house gas emissions (CO_2, N_2O and NO_x), promote a sustainable rural development and improve income distri-

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bution. Biofuels ability to reduce greenhouse pollutant emissions is due to the presence of oxygen in their molecular composition. The oxygen content contributes to better air-fuel mixture combustion, leading to reduced emissions [7, 8].

However, a better fuel burning process leads to an increase in NO_x pollutant emissions. The NO_x emission formation mechanism strongly depends on the combustion temperature and the oxygen concentration. As a direct consequence, the formation rate will decrease if the in-cylinder combustion peak temperature is reduced [9-12]. The complexity and high number of factors influencing the combustion process, Johnson [13] show that NO_x emissions are more difficult to control than other pollutants. The peak temperature in the cylinder can be reduced with multiple injection strategies, the use of exhaust gas re-circulation technique and/or using ethanol or an ethanol-water emulsion as an additive to the fuel [14, 15].

Bioethanol is a renewable energy source made of plant materials. First generation bioethanol is produced by distillation from crops such as corn, wheat, sugar cane and sugar beet. Improved technologies have made it possible to produce non-food competitive second-generation bioethanol (cellulosic ethanol) from a wider range of feedstocks including agricultural residues, energy crops or woody raw material [16].

Bioethanol (ethanol) combustion in Diesel engines represents a challenge due to its significantly different properties compared to diesel fuel: poorer ignition properties (low cetane number), higher heat of vaporization, higher oxygen content, lower stoichiometric A/F ratio, lower heating value, and higher H/C ratio. However, with altered fuel characteristics and adequate engine adaptations or a modified combustion process, it is possible to take advantage of its more efficient compression ignited, compared to spark ignited, combustion [17]. Nowadays, there many solutions for using (bio)ethanol in Diesel engines like: direct injection of alcohol-diesel fuel blends, fumigation, glow-plug assisted ignition or addition of ignition improvers, each of them with its own constraints and challenges to overcome [17-19]. The main problems are: ethanol-diesel fuel miscibility, combustion control and the amount of engine modifications required [20]. More and more researchers are focusing their studies on dual fuel technologies for Diesel engines. In the following, some of the most recent researches in this field are presented briefly.

Hansdah and Murugan [21] studied the effects of fumigating ethanol obtained from *maduca indica* flower and was determined that the ignition delay increases for all of the studied flow rates by about 2-4 °CA at full load. Compared to normal diesel fuel operation, NO_x and smoke emissions were lower while CO and HC emissions slightly increased. The study also revealed an increased brake thermal efficiency.

Imran *et al*. [22] published a review of the literature concerning ethanol use in Diesel engines. The study concluded that break specific fuel consumption (BSFC) increases when using alcohol fumigation, which can be attributed to the lower calorific value of ethanol. The thermal efficiency with ethanol fumigation in Diesel engines is lower than that of diesel at low loads but at medium and high loads it surpasses it. The results regarding NO_x emissions compared to neat diesel varied between cited authors, but a common conclusion was that NO_x formation strongly depends on the combustion temperature and the oxygen concentration present in the combustion process. All cited authors reported an increase in HC and CO emission believed to be a cause of the lower combustion temperature. On the other hand, CO_2, smoke, and PM emissions significantly reduced.

Fraioli *et al*. [20] focused on the distribution and temporal evolution of chemical intermediates like OH, HCO, and CO in the combustion chamber and is influence on the combustion process. Was determined that ethanol fumigation causes wider auto ignition areas, a slower rate of heat release and an increased combustion duration with respect to a direct injection n-heptane reference case.

The tests performed by Gargiulo *et al.* [23] lead to the conclusion that ethanol fumigation is very effective for reducing the number of emitted particles and that the chemical-physical characteristics of soot vary with the amount of injected ethanol.

