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THE INFLUENCE OF ADDED WATER ON FUEL INJECTOR WEAR IN A DIESEL ENGINE

WPŁYW DODATKU WODY NA ZUŻYCIE ELEMENTÓW APARATURY WTRYSKOWEJ SILNIKA O ZS

Key words: injector, ZS engine, diesel, water, wear.

Abstract The article presents the problem of the wear of the components of injection apparatus of a self-ignition engine during the addition of water. The observer was subject to an injector from the KIPOR KDE3500E generator set engine. The tests carried out consisted in observing the atomizer after 120 minutes of running the engine powered with diesel oil and after working at the same time but with the addition of water to the intake manifold.

Słowa kluczowe: wtryskiwacz, silnik ZS, olej napędowy, woda, zużycie.

Streszczenie W artykule przedstawiono problematykę zużywania się elementów aparatury wtryskowej silnika o zapłonie samoczynnym podczas dozowania wody. Obserwacji podlegał wtryskiwacz z silnika agregatu prądotwórczego KIPOR KDE3500E. Przeprowadzone badania polegały na obserwacji stanu rozpylacza po 120 minutach pracy silnika zasilanego olejem napędowego oraz po pracy w takich samych warunkach, lecz z dodatkiem wody do kolektora ssącego.

INTRODUCTION

Experimental studies have revealed that fuel consumption and nitric oxide emissions can be effectively minimized through the addition of a diesel-water emulsion into the inlet manifold or directly into the cylinder. Particulate matter emissions can also be decreased under specific conditions and when fuel consumption is reduced **[L. 1]**. In compression-ignition engines, injection systems have to guarantee the required engine power while minimizing fuel consumption. The combustion process inside the engine is influenced by fuel injection; therefore, the proportion of water in the diesel-water emulsion has to be adjusted to the quantity of burned fuel. The use of water in the combustion process shortens the life of engine parts, in particular injectors. Around 40% of engine failures are caused by fuel injection problems. Most injector malfunctions result from suboptimal fuel quality and contamination with particulate matter. High-precision systems which inject fuel at high pressure and with high frequency are particularly susceptible to damage **[L. 2, 3]**.

The fuel supplied by the injection pump is atomized into very small particles to maximize combustion efficiency and direct the fuel into the combustion chamber **[L. 4]**.

The fuel injector consists of three main assemblies **(Fig. 1)**:

– The spray nozzle composed of the injector needle and the nozzle seat;
– The valve spring mechanism which automatically closes the nozzle when the needle returns to its seat and maintains the required injection pressure; and,
– The injector body with a high-pressure fuel inlet, fuel leak-off and connecting elements for mounting the injector in the cylinder head.

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Electromagnetic and piezoelectric injectors are used in the fuel supply system of modern diesel engines. Despite structural differences between generations, electromagnetic injectors are still the most damage-prone elements of the fuel supply system. Injectors operate in extreme conditions which include high temperature and pressure, a ballistic range of travel, and turbulent fluid flow **[L. 5]**.

Injection characteristics, namely, the rate of fuel flow from nozzle holes, as a function of time or the crank angle significantly influence the combustion process. The fuel supply system significantly influences engine performance and fuel consumption; therefore, it has to ensure highly reliable long-term performance. Fuel injectors are most susceptible to damage due to their structure, complex operation, and mechanical and thermal loads **[L. 6]**.

Fig. 1. View of the injector
Rys. 1. Widok wtryskiwacza

Nozzle wear is an undesirable phenomenon, which induces changes in geometric and physicochemical parameters during operation. The nozzle's condition is determined by its geometric properties, including dimensions, shape, surface roughness, waviness, the direction of grinding operations, and surface irregularities. Its physicochemical parameters include the structure and the chemical composition of the material, microhardness distribution, and characteristics of dislocation stress **[L. 7]**.

The following types of wear can be observed on the surface of a fuel injector: chemical, abrasive, corrosive, erosive, oxidative, thermal, cavitation, and fretting. Chemical wear accelerates other types of wear or the formation of new substances that are easier to remove than the structural material. Oxidative wear is observed on surfaces that come into frictional contact, where an oxidized surface layer is created and removed. Oxidative wear occurs during boundary, sliding, and dry friction. Corrosion is the gradual degradation of material due to interactions with the environment. Abrasive erosion is caused by particles of abrasive material carried with fuel which grind away the structural material. Cavitation wear occurs during rapid phase change from the liquid phase to the gaseous phase when pressure is reduced. Fretting is the local loss of material in the elements of the fuel supply system that are subjected to vibration or sliding during rotational motion or reciprocating motion or are translocated during cyclic loads and intensive corrosive wear **[L. 8, 9]**.

