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The influence of the heating time of a catalyst-covered glow plug on the exhaust emissions from a diesel engine

The paper discusses the application of an in-cylinder catalyst allowing a reduction of the exhaust emissions from a diesel engine. Its placement in the combustion chamber, the area where the process of combustion takes place, allows reducing the emissions (carbon monoxide, hydrocarbons, particulate matter) 'at source'. The paper presents the possibilities of boosting the efficiency of catalysts in diesel engines by extending the time of heating of a glow plug (the catalyst applied on the glow plug). The tests were performed for the following conditions: no heating (marked 0+0), glow plug heating for 60 s after engine start (marked 0+60), glow plug heating prior to engine start for 60 s and glow plug heating for 60 s after engine cold start (marked 60+60). An improvement in the efficiency of oxidation of the exhaust components was observed as the glow plug heating time increased.

Key words: *combustion engine, in-cylinder catalyst, glow plug*

1. Introduction

Piston combustion engines are common sources of power in transport. They were initially used as stationary but owing to their multiple advantages, they became popular in vehicles. The attempts to obtain increasingly higher unit power outputs, improving the operating indexes and reducing the unit mass are only some of the requirements that are currently imposed by legislators and are vital in the process of improvement of the engine design, including its individual components [1]. The above requirements are also a reason for continuous changes in the engine operating routines aiming at the obtainment of the above benefits while reducing the environmental nuisance. The engine operation is characterized by the formation of harmful emissions, the source of which is to be sought in the process of combustion.

An increasing stress put on the reduction of the negative impact of motor vehicles on the environment by both the legislators in individual countries and the society forces the engineers to search for increasingly complex technical solutions that will ensure the reduction of the said impact and the fulfillment of the applicable emission standards [2-5]. Among such actions, are those that influence the emission of individual harmful exhaust components immediately after they are evacuated from the engine (aftertreatment systems). Due to the specificity of operation of aftertreatment systems (obtaining high temperatures of their operation) it is necessary to place them closer to the engine) [6, 7]. These, however, are actions aiming at reducing the already formed exhaust components [8, 9]. One should take a closer look at technologically available actions that would influence the intensity of formation of the harmful components 'at source', i.e. placing catalysts as close as possible to the combustion chamber. This is the reason for the idea of combining the in-cylinder processes with the aftertreatment systems, which allows the use of catalysts inside the cylinder.

Based on the literature data analysis, we may observe that the modification of the engine combustion area, consisting in the introduction of an active element (catalyst) most likely results in the reduction of the ignition delay by reducing the energy of activation of the preflame reactions, thus improving the engine operation and reducing the formation of harmful exhaust components inside the cylinder. The catalyst located in the combustion area may have impact on several phases of the process of combustion:

- mixture formation phase – the process of cracking of the injected fuel,
- pre-flame phase – reduction of the ignition delay,
- combustion phase – increase in the combustion rate – increasing the combustion temperature (disadvantageous increase in the concentration of nitrogen oxides),
- afterburn phase – burning of hydrocarbons in the wall layer and afterburning carbon monoxide.

The works treating on the application of an in-cylinder catalyst [10–14], clearly states the possibility of reducing exhaust emission during diesel engine operation. The fitting of the catalyst in the combustion chamber allows reducing the emission 'at source'. The presented results of the research works [10–14] under varied engine operating conditions (cold start, engine dynamometer in homologation tests and road test simulations, actual traffic operation) have confirmed that the application of an in-cylinder catalyst results in a reduction (a few percent) of the emission of carbon monoxide, hydrocarbons, carbon dioxide and particulate matter.

When analyzing the problem of engine start (cold start in particular) one needs to mind the need for the glow plugs. The duration of the glow plug heating is determined based to many parameters (engine start duration, ambient temperature, coolant temperature), yet, in this work, the following were adopted in order to determine the concentration/emission of the exhaust components (catalyst-coated glow plug only, upstream of the catalytic converter):

- no heating (marked 0+0),
- glow plug heating 60 s after engine cold start (marked 0+60),
- glow plug heating 60 s prior to engine start and 60 s after engine cold start (marked 60+60).

