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THE USE OF MODERN FUELS IN DIESEL ENGINES OF THE OLDER GENERATION

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Summary: *Intensive development of diesel engines over the past 25 years, has significantly improved their operating and environmental characteristics. The application of advanced diesel technology has set specific requirements in terms of the characteristics of diesel fuel. Both market requirements and legislation introduced new formulated diesel fuel. However, in our country is still in use a large number of outdated engine, particularly in the areas of agricultural and non road vehicles, military techniques ... This paper discusses the effect of changing the essential characteristics of the fuel on the working process and lifetime of these diesel engines. The results of the experimental research of working process diesel engine DMB 3DA450 with diesel fuel according to EN 590 (2005) are presented.*

Key words: diesel fuel, fuel propertis, diesel working process

1. INTRODUCTION

Starting from early 1990's EU introduced number of more and more stringent regulations regarding emission from diesel engine powered vehicles. In the table 1 is presented decrease of limit velues of emission in actual EURO VI, compared to reference EURO I (1992-94) regulations. In 1999 is intoduced regulations regarding emission form out-of-road diesel engines (Stage I-IV). Fulfillment of this requirements was achieved by application of advanced diesel technologies and fuel characteristics improvement.

First step toward harmonisation of standards was made by introduction of quality norm for diesel fuel SRPS EN 590:2005 (level EURO 4). Intending to bridge technological obsolescence of the road fleet, Serbia's goverment restricted import and first registration to vehicles fullfiling requirements defined by EURO 3 at least.

Accordingg to official data for 2013 year, in Serbia was 1 920 000 registered wehicles for public transportation (without motorcycles) [1]. There are no available data about age structure of those vehicles, but estimation is that 30% is older than 15 years. Also, there are a lot of agricultural machines (40 000 tractors, 20 years old in average)

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and military vehicles (?) not registered for public ransportation. Market share of 20% of D2 and bio-diesel fuel on domestic market in first half of 2013 [2] is indication of vehicle age (illegal use of heating oil and home made bio-diesel are not included).

Table 1 *Decrease of emission limit values in EURO VI compared to EURO I or III level*

	Test	CO	HC	NO_x	$HC+NO_x$	PM
Passanger cars Category M	EDC	5.44x	-	-	5.40x	28x
Light duty vehicles:						
Category N1-I (≤1305 kg)	EDC	5.44x	-	*) 6.25x	5.7x	28x
Category N1-II (1305 kg÷1760 kg)	EDC	8.20x	-	*) 6,16x	7.2x	38x
Category N1-III & N2 (1760 kg÷3500 kg)	EDC	3.04x	-	*) 6.24x	7.9x	50x
*) **Heavy duty vehicles & Busses**	ESC&ELR	1.4x	5.8x	12.5x	-	10x
	ETC	1.36x	4.87x	12.5x	-	16x
*) *ref. level EURO III (2000)*						

Starting of august 2013 there is no more diesel D2 fuel on the market. For special consumers groups (agriculture, rail transport, industrial equipment and military vehicles) low-sulfur replacement GasOil 0.1 was introduced.

Diesel engines of old technology were made and adjusted to work with fuels of old formulation. Changes of some of characteristics could be have negative impacts on this category of motors. In this paper is presented analysis how change of important fuel characteristics influence performance, efficiency and lifetime of an old engines. Also, there are results of investigation of use of EURO III fuel (trade name NIS EKO-3 diesel) on small agricultural engine DMB 3DA 450 module 328.

2. APPLICATION OF MODERN FUELS IN OLD TECHNOLOGY ENGINES

High driving and emissions performances are achieved by application of advanced diesel technologies:

- high turbo-charging (3÷4 bar) with inter-cooling (2÷3 turbo groups and/or variable geometry turbines),
- electronically controlled recirculation of cooled exhaust gasses (up to 40%),
- electronically governed high pressure injection system (> 2000 bar),
- exhaust gasses after treatment.

Combustion process control, measures to reduce raw emissions and the application of sophisticated exhaust gas after treatment, they set more stringent requirements to fuel quality. Comparative characteristics of fuel "old" and contemporary formulations are shown in Table 2.