The above processes apply mostly to friction pairs, and they are caused by active substances in fuel, in particular sulphur compounds. Fuel components contribute to the corrosion of combustion engine elements. Fuel injectors are particularly susceptible to the chemical and erosive impacts of fuel as well as high combustion temperatures in the cylinder.

Effective environmental protection policies aim to minimize both vehicle exhausts and non-exhaust emissions. Exhaust emission standards for engines with a low power output, such as the engines applied in diesel generators, will be introduced in 2019 **[L. 10]**. The presence of contaminating substances should always be checked when filling the fuel tank. Dirt and other contaminants can block injectors and speed up the wear of precision machined elements of the fuel supply system, and moisture can accelerate corrosion. In high-performance diesel generators, fuel consumption reaches around 0.26 kg/kWh at nominal load **[L. 11, 12, 13]**.

MATERIALS AND METHODS

The aim of this study was to examine the condition of injector elements under exposure to water supplied to the cylinder by the suction manifold. The results will be used in future experiments where various methods of supplying water to the cylinder will be analysed in a diesel generator to determine methods that are characterized by the lowest pollutant emissions. The accuracy of the performed measurements can be compromised by injector malfunctions under water exposure. The planned tests will last around 120 minutes; therefore, the injector was exposed to water for 120 minutes in the present experiment.

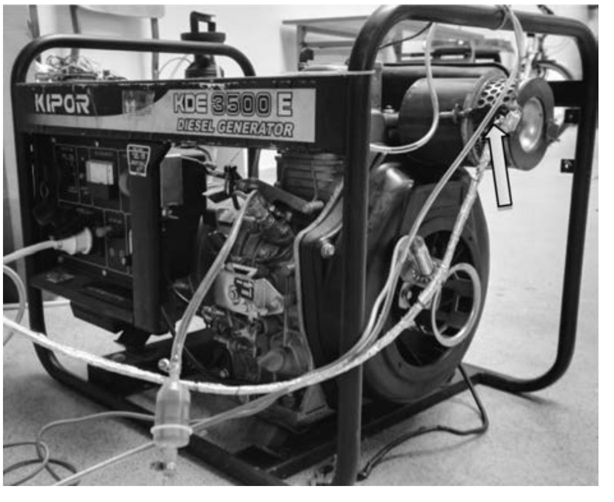

Fig. 2. View of the generator set KIPOR KDE3500E
Rys. 2. Widok agregatu prądotwórczego KIPOR KDE3500E

