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Simultaneous reduction of fuel consumption and toxic emission of exhaust gases of fishing fleet engines

O. Klyus[*], M. Szczepanek

Maritime University of Szczecin, Szczecin, Poland

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ABSTRACT

Attempts to obtain technically optimal economic and ecological parameters in piston diesel engines face a number of difficulties, mainly concerning the arrangement of the engine working process. We can achieve lower fuel unit consumption, i.e., increased engine efficiency, by raising maximum temperatures of the cycle, which leads to increased toxic emissions of exhaust gases, mainly nitrogen oxides. Common Rail injection systems with electronic control of fuel injection characteristics are used in newly built engines, while exhaust components are equipped with catalytic reactors, solid particle filters and others. Still the simultaneous reduction of fuel consumption and level of toxic emissions remains a major problem. The same refers to engines currently operated in ships, whose construction does not leave much space for essential improvements in fuel, exhaust and other systems. The Maritime University of Szczecin conducts research on medium and high-speed self-ignition engines used in fishing boats and vessels which focuses on the use of preliminary fuel treatment directly in the injector body. Such treatment is possible in new design engines leaving factories as well as those in operation.

1. Introduction

Attempts to obtain technically optimal economic and ecological parameters in piston diesel engines face a number of difficulties, mainly concerning the arrangement of the engine working process. We can achieve lower fuel unit consumption, i.e., increased engine efficiency, by raising maximum temperatures of the cycle, which leads to increased toxic emissions of exhaust gases, mainly nitrogen oxides. Common Rail injection systems with electronic control of fuel injection characteristics are used in newly built engines, while exhaust components are equipped with catalytic reactors, solid particle filters and others. Still the simultaneous reduction of fuel consumption and level of toxic emissions remains a major problem. The same refers to engines currently operated in ships, whose construction does not leave much space for essential improvements in fuel, exhaust and other systems.

The Maritime University of Szczecin conducts research on medium and high-speed self-ignition engines used in fishing boats and vessels which focuses on the use of preliminary fuel treatment directly in the injector body. Such treatment is possible in new design engines leaving factories as well as those in operation.

[*]Corresponding author.
E-mail addresses: o.klyus@pm.szczecin.pl (O. Klyus), m.szczepanek@pm.szczecin.pl (M. Szczepanek).

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2. Preliminary fuel treatment

Considering a diesel engine indicator diagram, we can observe that the basic time interval directly affecting economic and ecological engine parameters is the self-ignition delay time; its shortening may lead to both a slower increase of pressure and decreased maximum temperatures in the combustion chamber while a range of effective work remains at the same level [2].

From an analysis of various research findings [6] we can calculate self-ignition delay using this relation:

$$\tau = B \cdot 10^{-2} \sqrt{C} \sqrt{\frac{T_k}{p_k} \cdot e^{\frac{E_a C^{0,34}}{\bar{R} T_k}}}, \tag{1}$$

where

$$B = 2 \cdot 10^{-4} \left(1 - 1{,}6 \cdot 10^{-4} n_s\right) \tag{2}$$

$$C = \frac{1}{\varepsilon}\left[1 + 0{,}5\delta \frac{V_h}{V_{h_1}}(\varepsilon - 1)\right] \tag{3}$$

$$\delta = \left[\left(1 + \frac{\lambda}{4}\right) - \left(\cos\theta + \frac{\lambda}{4}\cos 2\theta\right)\right] \tag{4}$$

B, C, δ – constants,
T_k – temperature in the combustion chamber when fuel injection starts,
p_k – pressure in the combustion chamber when fuel injection starts,
Vh, Vh_1 – actual cylinder volume and volume corresponding to piston stroke with inlet valves closed,
ε – compression ratio,
θ – connecting rod inclination,
λ – piston stroke to connecting rod ratio.

According to Heywood, the delay time can be determined from this relation:

$$\tau = (0{,}36 + 0{,}22 \cdot c_m) \cdot \exp[E_a (\frac{1}{\bar{R} T_2} - \frac{1}{17{,}19}) \cdot (\frac{21{,}2}{P_2 - 12{,}4})^{0{,}63}], \tag{5}$$

where
cm – mean piston speed,
P_2 and T_2 – pressure and temperature in the combustion chamber.