Biodiesel fuels based on FAME are a good substitution of oil-based fuels. Its characteristics are standardized (EN ISO1421) and is available on the market. Manufacturers him often recommended as an alternative. Consumption of biodiesel in the Republic of Serbia in the first half of 2013 was primarily happens 1.21% [2].

Table 2 *Comparasion of selected characteristics of old and contemporary diesel fuels*

Property	Unit	FUEL STANDARD				Test Method
		SRPS B.H2.410	EN590:1999	EN590: 2010	EN2869: 2010	
		D2	EURO 3	EURO 5	GasOil 0,1 cl.D	
Density @ 15 °C	kg/m³	810÷860	820÷845	820÷845	min. 820	EN ISO 3675
Viscosity @ 40 °C	cSt	(@20°C) 1.8÷9	2÷4.5	2÷4.5	1.5÷5	EN ISO 3104
Cetane Numb. min	÷	45	51	51	45	EN ISO 5119
Cetane Index min	÷	n.r.	46	46	45	EN ISO 4264
Sulphur max	mg/kg	10000	50	10	*)1000	EN ISO 20846 *) ISO 8754
PAH max	% Wt.	n.r.	11	8	n.r	EN ISO 12916
Didtillation: % Vol. @ 250 °C % Vol. @ 350 °C 50 % Vol. 95% Vol.	 °C °C	 n.r. 90%/360°C n.r.	 max. 65 min. 85 max. 360	 max. 65 min. 85 max. 360	 max. 65 min. 85 240÷340 n.r.	EN ISO 3405
Lubricity WSD	μm	/	max. 460	max. 460	max. 460	EN ISO 12156-1
Residue Wt on 10%	÷	max. 0.3	max. 0.3	max. 0.3	max. 0.3	EN ISO 10370
Ash max.	% Wt.	0.02	0.01	0.01	0.01	EN ISO 6245
FAME max.	% Vol.	/	5	7	7	EN ISO 14078

2.1 Sulphur content

This charasteristic is subject to the strictest restrictions. Since the introduction of standard EN 590, the sulfur content has been reduced with the following sequence: 2000 ppm (1993), 350 ppm (1999), 50 ppm (2004), 10 ppm (2010). The main reason is that the hydrated sulphate, created by combustion, directly generate particles (up to 30% for engines and fuels of the older generation). The application of modern exhaust gases after-treatment technology requires ultra-low-sulfur fuels (<10 ppm), primarily due to the efficiency and durability of oxidation catalyst and particulate filter.

For the older generation engines low sulfur fuel favorably affects the life of motor oil and particulate emissions. Removing sulfides, disulfides and mercaptans of olefin base greatly deteriorates lubricity of diesel fuel, which threatens the durability of injection equipment. Diesel fuel D2 manufactured by NIS "Rafinerija Pančevo" tipically have 0.27% sulphur content. Permissible sulphur content in fuel GasOil 0.1 presented in the table 2 is about three time lower. This value can be easily achieved by using modern methods of refining.

2.2 Polycyclic aromates content (PAH)

Diesel fuel old technology had over 20% aromatics. This group of hydrocarbons, especially polycyclic aromatics (PAH), are responsible for the increased emission of HC, NOx and particulate matter and making coke deposits in the engine. At low engine loads unburt PAH are absorbed in the particles, giving them carcinogenic properties. Existing technologies for the conversion of aromatics to prescribed amounts simultaneously removes sulfur and nitrogen, and comes to an increase in cetane number (CB) [3].

Aromatic hydrocarbons have a high C/H ratio and density. Their removal reduces the calorific value which is manifested by a slight decline in the maximum engine power. It is indicative that in GasOil 0.1 is not limited to the contents of PAH, as well as diesel fuel D2.

2.3 Flammability - cetane number (CN) and cetane index (CI)

Optimisation of burning process for economy and raw emission require fuel with improved flammability (CN≥51). Technological measures for decrease of sulphur and aromate content increase CN for 3-5 units, and if it is not sufficient- nitrate additives are applied. Flammability of diesel fuel can be estimated using cetane index (CI). Basically it is correlation between flammability and certain physical characteristics of diesel fuel. It is applicable only to oil based fuel without additives for flammability improvement.