2. Research methodology

The objects of the research analyses were glow plugs (standard size) with a catalytic coating. The catalyst materi-

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al was platinum that reduces the concentration of carbon monoxide, hydrocarbons and, to a small extent, particle number in a diesel engine.

The authors performed an analysis of the glow plug heating time and its influence on the exhaust emissions: carbon monoxide, hydrocarbons, nitrogen oxides, carbon dioxide and particulate matter.

The object of the research was a Euro 4, 1.3 dm^3 turbocharged diesel engine (1.3 JTD MultiJet).

The tests were carried out on a DYNOROAD 120 kW test stand by AVL. The authors investigated the concentration of the exhaust components and, allowing for the power output/covered distance, unit emission was obtained (g/kWh) of a given exhaust component.

The main component of the test stand (Fig. 1) was a three phase asynchronous electric motor. It allows a take-off of a maximum power of up to 120 kW. During operation, a combustion engine generates mechanical work converted in the brake into electrical energy that, upon voltage-frequency transformation, is transferred to the external power grid. The software ISAC 400 interface installed on the test stand allows identifying the research cycle covering the chassis (NEDC) and engine (ESC) dynamometer tests, but primarily enables the adaptation of an individual algorithm using the function of change of the vehicle speed in time and the change of the road gradient in time.

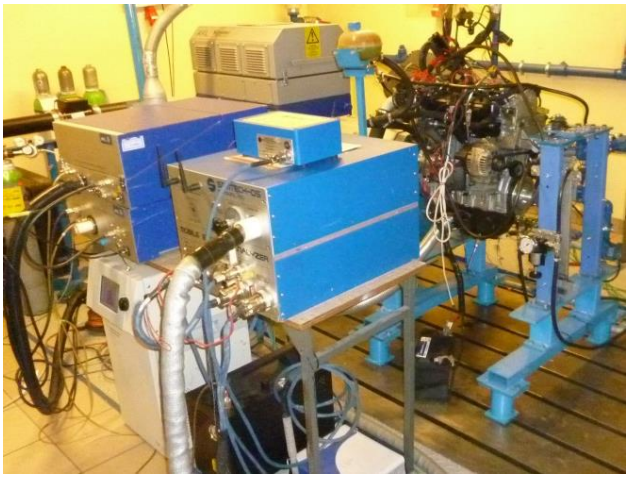

Fig. 1. View of the test stand

The measurements of the exhaust emissions were carried out according to the algorithm below.

Humid exhaust mass flow rate G_{exh} is calculated according to the formula:

$$G_{exh} = G_{air} + G_{fuel} \tag{1}$$

where: G_{air} – mass flow rate of the humid air [g/s], G_{fuel} – mass fuel consumption rate [g/s].

The emission intensity of individual gaseous exhaust components is calculated based on the relation:

$$E_{CO} = 0.000966 \cdot c_{CO} \cdot G_{exh} \cdot \beta \tag{2}$$

$$E_{NOx} = 0.001587 \cdot c_{NOx} \cdot G_{exh} \cdot \beta \cdot K_H \tag{3}$$

$$E_{HC} = 0.000966 \cdot c_{HC} \cdot G_{exh} \tag{4}$$

where: c_{CO}, c_{NOx}, c_{HC} – concentration of carbon monoxide, nitrogen oxides and hydrocarbons [ppm] in the exhaust gas, K_H – correction factor of humidity of nitrogen oxides, β – correction factor of the concentration of carbon monoxide and nitrogen oxides in dry exhaust.

The K_H factor is calculated from the formula:

$$K_H = [1 + A(H - 10.71) + B(T_{air} - 298)]^{-1} \tag{5}$$

where: $A = 0.309 \cdot G_{fuel}/G_{air} - 0.0266$, $B = -0.209 \cdot G_{fuel}/G_{air} + 0.00954$, T_{air} – temperature of the intake air [K], H – humidity of the intake air in grams (of water) per 1 kg of dry air [g/kg].

Absolute humidity of air can be calculated from the following relation:

$$H = 6.22 \cdot \varphi \cdot p/(p_a - p \cdot \varphi \cdot 10^{-2}) \tag{6}$$

where: φ – relative humidity of the intake air [%], p_a – ambient pressure [Pa], p – water vapor saturation pressure in the intake air [Pa].