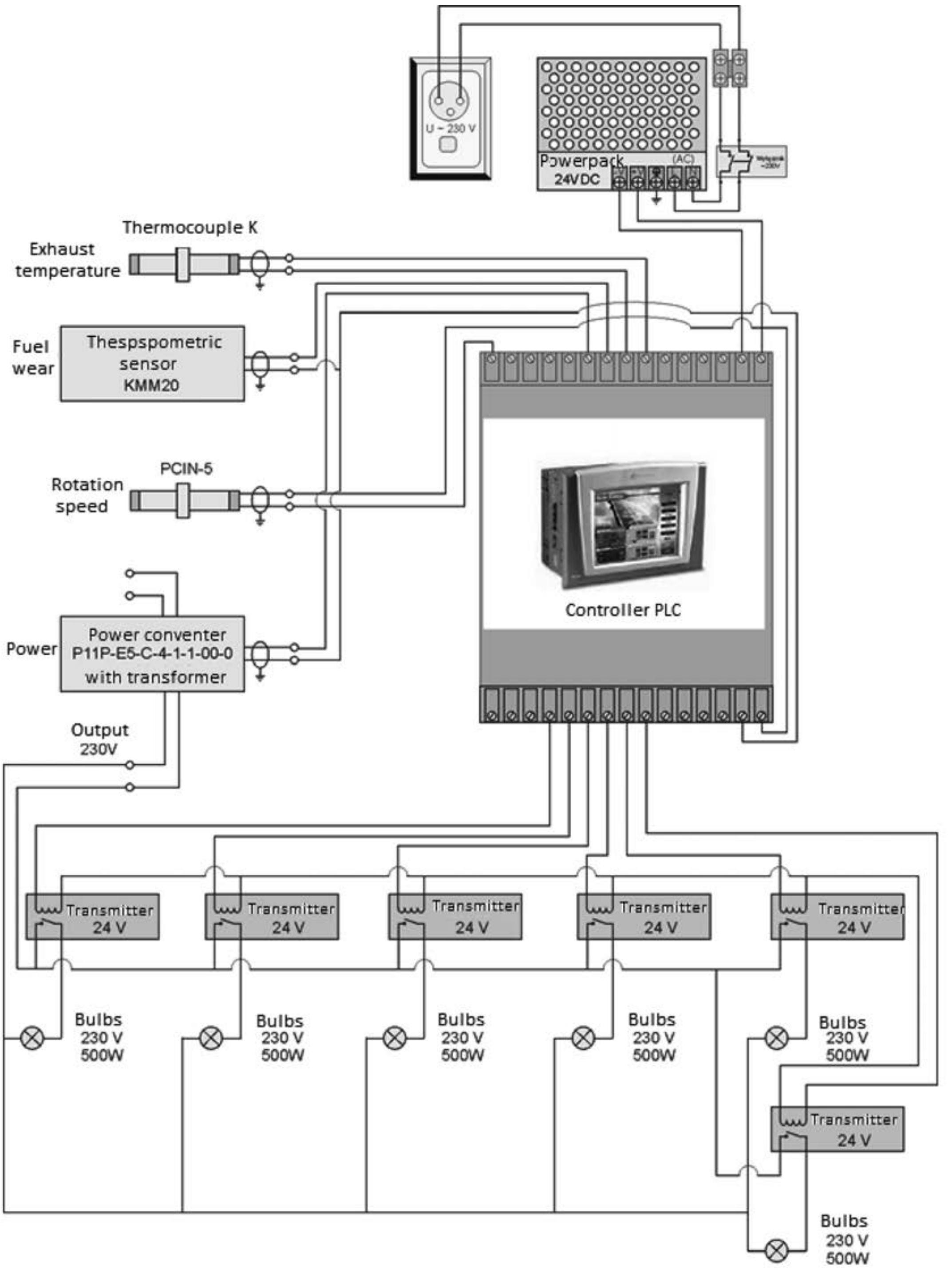

Fig. 3. View of the operating system for the operation of the generator set
Rys. 3. Widok układu nadzoru funkcjonowania agregatu prądotwórczego

The study was performed on a fuel injector with three nozzle holes in a KIPOR KDE3500E diesel generator. The engine was equipped with a water injection system, whose location is marked with an arrow in **Figure 2 [L. 14]**. The injector was inspected for external damage with the use of a Motic SMZ-143 Series microscope and a Moticam 2300 camera **[L. 15]**. Two tests were carried out under identical conditions, identical load, and identical crankshaft rotational speed. Testing time was 120 minutes. In the second test, water was supplied to the suction manifold. In both tests, the load in the diesel generator was controlled by a programmable logic controller (PLC), which activated load resistors **(Fig. 3**). The controller also monitored fuel consumption and exhaust gas temperature. Exhaust gas composition (CO_2, CO, O_2, and NO) was determined in both tests (**Tables 1** and **2**) with the use of a Kane Auto Plus 5-2 emission analyser (**Fig. 5**). Nitric oxides were reduced with the addition of water and an increase in load. Lower loads increased CO concentration during the combustion of diesel oil both with and without the addition of water. Carbon dioxide levels remained constant in both tested scenarios. Fuel consumption was determined at 0.59 kg/h and water consumption – at 0.243 kg/h under nominal load. The consumption of pure diesel oil was reduced by 2% during the test.

Table 1. The results of measurements of the exhaust gas volume during the combustion of diesel oil
Tabela 1. Wyniki pomiarów strumienia objętościowego spalin podczas spalania oleju napędowego

Load [W]	CO_2 [%]	CO [%]	O_2 [%]	NO [ppm]
0	2	0.13	17.72	153
466	2.9	0.08	16.37	340
927	3.7	0.04	15.33	489
1396	4.4	0.05	14.12	644
1862	5.4	0.07	12.68	834

Table 2. The results of measurements of the exhaust gas volume during the combustion of diesel oil with the addition of water
Tabela 2. Wyniki pomiarów strumienia objętościowego spalin podczas spalania oleju napędowego z dodatkiem wody

Load [W]	CO_2 [%]	CO [%]	O_2 [%]	NO [ppm]
0	2.1	0.11	18.09	127
466	2.6	0.09	17.42	205
927	3.2	0.09	16.57	305
1396	4	0.06	15.53	446
1862	4.9	0.06	14.34	609