Analyzing the relations defining self-ignition delay time we can see that it depends on such factors as pressure and temperature in the combustion chamber, rotation speed of the shaft and engine kinematics as well as activation energy. It should be noted that in attempts to improve economic and ecological performance of new and used engines there is no practical possibility to change parameters such as pressure or temperature, and basic design features. One possible direction to affect these self-ignition engine parameters is to decrease values of activation energy.

For polyatomic molecule compounds (to which hydrocarbon fuels belong) activation energy is defined as the minimum kinetic energy by which the potential energy of a system should be greater for a chemical reaction to occur.

Activation energy depends on molecule structure and bond strength. In the work [1] the behavior of paraffin hydrocarbons CnH2n+2 is discussed in this context. In these hydrocarbons the energy of breaking C–H bonds is greater than the energy of breaking C-C bonds, that is why the more carbon atoms there are in a molecule, the less activation energy is needed to break the bonds. This explains a high stability of isooctane C8H18, used as reference fuel to determine octane ratings of other fuels. To facilitate overcoming the activation energy, we can deliver more energy to the reaction environment (e.g., by heating) or use a substance that easily reacts with the substrate (low activation energy), and thus formed compound easily converts into a product (also low activation energy). A catalyst is a substance that facilitates a conversion from a reactant into a product and, notably, is not consumed in the reaction. It follows that the presence of a catalyst (e.g., metals of the platinum family) and its contact with fuel before injection into the combustion chamber is desired.

The presence of a catalyst in the fuel system has another justification. Chemical properties of fuels used in self-ignition engines can be changed. In paraffin hydrocarbons, the most common group among diesel fuels, paraffin can be dehydrogenated in the presence of a catalysts. In the relevant reactions paraffin hydrocarbons change into olefins CnH2n and hydrogen molecules are released. Hydrogen, with its high diffusion coefficient, high flammability, high rate of combustion and a wide range of mixture combustibility, reduces self-ignition delay time in the conditions prevailing in the combustion chamber.

The presence of hydrogen in the injected fuel may affect chemical and physical phenomena. For instance, the self-ignition delay time depends on such physical factors as the diffusion rate of fuel, oxidizer and active nuclei of reaction. The process of diffusion is accompanied by evaporation of liquid fuel; its mathematical description has a form of drop evaporation rate [5].

$$\frac{dm}{d\tau} = \pi Nu_D D_p d_k \left(p_s - p_0\right) = \int_0^{\tau} \frac{2Nu_D D_p}{\rho_{pal}} \left(p_s - p_0\right) d\tau \,, \qquad (6)$$

where:
Nu_D – Nusselt criterion for diffusion processes,
Dp – coefficient of vapor diffusion in reference to partial pressure gradient,
p_s, p_0 – partial pressure of fuel vapor in vicinity of a drop with a diameter dk and in a medium surrounding drops,
ρpal – fuel density.

It is known that a catalyst will be more effective if it is used in high temperature and the fuel has turbulent flow along catalyst surfaces [3]. For this reason, we propose 'preliminary fuel treatment' that consists in depositing a catalytic material on the surface of an atomizer needle. The injector has the highest thermal load of all engine elements. To create turbulent fuel flow, the needle surface has properly situated passages. The part of the atomizer needle connecting the precision surface and the conical tip was chosen for preliminary fuel treatment. Such solution makes deposition of a catalyst (e.g., by electro-spark alloying) and machining of turbulizing passages technologically feasible in new as well as used injectors.

3. Laboratory tests

As mentioned before, the term 'preliminary fuel treatment' is understood as the use of heterogeneous catalysis during fuel flow in atomizer passages. To enhance the treatment, the catalyst is placed on the most thermally loaded part of the atomizer while special turbulizing passages are located on the part of atomizer needle that itself is not a precision nor closing element. An example layout of turbulizing passages with deposited catalyst is shown in Fig. 1.