Sarjovaara *et al.* [24] tested the influence of charge air temperature on combustion for an engine running with E85 fuel fumigation and direct diesel fuel injection at 1500 min^{-1} for two different loads. A major conclusion was that the maximum acceptable rate of E85 fuel decreased with charge air temperature. In comparison to normal diesel fuel operation, ignition delay increased, except for higher loads, and air temperatures, where E85 fuel auto-ignition occurred. The NO_x emissions decreased at low loads but increased at higher loads. The total hidro-carbon (THC) and CO emissions where slightly higher for all operating regimes, in contrast to smoke number which was lower in all cases.

Goldsworthy [25] tested the use of aqueous ethanol fumigation in a heavy-duty marine Diesel engine with two-stage injection operating at constant speed, for two different loads. It was observed that with ethanol addition, the injection is retarded by the electronic control unit (ECU) and that early combustion rates increase, which translates into a slightly improved thermal efficiency. The CO emissions increased during these tests except for low loads and moderate ethanol rates up to 10% energy content. The NO_x emissions performed as expected and decreased with the addition of ethanol. It was noted also that for an ethanol content in energy higher than 30%, knock phenomenon occurs.

Testing ethanol-water mixtures fumigation in a single cylinder engine, Morsy [26] noted that NO_x emissions and exhaust temperature decreased with the addition of ethanol-water mixtures except for pure ethanol. The CO and HC increased for all of the performed tests. Due to the lower energy content of ethanol, the BSFC increased but was noted a small improvement of thermal and exergy efficiency.

Bodisco and Brown [27] investigated inter-cycle variability of in cylinder pressure parameters in an ethanol fumigated common rail Diesel engine. Their study showed that substitutions by energy content up to 30% at full load and 20% at half load have only a minimal effect on the pressure parameters and the inter-cycle variability. At full load, higher ethanol substitutions lead to a decrease of the ignition delay and an increase in the inter-cycle variability.

Based on previous experiments it can be concluded that the general tendency when using ethanol fumigation in Diesel engines is that NO_x and PM emissions decrease while HC and CO pollutants emission increase [14, 28-31]. Few of the presented studies highlighted and some even minimized the importance of the major disadvantages of ethanol use in CI engines:

- the necessity of a separate fueling system and the associated control and command devices (with associated economic costs),
- the corrosive effect of ethanol,
- for values above 15% ethanol in blend, ethanol-biodiesel (diesel) blends are unstable,
- the use of anhydrous ethanol with high purity (99.2-99.6%) requires supplementary technological operations (and also a higher energy consumption), and
- the low cetane number and lubricity (lubricating characteristics) of ethanol.

To eliminate those shortcomings, the present paper proposes a new approach regarding the ethanol fumigation process. Based on previous experiments [32] that studied the effect of external energy (ultrasonic and microwave irradiation) on IC engines performance fueled with biofuel blends, a new evaporation process was proposed involving a device that performs an almost instant evaporation of bioethanol using ultrasounds. The application of ultrasound energy to the vegetable oil and in biofuel causes cavitation (under specific conditions). This is because the expansion and contraction of the transfer media create the conditions necessary for generating local droplets of very high temperature and pressure (instantaneous vaporization due to the cavitation process). Depending on the specific conditions of the ultrasonic process, the so formed droplets can be converted into a fine mist, using a current of air.

Figure 1. AVL 5402 engine test bed
1 – AVL 5402 research engine, 2 – DynoRoad 202 dyno, 3 – ECU AVL RPEMS ETK7 engine management system, 4 – FTIR equipment for pollutants analyse, 5 – AVL visioscope system, 6 – AVL 577 engine oil and coolant conditioning unit

Material and methods

To study the effect of ultrasonic fumigation of bioethanol on the performance of a DI Diesel engine and the resulting pollutant emissions characteristics, an experimental AVL 5402 optical DI Diesel engine test bed was used (fig. 1). The 5402 AVL engine is an experimental, four-stroke, common rail DI mono-cylinder engine, which has the main characteristics presented in tab. 1. The IC engine testing cell consists of an engine dynamometer, which is coupled to a research engine and related equipment. The DynoRoad 202 dynamometer is an asynchronous (AC) machine equipped with a converter power module insulated gate bipolar transistor (IGBT) for direct connection to the voltage power source. The power module uses a hybrid interface that facilitates control over engine torque and speed.