Improved flammability helps cold starting of old generation motors. Significant increase of CB can produce mechanical overload of engine (maximum pressure approaches TDC). Deterioration of burning efficiency is possible at high load regimes, if last amounts of fuel are injected in already formed flame (engine intensively produce smoke).

Application of diesel fuel with CB>51 to old generation motors requires optimisation of injection parameters – most importan is angle of preinjection. Investigations conducted on tractor motors produced by IMR [4] showed potential of 2-10 % fuel economy improvement.

Biodiesel based on methyl esters of fatty acids (FAME) have good inflammability characteristics. The standard requires CB> 51. However, CN of biodiesel depends on the raw material base, and even of his age. Calorific value of biodiesel is slightly less than the fuel oil origin. Our tests have shown that biodiesel from soybean oil has a CN = 55, and the lower calorific value Hd = 36220 $kJ \cdot kg^{-1}$. It is obvious that optimisation of injection parameters (injestion timing, maximum cyclic amount of fuel, injecor opening pressure) is desirable.

GasOil 0.1 have similar inflammability characteristics to diesel fuel D2, and change of injection parameters is unnecessary.

2.4 Viscosity

Contemporary injection systems are characterised by high pressures and rate of injection, multiphase injection and adaptive process control. Fuel viscosity is characteristics affecting injection resistance and fuel atomisation, so this parameter must be held in tight tolerances.

Old generation motors mostly use injection system *pump→pipe→injector*, with volumetric metering of cyclic fuel amount. Injection pressure decreases with both load and speed. At those regimes low viscosity of hot fuel deteriorate fuel atomisation. Drop of viscosity bellow 1,5 mm^2s^{-1} threatens stability of boundary layer between friction elements, leading to increased wearing of fuel pump.

2.5 Volatility

Diesel fuel volatility depends on its fractional composition, and is defined by the distillation curve. Typically, the start of the distillation of the diesel fuel is about 180°C. The volatile components are limited because of possible cavitation in the injection system and poor penetration of the fuel spray. End of distillation temperature is prescribed because that limit amount of heavy hydrocarbons, which reduces HC emissions.

There is no defined end of distillation limit for GasOil 0.1, but it is defined range of temperatures for distillation of 50% of the sample.

2.6 Content of Fatty Acid Methyl Esters (FAME)

FAME content limit of 7% in modern diesel fuel is a compromise between improving lubricity and deterioration of the oxidation stability of the fuel. The tendency of a mixture of diesel fuel and FAME to polymerization limits their useful life (unsuitable for the long-term storage and strategic fuel reserves).

2.7 The use of biodiesel fuel in old technology engines

The use of biodiesel fuel for engines of the older generation, especially uncontrolled quality (home made production), may have a negative effect on the fuel system [5]:

- fuel leak due to the incompatibility of gaskets (elastomers based on nitrile)
- corrosion of elements of the fuel system made of Al-Zn alloy due to the presence of free fatty acids, methanol and organic acids resulting from the aging of the fuel
- injector coking and blocking due to the presence of glycerin and complex sodium and potassium compounds
- shortening century fuel filter due to the presence of mono and poly glycerides (glyceride), salts of organic acids as well as products of biodegradation
- failure of the high pressure pump because of mechanical overload at low temperatures and deposits at the pump elements.

2.8 Lubicity

Lubricity is tribological characteristic of diesel fuel, essential for the durability of injection equipment. Modern injection systems are exposed to very high both mechanical and thermal stresses. These systems are the state-of art of mechatronics and materials technology.

Lubricity is estimated by HFRR (High Frequency Reciprocating Rig) method. Figure 1 shows the schematic of the method with the basic parameters. Lubricity is determined by the mean diameter of wear on the test balls, WSD (Wear Scar Diameter). As seen in Table 2, the norm is set to WSD <460 µm.

Fuel old formula did not have a problem with lubricity, so this feature is not prescribed by the standard. The high content of sulfur in the form of sulfides, disulfides and mercaptans olefinic base, alkyl thiophene derivatives, benzothiophene and dibenzothiophene was providing excellent lubricity. Along with the introduction of low-sulfur fuel, market have emerged lubricity improvers. Apparently that lubricity of modern fuels does not correspond to the needs of the older generation engines.