Coefficient β is calculated from the formula:

$$\beta = 1 - 1.865\ G_{fuel}/G_{air} \tag{7}$$

3. Results

In the case of the evaluated concentration of carbon monoxide throughout the entire period of 1200 s, the lowest was observed for the case (60+60) and the highest for the 'no heating' case. The same effect was observed for the emission intensity of carbon monoxide (constant exhaust flow rate). As a result, the emission of carbon monoxide in the test was 7–10 g (Fig. 2).

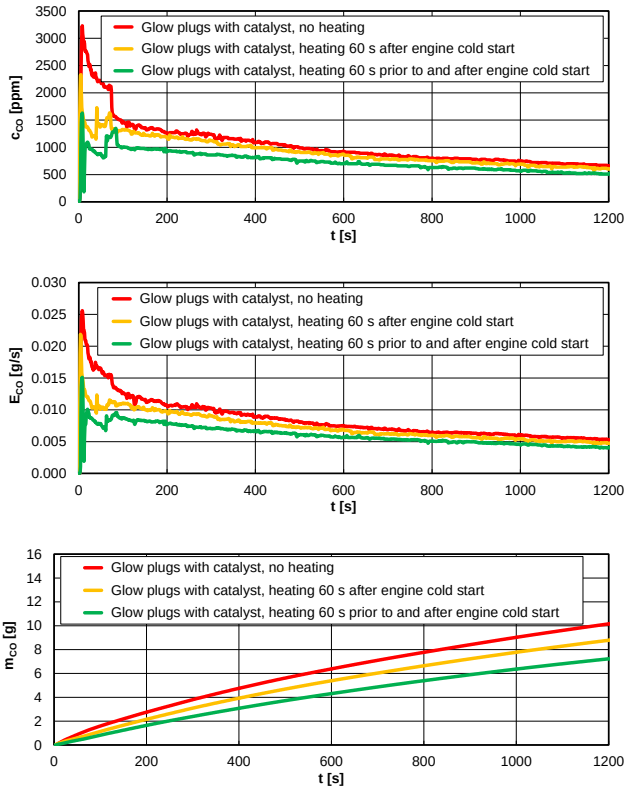

Fig. 2. Concentration, intensity of emission and emission of carbon monoxide during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

A similar situation was observed for the concentration of hydrocarbons. The greatest increase in the concentration (over 600 ppm) was observed for the 'no heating' case (0+0). When heated only after the engine start (0+60) and for the case (60+60) this value was approx. 300 ppm. After approx. 200 s a slow decrease was observed of this concentration from 250 ppm for the cases (0+0) and (0+60) and from 200 ppm for the cases (60+60) to the value of approx. 150 ppm at the end of the measurement. The emission intensity of hydrocarbons was very similar to the course of the concentration and the final value was the same for all the cases and amounted to approx. 0.0005 g/s. The values of the emission of hydrocarbons for the three analyzed modified glow plug heating cases were in the range 0.8–1 g (Fig. 3).

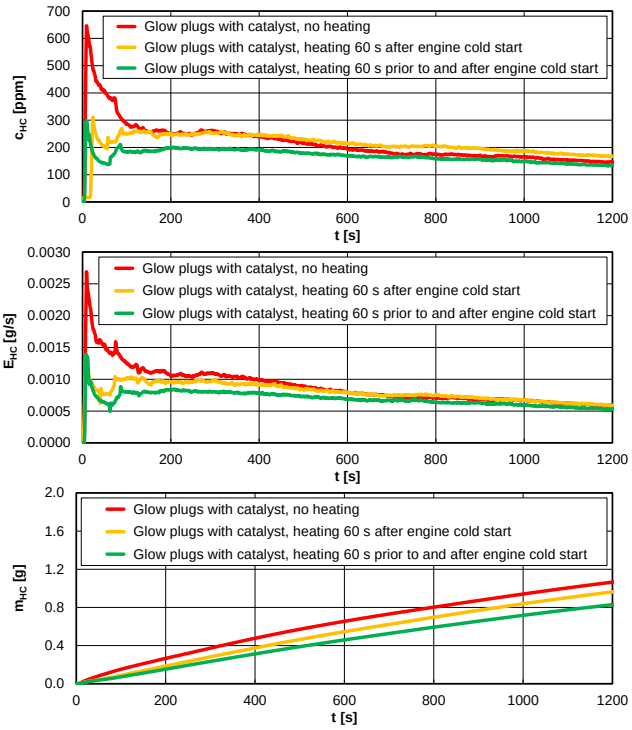

Fig. 3. Concentration, intensity of emission and emission of hydrocarbons during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