Table 1. Technical characteristics of the AVL 5402 engine

Parameter	Value	U.M.
Type	4-stroke, vertical single cylinder	–
Bore × Stroke	85 × 90	mm
Displacement	510.7	cm^3
Combustion type	DI single injector	–
Continuous rating output	6 (at 4200 min^{-1})	kW
Fuel injection pressure	1800	bar
Compression ratio	17.5 : 1	–
High pressure system	Common Rail CP4.1 Bosch	–
Engine management system	AVL-RPEMS + ETK7 Bosch	–
Cylinder pressure	50	MPa
Inlet valve open	8	° bTDC
Inlet valve close	226	° aTDC
Exhaust valve open	128	° aTDC
Exhaust valve close	18	° aTDC

The electronic control equipment consists of an AVL RPEMS management system comprising the electronic control unit ETAS ETK 7.1 and a CAN interface data bus. Engine load is controlled using the AVL throttle actuator control and the drive of the actuator. Lubricating oil and engine coolant conditioning is performed by the AVL577 conditioning unit, which controls the flow, temperature and pressure of both fluids set in the Puma Open operating system (control panel).

The AVL 735 measures the hourly fuel consumption and allows the conditioning of the fuel temperature.

Pollutant formation processes and emission intensity inside the combustion chamber were optical recorded and analyzed using AVL visioscope and AVL fourier transform infrared (FTIR) equipment. The AVL visioscope system provides optical access in the combustion chamber, which allows the investigation of the injection and combustion processes. The system incorporates the latest image recording technology in the field of internal combustion engines, and gives the possibility of optical investigation and recording of the phenomenon inside the engine cylinder (for *e. g*. flames temperature inside the combustion chamber and pollutants formation process).

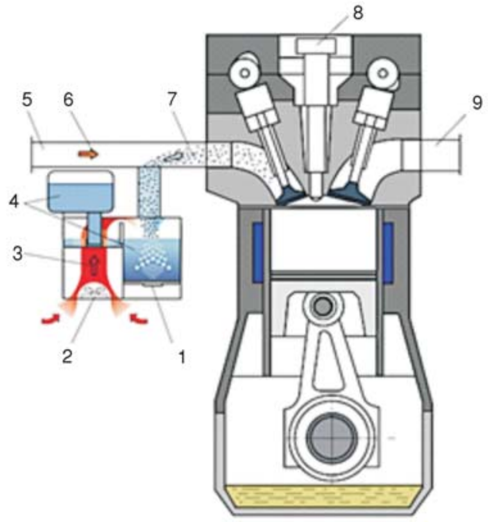

Figure 2. Schematic principle of ultrasonic fumigation process:
1 – ultrasonic emitter, 2 – fan, 3 – air, 4 – bioethanol, 5 – intake pipe, 6 – intake pipe air stream, 7 – fumigated bioethanol, 8 – fuel injector, and 9 – exhaust pipe

The experimental ultrasound based instantaneous fumigation system was manufactured by modifying a low-power ultrasonic electronically controlled air humidifier AOS 7146 type (Plaston AG, Swiss), 25 W power, 35 Hz frequencies, 24/220V AC. A plastic pipe (Polytetrafluoroethylene high density, 10 mm long, 30 mm in diameter) connected the exhaust orifice of the ultrasonic device with the engine's air intake manifold. The connection pipe was positioned at 30 mm ahead of the engine's inlet manifold. This positioning offered the advantage that the fumigated fluid was uniformly mixed with the intake air and reduced the possibility of condensation in the air intake pipe. The fumigated bioethanol mass flow was measured (and controlled) using a system consisting of an electronic weighing scale (Kingship GEW 6 type) coupled with an electronic timer. Using the engine test bed electronic control panel interface, the power of the ultrasonic emitter (fumigation intensity) was correlated with the open position of throttle valve (fig. 2).