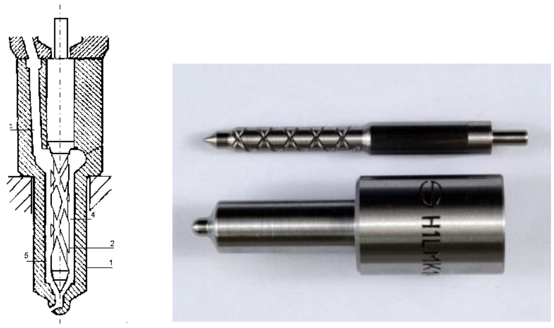


Fig. 1. A diagram and photo of a multi hole diesel injector with preliminary fuel treatment

1 – atomizer body, 2 – needle, 3 – space between needle and body, 4 – turbulizing passages

Lab tests aimed at analyzing the fuel atomizing process were carried out at a test station composed of a set for Bosch EPS200A injector adjustment and a Malvern-made Spraytec analyzer for determining the distribution of droplet diameters in jets and aerosols (Fig. 2)

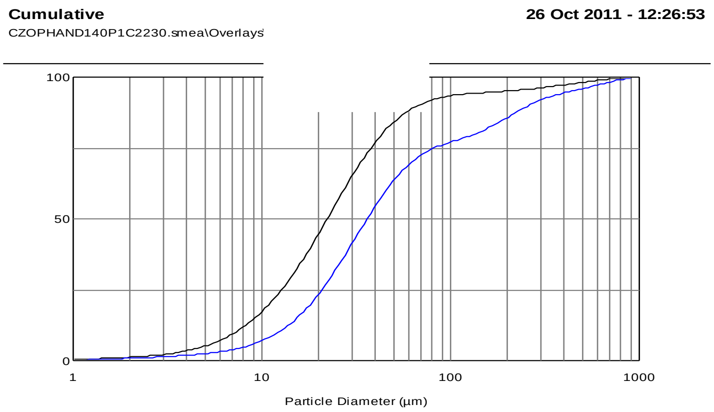
Fig. 2. A test station for determination of fuel drop diameter distribution

A fuel injector of a diesel type 359 engine was used in experimental tests. The engine type was deliberately chosen. An analysis of data base of the fishing fleet engines indicates that among several types in use, with different constructions and combustion systems, the 359 engine with direct fuel injection represents a majority of the engines under consideration.

The atomizers in 359 engines have three injection holes, one of which in laboratory tests was directed horizontally, in a plane perpendicular to a laser beam of the Spraytec device. Another component of the test station was properly positioned tubes capturing two other jets of fuel and an absorber of atomized fuel mist (Fig. 3).

Fig. 3. Recording of atomized fuel jet

Fig. 4 shows an example diagram with a distribution of fuel droplet diameters, where the curve 1 refers to a manufactured atomizer, curve 2 an atomizer adjusted for preliminary fuel treatment.



	Date-Time	File	Sample	Dx(10)	Dx(50)	Dx(90)
[V]	26 Oct 2011...	230 1 ...	230	7.22	22.19	66.76
[V]	26 Oct 2011...	230 2 1	230	12.23	36.13	259.85

[V]=Volume [N]=Number

Fig. 4. Droplet distribution in an atomized jet of fuel

In laboratory tests a change in acoustic signal accompanying the atomization process was observed. The changes were recorded using the equipment for measuring acoustic emission signals (Fig. 5) [4].

a) b)

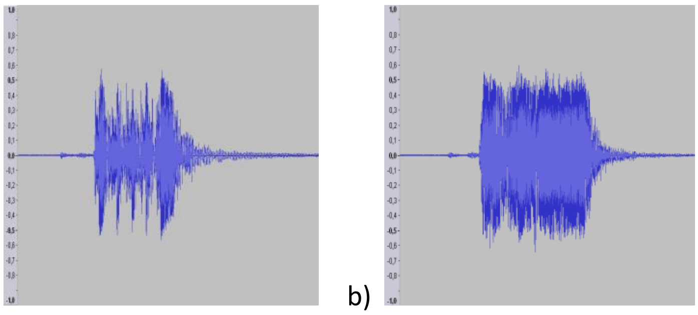


Fig. 5. Characteristics of acoustic emission signal
a) manufacturer's injector, b) injector with special preliminary fuel treatment

The results show that the preliminary fuel treatment has a beneficial effect on atomized fuel characteristics – mean Sauter diameter has decreased, number of droplets with smaller diameter has increased, and the acoustic energy of signal from fuel atomizing holes has increased.