A different situation occurred for the analysis of the concentration of nitrogen oxides. The greatest increase in the concentration of this component (over 200 ppm and the longest upkeep time) was observed for the case of glow plug heating (60+60). For the heating only after engine start (0+60), the upkeep time in the initial period of higher concentration of nitrogen oxides was shorter (the maximum is approx. 150 ppm) and for the case (0+0) a sudden increase in the concentration of nitrogen oxides was only momentary. After approx. 100 s, slow changes in the concentration were observed with a fluctuation of approx. 20 ppm. The intensity of the emission of nitrogen oxides was close to the tracing of the concentration and the final value was similar for all the cases of glow plug heating and amounted to 0.001 g/s. The final values of the emission of nitrogen oxides for the three analyzed catalyst-covered glow plug heating cases fell in the range 1–1.5 g (Fig. 4).

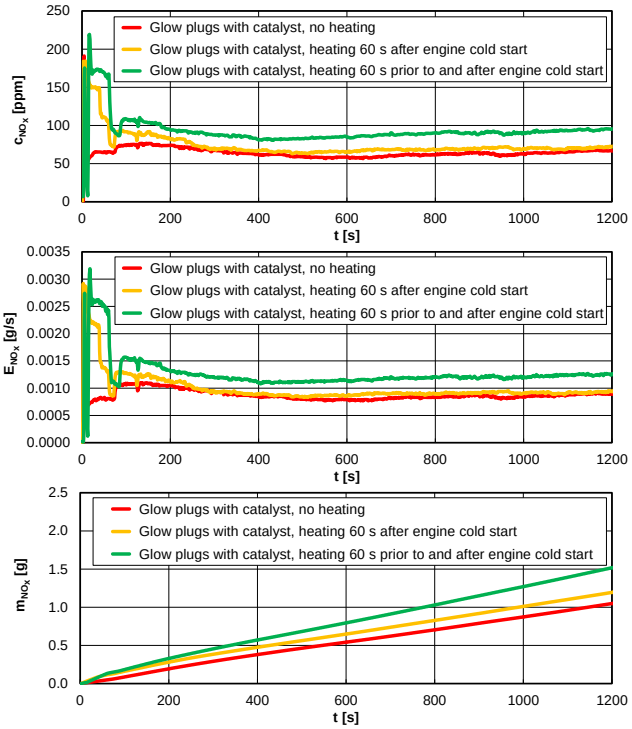

Fig. 4. Concentration, intensity of emission and emission of nitrogen oxides during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

In the case of particle number, the test results are not varied. All tracings of the particle number intensity are similar in their nature and values and only the final values of the particle number allow a correct assessment of the environmental benefits. The particle number in the entire measurement period for different glow plug heating cases fell in the range $3–3.5 \cdot 10^{11}$ (Fig. 5).

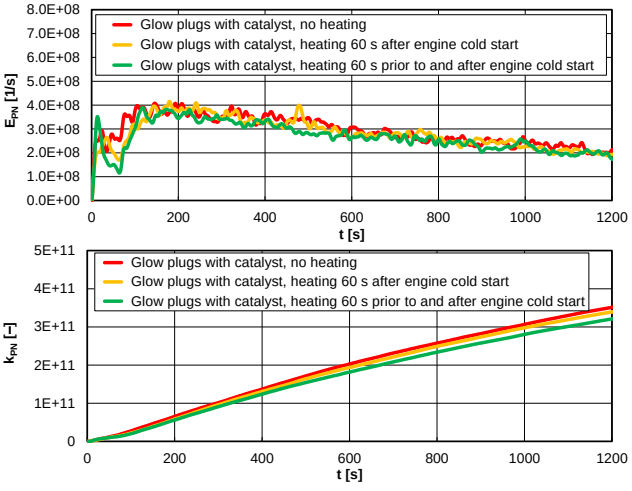

Fig. 5. Particle number intensity and particle number during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

When analyzing the concentration of carbon dioxide for all the cases of glow plug heating, no significant differences in its values were recorded. The greatest unrepeatability occurs only in the first 100 s after engine start and the further tracings of the concentration and the intensity of emis-

sion are identical. The values of the emission of this component are close for all the heating cases (Fig. 6).