The experiment focused on achieving the same quantity of fuel inside of combustion chamber taking into account the particularities of the used fuels and the different fueling methods. The mass flow of fumigated bioethanol was correlated with engine's loads regimes using the control and operating panel. The engine management system (ETAS ETK 7.1 with open ECU) allows modifications of the injection maps and therefor, the injection of a reduced quantity of fuel for the biodiesel injection + fumigated bioethanol (B5FE) experimental case. Detailed methodology is described in previous works of authors [33] and specific engine's management maps are presented in fig. 3.

In accordance with mandatory EU directives, a mixture of minimum 5% by volume of diesel mineral fuel and biodiesel (methyl ester) is sold at gas stations. So, what users usually call as *diesel fuel* is actually a blend of 95% diesel fuel and 5% methyl ester (biodiesel). The experimental works considered three types of fuels: B5 (diesel fuel + 5% rapeseed methyl ether biodiesel), B5E15 (95% BD fuel + 15% bioethanol blend), and B5FE (BD fuel + fumigated bioethanol). Physicochemical properties of the fuels used in the experiment are presented in tab. 2, and the bioethanol fuel is grain based and produced by a double distillation process.

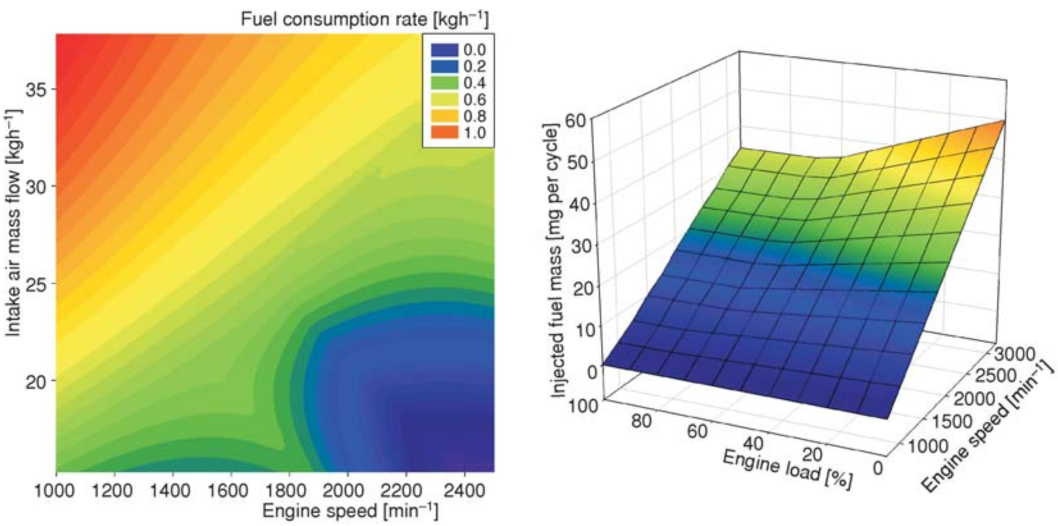

Figure 3. AVL 5402 engine's management maps for B5 case

Table 2. Physico-chemical characteristics of the tested fuels

Parameter	UM	Fuel		
		Bioethanol	B5	B5E15
Lower heating value	MJ/kg	28.60	42.38	40.27
A/F ratio	–	9.00	14.47	13.64
Density (at 20 °C)	kg/m^3	789.00	842.52	834.83
Carbon	%	52.14	86.03	80.88
Hidrogen	%	13.13	13.43	13.37
Oxigen	%	34.73	0.54	5.75
Molar mass	g/mol	46.07	213.23	188.80
Viscosity	mm^2/s	1.04	2.81	2.56

As the engine's manufacturer recommends, the measurements were taken after the engine warm-up period, when the engine enters the steady--state operating mode. The engine was run at the constant speed of 1800 min^{-1} while the dynamometer was used to load the engine. Engine loads at 20, 40, 60, and 80% correspond to 0.12, 0.22, 0.34, respectively, 0.42 MPa of brake mean effective pressure. The experimental tests were performed ten times for each considered fuel at each considered engine loads, and the results of those repetitions were averaged to reduce the level of uncertainty.