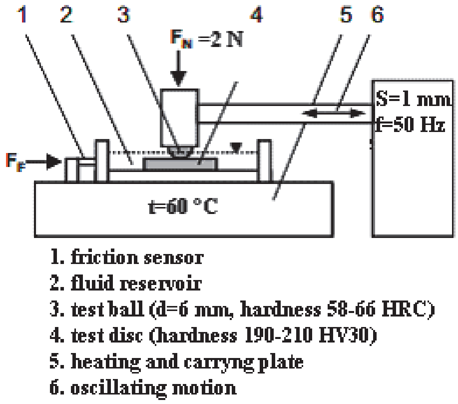

Fig. 1 *Schematic HFRR method*

Raw ultra-low sulfur fuel has a very poor lubricity (WSD> 600 μm). Meeting the standard requirements is achieved by additives based on esters and amides in low concentrations ≈200 ppm (Fig. 2). It is interesting that the additive concentration-enhancing at 1000 ppm does not result in a proportional improvement of lubricity. FAME have excellent effects on the lubricity. Already at a concentration of 5%, with no special additives, lubricity is achieved twice the norm.

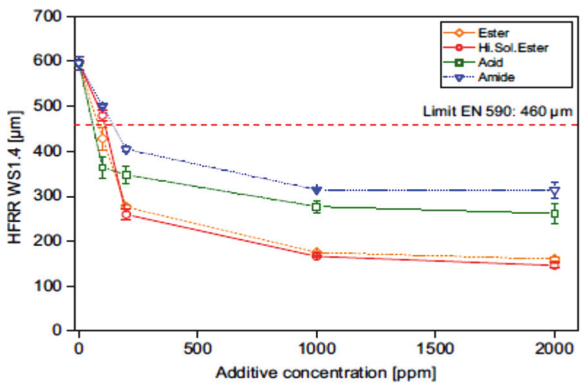

Fig. 2 *Aditives concentration influence on diesel fuel lubricity*

Tests of diesel fuel treated with lubricity additives have shown that sulfur content (80 ÷ 1276) ppm has no influence on the lubricity -WDS = (180 ÷ 200) μm [6].

3. EXPERIMENTAL RESEARCH

The aim of this experiment is to identify the potential harmful effects of the use of modern fuel to an old generation diesel engine. The working process of the engine and its emissions are studied in detail, and tribological effects are not considered.

3.1 Engine and test procedure

Research was conducted on small agricultural machinery engine DMB 3DA 450 module 328. Fig. 3 show its factory declared characteristics with diesel fuel D-2 (high pressure pump blocked).This is a single cylinder, air-cooled, naturally aspirated DI engine, with a pump → tube → injector injection system (all regimes governor). Its main characteristics are: Displacement Vh = 454 cm^3 (bore D = 85 mm, stroke S = 80 mm), compression ratio ε = 17.5, fixed injection advance 18.5 CA BTDC. The engine is tuned according factory standard.

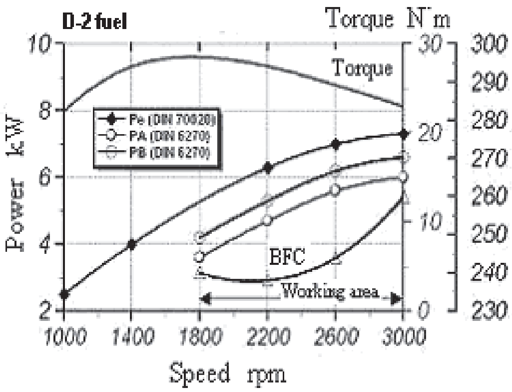

Fig. 3 *Engine characteristics*

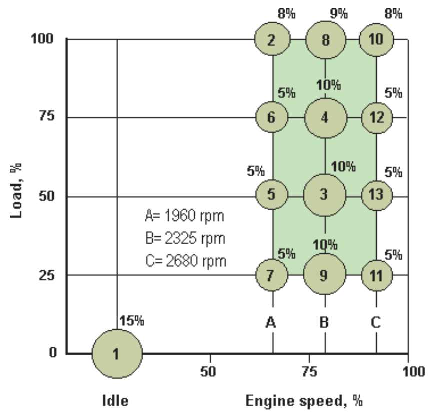

Fig. 4 *Test regimes*

Engine operating regimes are determined according to ESC (European Stationary Cycle) procedure (Figure 4), which is used for emission certification of the commercial vehicles (*Directive 1999/96/EC*). This procedure provides an opportunity to evaluate the emissions in the whole working area of the engine. The same methodology of calculating was applied for the evaluation of the engine efficiency.