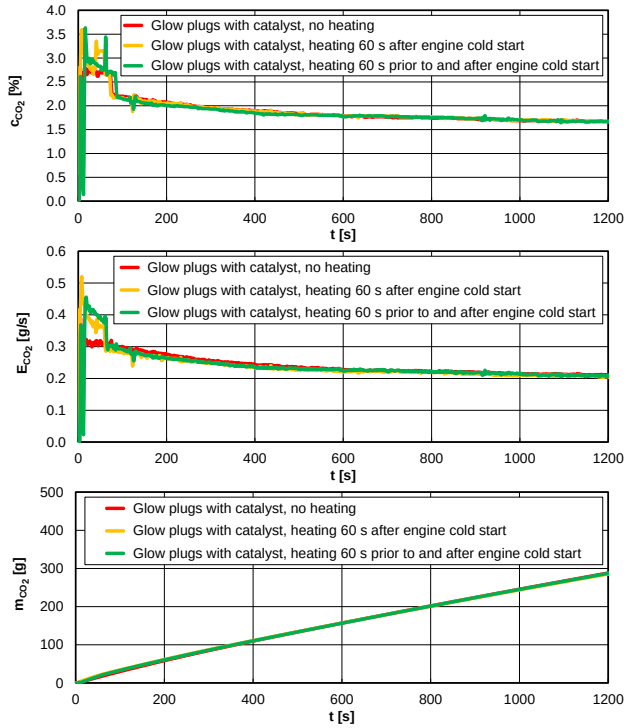

Fig. 6. Concentration, intensity of emission and emission of carbon dioxide during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

4. Conclusions

Summarizing the performed investigations of the influence of the time of heating of the catalyst-coated glow plugs during a cold engine start on the exhaust emissions, the following final results were recorded:

1. Emission of carbon monoxide (Fig. 8a):
– no heating condition: 10.14 g,
– heated 60 s after engine start (0+60): 8.77 g,
– heated for 60 s prior to and 60 s after engine start (60+60): 7.21 g.
2. Emission of hydrocarbons (Fig. 8b):
– no heating condition: 1.06 g,
– heated 60 s after engine start (0+60): 0.96 g,
– heated for 60 s prior to and 60 s after engine start (60+60): 0.83 g.
3. Emission of nitrogen oxides (Fig. 8c):
– no heating condition: 1.05 g,
– heated 60 s after engine start (0+60): 1.19 g,
– heated for 60 s prior to and 60 s after engine start (60+60): 1.51 g.
4. Emission of carbon dioxide (Fig. 8d):
– no heating condition: 287 g,
– heated 60 s after engine start (0+60): 285 g,
– heated for 60 s prior to and 60 s after engine start (60+60): 287 g.
5. Particle number (Fig. 8e):
– no heating condition: $3.5 \cdot 10^{11}$,
– heated 60 s after engine start (0+60): $3.4 \cdot 10^{11}$,
– heated for 60 s prior to and 60 s after engine start (60+60): $3.2 \cdot 10^{11}$.