4. Filed test

Tests of engines in operation included three types representing the entire population of engines mounted in Polish fishing boats and vessels.
<u>Engine with a turbulence combustion chamber.</u>

A high speed four-cylinder self-ignition engine has a Ricardo Comet MrkV combustion chamber and pintle injectors. An example of 'preliminary fuel treatment' for those injectors is shown in Fig. 6

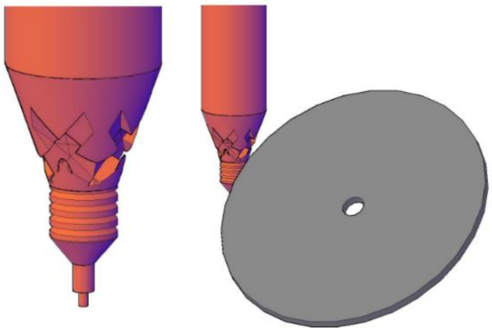
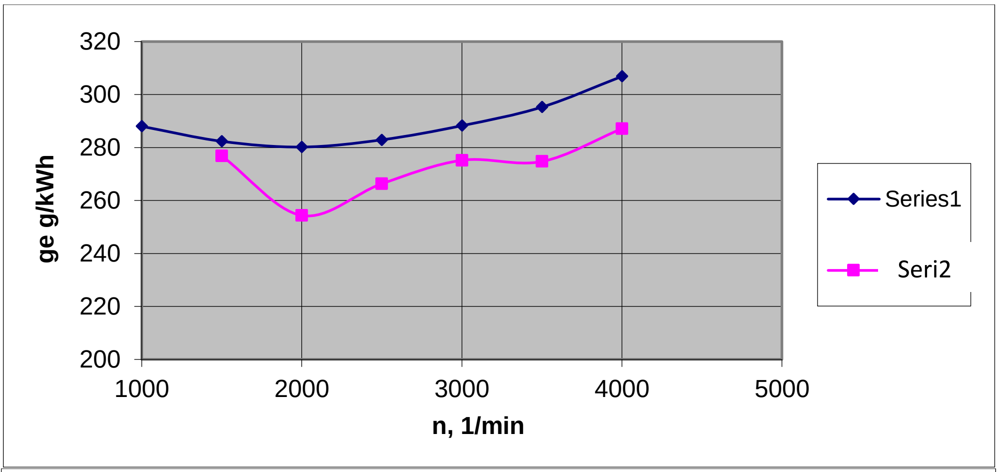


Fig. 6. A pintle injector with preliminary fuel treatment

Fig. 7 shows selected speed characteristics of a high-speed engine with a turbulence combustion chamber.