RESULTS

The working surfaces of the injector needle (**Fig. 4**), particularly its cylindrical and conical surfaces, were evaluated during a visual inspection. This friction pair had a 1–3 µm clearance in the cylindrical section, and the

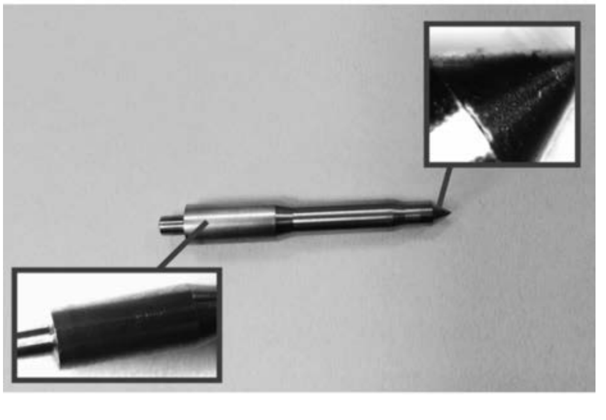

Fig. 4. View of the working surfaces of the injector needle after the test
Rys. 4. Widok powierzchni roboczych iglicy wtryskiwacza po badaniu

Fig. 5. The appearance of the external surface of the nozzle after the test
Rys. 5. Wygląd powierzchni zewnętrznej rozpylacza po badaniu

roughness of the conical section, which is responsible for the tightness between the needle and the nozzle seat, was determined at R_a = 0.25–0.16 μm. The condition of the evaluated working elements was similar in both tests, which suggests that the addition of water over a period of 120 mm did not contribute to nozzle wear.

The production of carbon and tar deposits, and, consequently, high-temperature pyrolysis **[L. 16]** in nozzle holes were accelerated when more water was added to the inlet manifold (**Figs. 5** and **6b**). The above resulted from a temperature decrease in the cylinder (**Fig. 7**), which contributed to incomplete fuel combustion. Injector failure rates increase during prolonged operation under the above conditions due to the accelerated wear of components. Incomplete combustion of hydrocarbons leads to the formation of carbon deposits. However, carbon deposits can be minimized by adjusting the nozzle angle (**Fig. 6c**).

The observed amount of carbon deposits in nozzle holes indicates that the addition of water to an operating diesel engine increases the deposition of incompletely burned hydrocarbons.

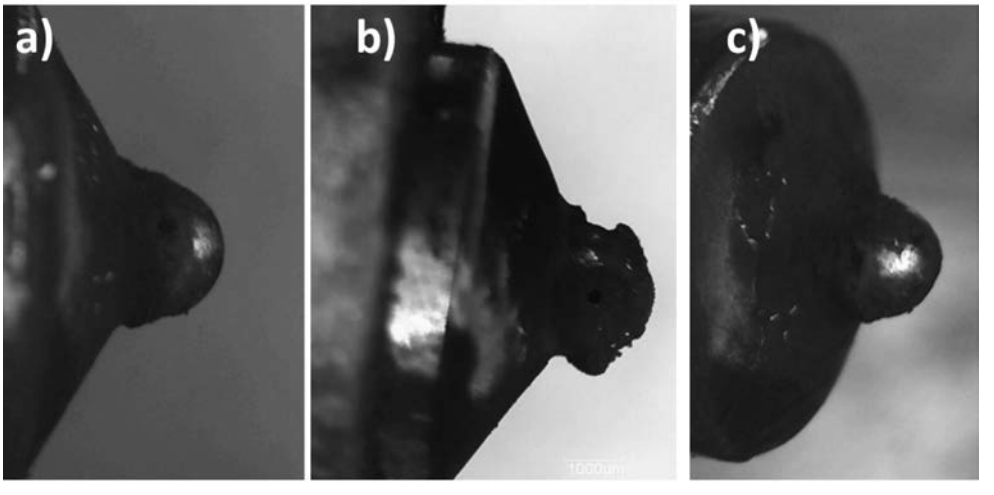

Fig. 6. View of the nozzle head: a) wear of the nozzle surface, b) nozzle surface wear (41% water added), c) nozzle surface wear (41% water added, increased injection start angle)

Rys. 6. Widok głowicy rozpylacza: a) zużycie powierzchni rozpylacza, b) zużycie powierzchni rozpylacza (41% dodatku wody), c) zużycie powierzchni rozpylacza (41% dodatku wody, zwiększony kąt początku wtrysku)