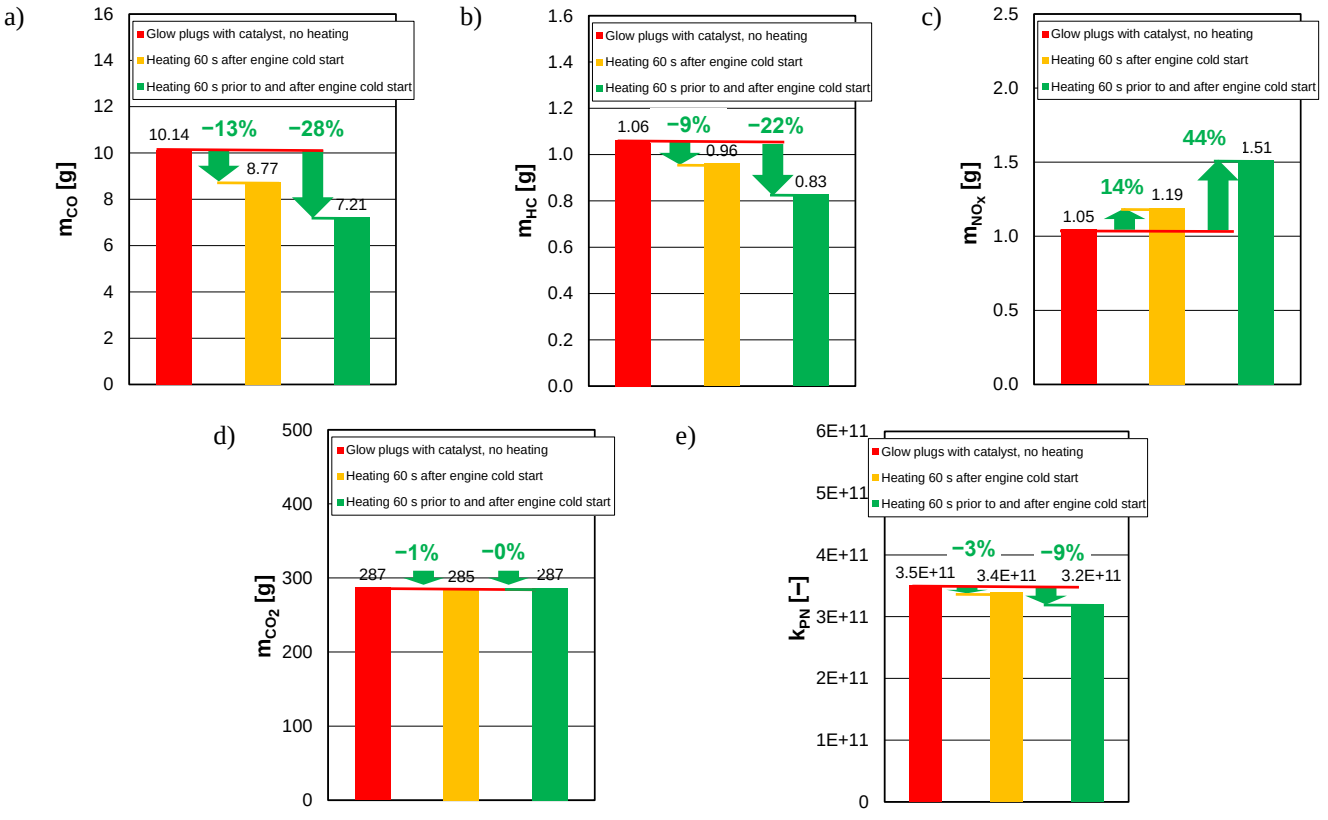

Fig. 8. Comparison of the emission of carbon monoxide (a), hydrocarbons (b), nitrogen oxides (c), carbon dioxide (d) and particle number (e) during the tests performed on a diesel engine depending on the catalyst-coated glow plug heating time

During the comparative investigations of the exhaust emissions with the application of catalyst-coated glow plugs in the measurements carried out for a cold started diesel engine, the following were obtained (values referred to the case when no glow plug heating was applied):

1. For glow plugs heated 60 s after engine start:
– relative reduction of the emission of carbon monoxide by 13%,
– relative reduction of the emission of hydrocarbons by 10%,
– relative reduction of the emission of nitrogen oxides by 14%,
– relative reduction of the particle number by 3%,
– relative reduction of the emission of carbon dioxide by 1%.

2. For glow plugs heated 60 s prior to and 60 s after engine cold start:
– relative reduction of the emission of carbon monoxide by 28%,
– relative reduction of the emission of hydrocarbons by 22%,
– relative reduction of the emission of nitrogen oxides by 44%,
– relative reduction of the particle number by 9%,
– a comparable emission of carbon dioxide.

Therefore, the authors have confirmed an improvement in the efficiency of the oxidation of the exhaust components as the heating time of the glow plug increased.

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