Results and discussion

To compare the performances of the three different fuel types in the Diesel engine, the BSFC was considered as the main comparison parameter. As seen in fig. 4 the measured values of BSFC decreased with increasing engine load for all tested fuels. That trend was expected since there are differences of heating value of biodiesel (B5), biodiesel-bioethanol blend (B5E15), and B5FE fuels. The average differences of BSFC parameter for B5E15 blend and B5FE fuel is with +13.4% and +5.0%, respectively, higher than in B5 case. This is due to the more specific homogeneity of A/F mixture (for ultrasonic fumigated bioethanol), and also because the amount of the bioethanol inside of combustion chamber play an important role in the combustion phasing and combustion rate. It is generally considered that a rapid rate of heat is released (due to the increase of the ignition delay), with immediate effects on reducing the heat loss from the engine to the cylinder (and further, to the engine coolant) [21, 26]. A small quantity of the bioethanol will be consumed in the premixed combustion phase (during the early part of the biodiesel combustion process) and further, the remnant bioethanol is burned later in the combustion process as it continuous mixes with the formed hot products (in the expansion stroke) with direct influence on rate of heat release quantity during an engine cycle [25].

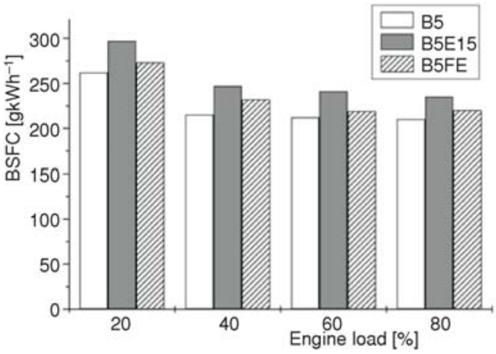

Figure 4. The BSFC *vs.* engine loads

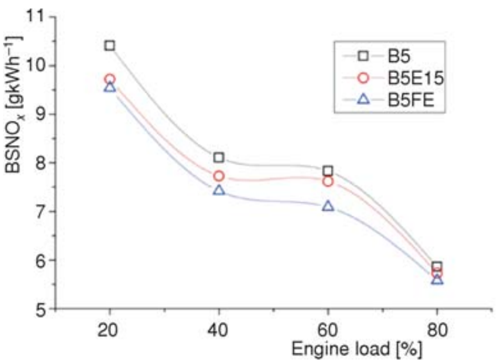

Figure 5. NO$_x$ emissions *vs.* engine loads

The pollutant emissions considered in the experimental tests were NO_x, CO, and THC. The results are presented in figs. 5 to 9.

The chemical reactions between nitrogen and oxygen that cause the formation of NO_x are possible only at high temperatures. The effect of the fumigated bioethanol on reducing the peak temperature in the ignition and combustion process is responsible for lower NO_x emission production (fig. 5). This effect is possible due to the intense latent heat of evaporation for bioethanol (in-cylinder temperature at the end of compression stroke drop substantially). A maximum (and major) reduction of 9.45% was achieved for 60% engine load, and the average reduction (for all considered loads) was –8.01%, respectively, –4.37% for B5E15 fuel comparative to B5 fuel. The temperature reduction inside of combustion chamber (and consequently as direct effect on NO_x formation process) using ultrasonic bioethanol fumigation technique is presented in fig. 6 using captured optical images from combustion chamber.

The effect of combined processes is responsible for higher CO emissions using fumigated bioethanol. The combustion parameters (the ignition delay, the latent heat of vaporization process and combustion duration) lead to lower engine cycle temperatures, with the effect of an inhibited oxidation process of CO to CO_2. The cooling effect of bioethanol vaporization inside the combustion chamber can also be responsible for increased CO production.

The increase of engine loads increases also the CO emissions level (fig. 7), data confirmed by experimental investigations done by other researchers [14, 29, 31, 32, 34]. Comparatively, the average emission of CO pollutant for the fumigation process (B5FE case) is with +4.34% higher than that in the case of the blended fuel B5E15, and also with +22.3% higher than in the case of the B5 fuel. The lowest values of CO emission for tested fuels were obtained for 40% engine load case, and the higher values of CO emissions for higher engine loads confirm the effect of engine load on CO pollutant production.