Effective parameters (standard engine test bench), in-cylinder parameters (AVL system Indimer 619), gas emission (AVL DICOM 4000 system), smoke emission (Bosch AVL Smoke Meter 409 / 2M) was measured. The emission of particles was determined indirectly, through correlation with the emission of black smoke.

We used a commercial fuel NIS ECO-3 which meets the requirements of SRPS EN 590: 2004 standard, except in terms of sulphur content (> 50 ppm).To protect the fuel injection system, additive LUBRIZOL 639 M was added in the amount of 200 ppm. The results of fuel control testing are listed in table 3.

Table 3 *Cheched fuel characteristics*

Property	NIS EKO-3	Test Method
Density @ 15°C	835 kg/m^3	IP 190/64
Viscosity @ 40°C	2.20 mm^2/s	Vogel-Ossag
Flash point	76,3°C	EN ISO 2719
Uper caloric value	45770 kJ/kg	SRPS B.H8.318
Lower caloric value	42850 kJ/kg	calculated
Cetan number	52.0	MFK metod [7]

3.2 Test results

Indicated efficiency (ηi) is the best in the central part of the working area, at moderate load and speed (modes 5, 3, 6 and 4). At maximum load, with an increase in speed (modes 2 8 and 10) efficiency decreases due to deterioration of combustion efficiency. At idling (mode 1) indicated efficiency is only 27.1%.

Brake efficiency (ηe) decreases with the load, especially at higher speeds, which is normal for the engine of this concept (unregulated cooling fan).

The maximum value of cylinder pressure (p_{CMAX}) and its position (α_{Pcmax}) give us an insight into the mechanical load on the engine structure.The maximum value of 82.9 bar was observed in mode 2 (low speed at maximum load). In general, maximal pressures are moderate.

Table 4 *The parameters of the engine working process*

EKO-3 diesel fuel, compression ratio 17.5, injection timing 18.5 ºBTDC												
ESC mod	**ηi** -	**ηe** -	**TcMAX** K	**pcMAX** bar	**apcMAX** ºCA	**RMAX** bar/ºCA	**aRMAX** ºCA	**ID** ºCA	**aQ05%** ºCA	**aQ10%** ºCA	**aQ50%** ºCA	**aQ90%** ºCA
1	0.271	-	1104	54.6	0.5	4.9	-7.4	7.9	-7.4	-7.2	0.5	30.4
2	0.419	0.326	1736	82.9	5.3	8.2	-3.0	10.8	-4.2	-3.5	9.8	47.1
3	0.435	0.281	1452	66.5	3.3	6.4	-0.6	14.1	-1.2	-0.7	11.3	48.3
4	0.443	0.309	1656	73.0	4.2	8.3	0.1	13.9	-1.0	-0.5	11.7	50.1
5	0.425	0.283	1411	71.0	4.4	6.6	-4.0	10.9	-4.1	-3.6	8.4	38.0
6	0.440	0.318	1583	77.1	4.8	7.5	-3.5	11.1	-4.1	-3.5	9.1	42.5
7	0.399	0.207	1224	65.1	2.7	5.7	-3.7	11.2	-3.9	-3.5	8.6	38.7
8	0.387	0.292	1839	76.0	6.1	8.0	-0.6	13.6	-1.2	-0.5	13.5	56.3
9	0.404	0.205	1246	59.4	3.5	4.9	-0.4	14.3	-0.6	-0.2	11.7	47.8
10	0.374	0.274	1855	71.9	6.5	7.2	1.7	15.2	1.0	1.7	16.1	59.1
11	0.390	0.191	1254	57.0	4.5	4.2	1.0	15.8	1.5	2.0	13.8	48.0
12	0.412	0.291	1644	67.6	5.8	7.4	1.5	15.4	1.0	1.7	15.1	53.6
13	0.408	0.262	1426	62.2	5.5	5.7	1.1	15.6	1.2	1.8	14.5	49.0

A particular problem occurs during cold start. Then the first firing occurs very early, so the maximum pressure above 100 bar is achieved before TDC. In this case, better inflammability fuel is counterproductive. Start is brutal and most critical from the standpoint of mechanical overload. It is obvious that injection tajmig must be advanced.