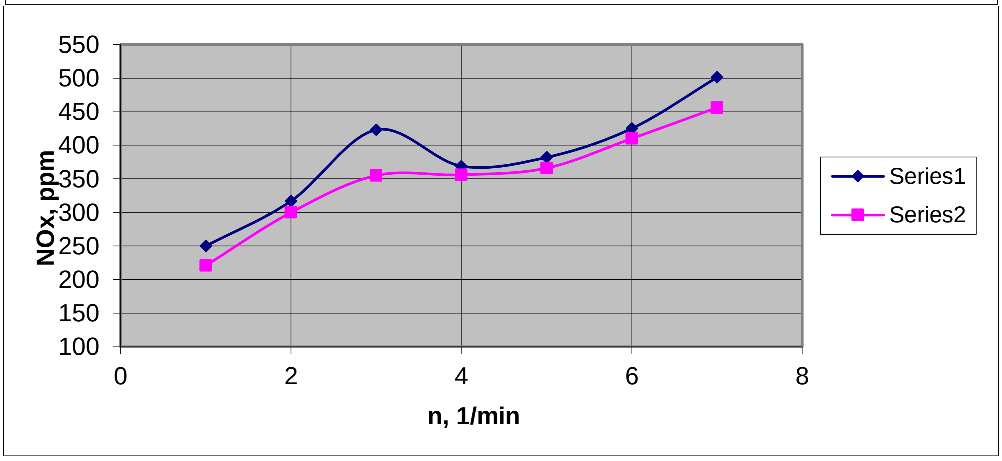


Fig. 7. Speed characteristics of unit fuel consumption and nitrogen oxide emission
series 1 – engine with maker's injection system, series 2 – engine with preliminary fuel treatment

<u>Engine 359 with direct fuel injection</u>

This type of engine represents a major group of engines installed in fishing boats and vessels. The engine has a combustion chamber placed in the piston. Its atomizers were particularly examined at test stands. The modified atomizer design for preliminary fuel treatment is shown in Fig. 8, while Fig. 9 displays some speed characteristics.

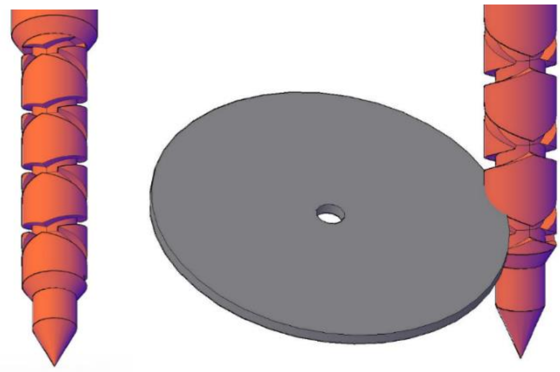


Fig. 8. The method of making turbulizing passages in engine 359 injectors

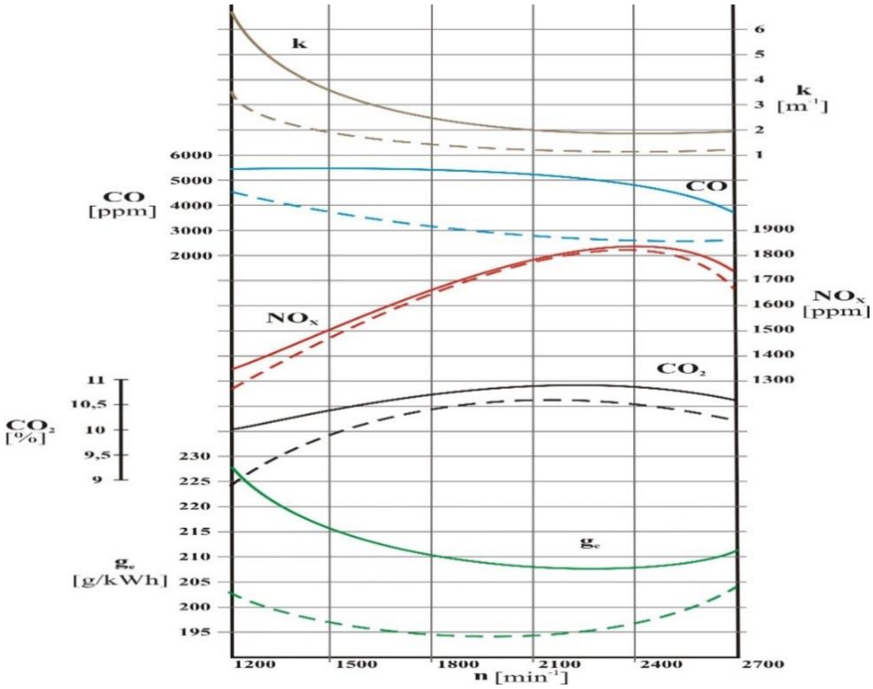


Fig. 9. Unit fuel consumption and emission of toxic compounds of a 359 engine
---------- standard injector, - - - - injector with preliminary fuel treatment

VD24 engine with direct fuel injection

This type of engine was chosen due to its slightly different design of injector needle, that unlike the one in 359 engines has a much shorter part connecting the precision and closing elements. Fig. 10 presents the preliminary fuel treatment design in this type of atomizer, while Fig. 11 shows a load characteristic of an NVD24 engine.