In case of THC emission the major reasons for production in case of bioethanol use are the slow rate of vaporization and the possibilities of biodiesel-bioethanol mixture positioning in

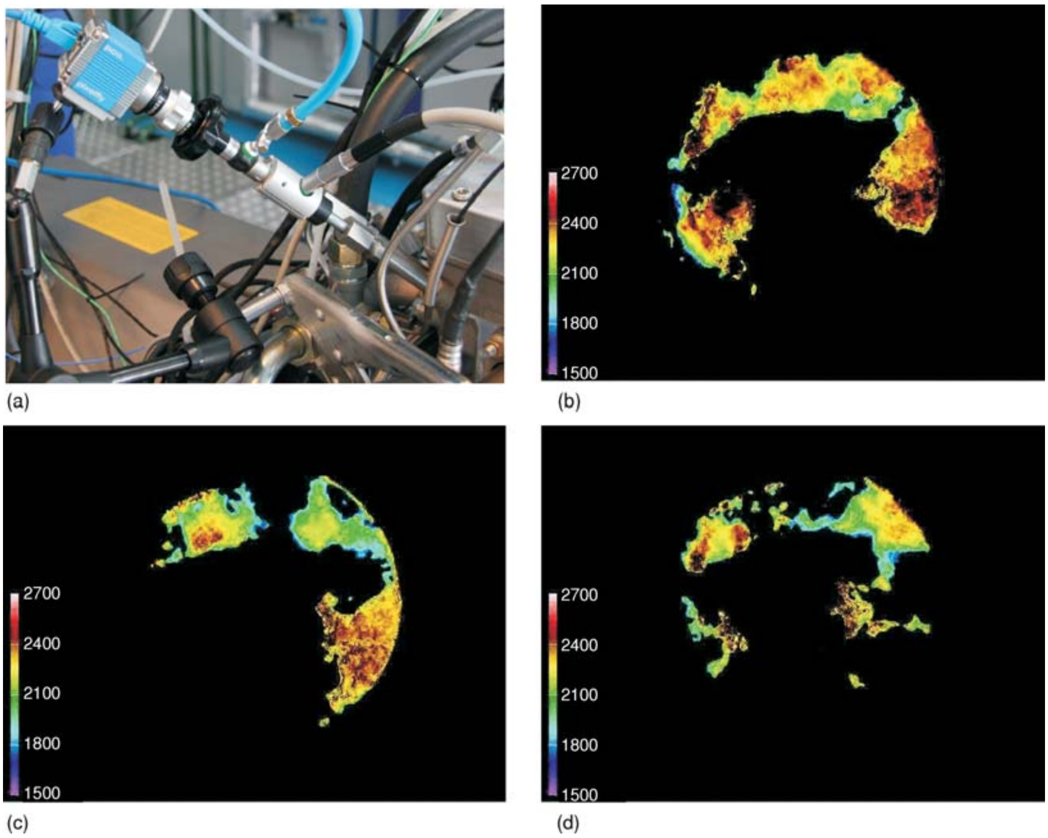

Figure 6. Thermal images of combustion process for considered fuels at 8 °CA aTDC; (a) Visioscope equipment, (b) B5 case, (c) B5E15 case, (d) B5FE case

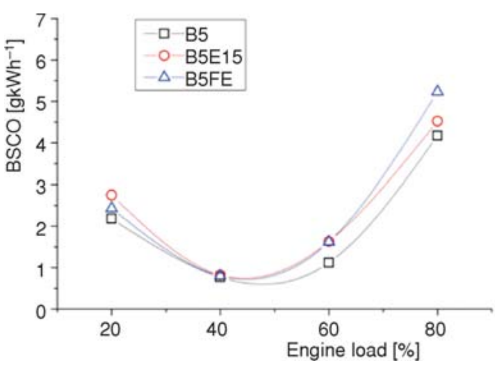

Figure 7. The CO emissions *vs.* engine loads

available spaces between the piston, liner and piston top ring during the intake and compression strokes. At can be see in fig. 8, some bioethanol mixture or liquid droplets were trapped inside the crevice during the intake and compression strokes prior to diesel injection and react with pumped lubricating oil inside of combustion chamber. Further, the burn of this mixture (bioethanol and lubricating oil) increase THC emissions.