The pressure increase rate (R_{max}) and the position of the maximum value (α_{RMAX}) provide insight into the regularity of the combustion process. The measured values in the range (4.9 ÷ 8.0) bar·°CA^{-1} are high, but they are in regular terms. As a result operation of the engine is "rough", with increased combustion noise. The reason is combinations of better fuel inflammability and the early injection.

The combustion process is represented by discrete values in Table 4 and by diagram in Fig. 6. Ignition delay period (ID) is balanced at the same speed and almost independent of the load. The position of the center of combustion ($\alpha_{Q50\%}$) is in the range (10 ÷ 15) CA ATDC. The period of combustion of the first half cyclical fuel quantity ($\alpha_{Q0\%-Q50\%}$) is uniform and corresponds to the phase of uncontrolled combustion.

For the same speed, along with load decrease the center of combustion moves closer to the TDC! The combustion dynamics of the second half of cyclical amount of fuel ($\alpha_{Q50\%-Q90\%}$) are influenced by oxygen inrush into the flame zone. Obviously this period are extended on test modes 8 and 10.

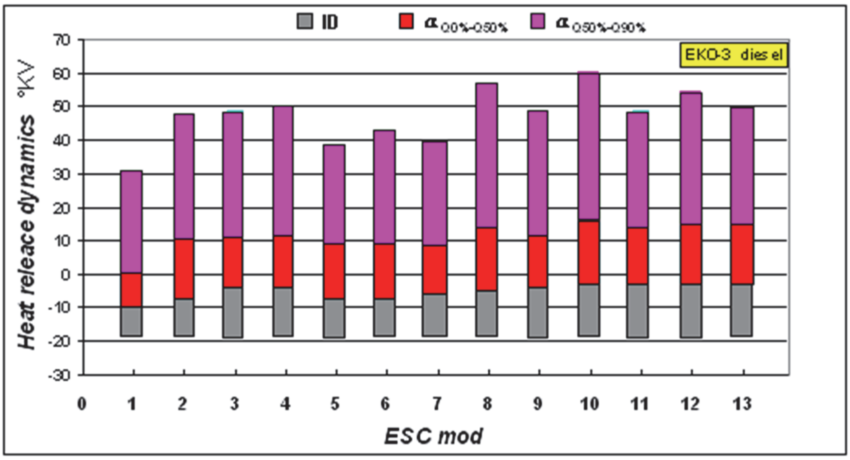

Fig. 5 *Heat releace dynamics*

Table 5 *Summary results of emission and efficiency*

ESC test procedure	***EMISSION***	$g \cdot kW^{-1} \cdot h^{-1}$			***EFFICIENCY***	
	CO	***HC***	***NOx***	***PM***	η_i	η_e
Test engine results	17.1	0.91	8.4	1.73	0.388	0.235
EURO 3 norme (2000)	2.1	0.66	5.0	0.13	/	

The summary results of the emission test are presented in table 5. Comparison with the Euro 3 requirements points to technological inferiority of test engine. It is obvious that the only introduction of modern fuels can not solve the emission problem of old engines.

4. CONCLUSION

Direct usage of the fuel according to EN 590 and biodiesel to EN ISO1421 can cause mechanical overload at the older generation engines (cylinder head connection, piston mechanism, bearings). Therefore, it is necessary to readjust the injection parameters according to the instructions of producers (if any).

Usage of biodiesel fuel of poor quality (especially the home made) is harmful and can lead to a malfunction of the injection system. Biodiesel fuel is subject to aging and it does not need to be stored for more than a few months.

GasOil 0.1 is generally suitable replacement to former D-2 fuel. There are some reservations regarding lubricity. As a preventive protection of old injection system, is recommended to add 5-10% of biodiesel, just before use.

The only introduction of modern fuels can not solve the emission problem of old engines.

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