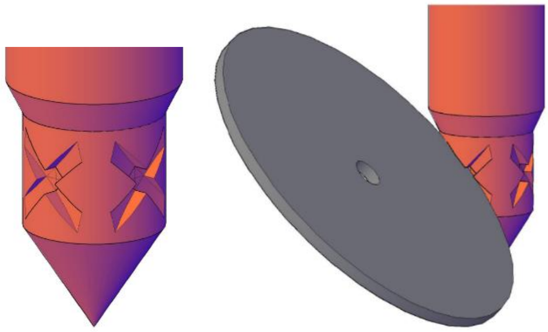


Fig. 10. Preliminary fuel treatment devised in injectors of an NVD24 engine

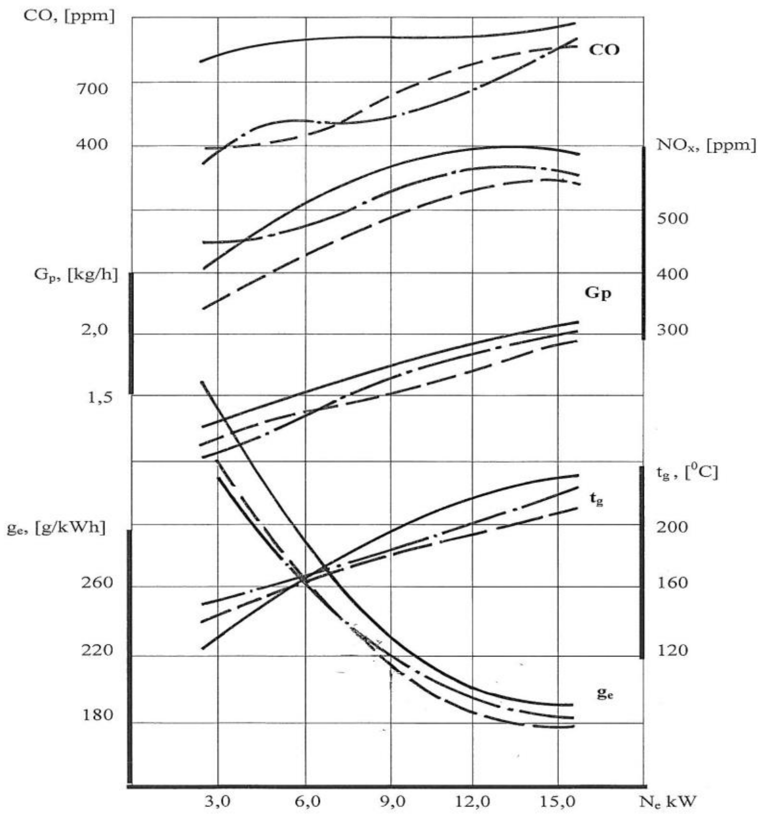


Fig. 11. Load characteristics of an NVD24 engine
.... engine with maker's injector, ----- engine with injector for preliminary fuel treatment, engine with injector for preliminary fuel treatment with larger angle of injection start

5. Conclusion

It is possible to increase the efficiency of self-ignition engines and at the same time reduce the level of toxic emissions by implementing preliminary fuel treatment. The method consists in applying a catalytic coating deposited on a part of atomizer needle. The catalyst is more effective when put on specially made turbulizing passages forming crossing grooves or threads. The relevant method, consisting in depositing a metal of platinum group by electro spark alloying and making turbulizing passages, is technologically feasible in the process of making new injectors as well as by modifying those in use. Low temperatures of the process do not cause any changes or thermal strains of the precision pair, and portable equipment allows to make minor constructional changes directly at operator's base.

The results of laboratory and field tests indicate that the use of preliminary fuel treatment reduces fuel consumption (by 8% on average), and the level of toxic emissions in exhaust gases (nitrogen oxides by 15%). The tested engines represented types with various injection solutions – both direct and indirect injection as well as different atomizer design.

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