Beside those factors, the lowered combustion temperature caused by the bioethanol vaporization also leads to incomplete combustion of fuel (especially near the walls of the combustion chamber) and thereby also can causes increased THC emissions (fig. 8). Due to their poor ignition properties, these mixtures are partially oxidized during combustion process, and the unburned products are discharged from the cylinder leading to a high THC level. It is also possible that, during the valve overlap duration, a small amount of unburned bioethanol may directly escape into exhaust gases, where start a diffusive combustion process and increase of THC emission measured at the exhaust tail pipe end.

Still, the THC emissions production decrease with the increasing of engine loads for all considered fuels, due to a rapid vaporization rate of bioethanol caused by higher thermal load of cylinder. Comparative, the average experimental results shown that THC pollutants are with 12.3% (for B5FE) and 14.2% (for B5E15) higher that in the case of using B5 fuel (fig. 9). For small loads the THC emissions present major differences between fuels but with increasing of engine loads the values have relative same values (for 60 to 80% engine load regimes).

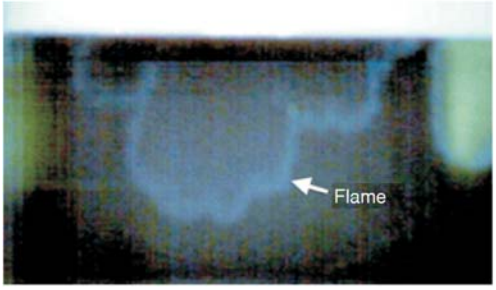

Figure 8. The bioethanol-lubricating oil mixture burning process in spaces between piston, liner, and piston top ring

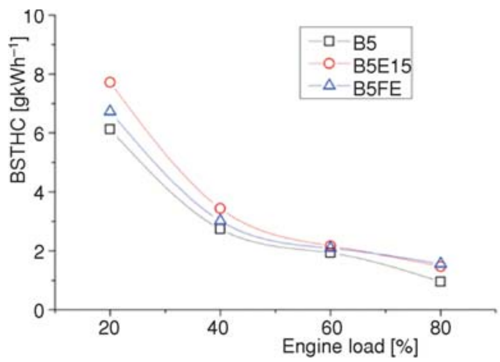

Figure 9. The THC emissions *vs.* engine loads

Conclusions

This paper presents an experimental study of the effects of bioethanol fumigation (as form of aerosols) on the performance (BSFC) and pollutant emissions of a DI single cylinder Diesel engine. The proposed fumigation method is based on the possibilities to intake into engine cylinder a quantity of bioethanol in form of ultrasonic generated aerosols.

Based on the results from the experiments, the following major conclusions and observations can be drawn.

- A simple and easy to use device was developed to realize the fueling fumigation process in form of aerosols, for a dual-fuel DI Diesel engine.
- The use of bioethanol as aerosols form in Diesel engine fueling process offers a major reduction of NO_x (when compared to biodiesel and biodiesel-bioethanol blend fuels). Water from the bioethanol enters the combustion chamber and lowers the combustion process peak temperature, causing a decrease of NO_x emissions. Strong correlation with the results from the literature was achieved, in conditions of a using this novelty fumigation fueling technique.
- The use of modern investigation apparatus offer the possibility to highlight the effects of mixture positioning in available spaces between the piston, liner and piston top ring on THC pollutant's formation and production.
- When compared to the B5E15 blend, the proposed fumigation procedure using ultrasound-generated aerosols (B5FE) leads to reduced BSFC (–7.45%), a decrease in NO_x (–3.8%) and THC (–1.63%) pollutant emissions while the level of CO (+11.1%) emissions increase.

- Further experiments are necessary to determine the effects of bioethanol ultrasonic generated fumigation technique on particulate emissions.

Acknowledgment

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