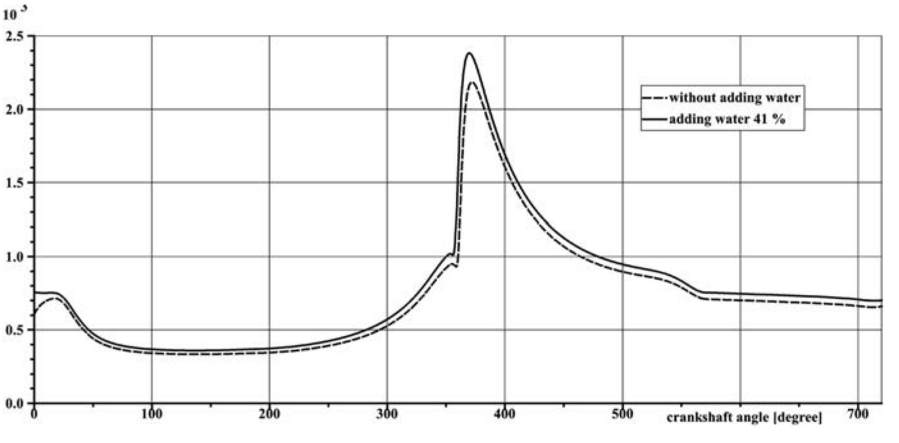

Fig. 7. Temperature change in the engine cylinder

Rys. 7. Zmiana temperatury w cylindrze silnika

CONCLUSIONS

According to experimental studies, fuel consumption and nitric oxide emissions can be effectively reduced by adding water to the inlet manifold. The results of this study indicate that NO_x emissions can be minimized by supplying water to the cylinder. Carbon deposits are formed on the external surface of the injector needle when a standard nozzle angle is used. The nozzle angle should be increased to reduce carbon deposits.

The fuel injection process influences combustion in the cylinder. The amount of injected water should be closely adjusted to the quantity of burned fuel. Optimal water injection decreases the content of nitric oxide in exhaust gas and lowers fuel consumption. In the current experiment, NO_x concentration in exhaust gas decreased by 30% with 41% addition of water.

The production of carbon and tar deposits and, consequently, high-temperature pyrolysis in nozzle holes are accelerated when more water is added to the inlet manifold. The above results from a temperature drop in the cylinder during combustion. These undesirable phenomena can be minimized by adjusting the spray angle.

The results of this study indicate that the condition of fuel injections should be closely inspected when water is added to the inlet manifold. Based on the method proposed in this study, the injector could be inspected visually to determine the effect of added water on the surface wear of the injector needle and the nozzle.

The condition of the evaluated working elements was similar in both tests, which suggests that the addition of water over a period of 120 min does not contribute to nozzle wear.

REFERENCES

1. Murayama Tadashi, Tsukahara Minoru, Morishima Yaushi, Miyamoto Noboru: Experimental reduction in NOx, smoke and BSFC in a diesel engine using uniquely produced water (0–80%) to fuel emulsion. Society of Automotive Engineers. SAE paper no. 780224; 1978.
2. Durczak T., Sander P., Longwic R., Lotko W.: Analiza przyczyn niezdatności układów wtrysku paliwa stosowanych w silnikach samochodów ciężarowych. Autobusy 6/2016, s. 844–848.
3. Włodarski J.K.: Tłokowe silniki spalinowe – procesy trybologiczne. WKiŁ, Warszawa 1982.
4. Stoeck T., Osipowicz T. 2015: Analiza uszkodzeń i stopnia zużycia wtryskiwaczy Common Rail Bosch. Autobusy. Eksploatacja i testy, s. 240–244.
5. Ambrozik A., Ambrozik T., Kurczyński D., Łagowski P.: The Influence of Injection Advance Angle on Fuel Spray Parameters and Nitrogen Oxide Emissions for a Self – Ignition Engine Fed with Diesel Oil and FAME. Polish Journal of Environmental Studies, Vol. 23, No 6, 2014, pp. 1917–1923.
6. Bejger A. 2006: Zużycie i możliwości diagnozowania wybranych elementów układu wtryskowego silników okrętowych, Diagnostyka'4 (40) s. 47–50.
7. Lif A., Holmberg K.: Water in diesel emulsions and related systems. Adv Colloid Interface Sci 2006, s. 123–126.
8. Monieta J., Kusiak P. 2008: Badania zużycia przez utlenianie i korozję powierzchni rozpylaczy wtryskiwaczy silników okrętowych. Problemy Eksploatacji 1, s. 113–120.
9. Antoszewski B., Tofil S.: Odporność na zużycie erozyjne i ścierne powłok natryskiwanych cieplnie. Przegląd Spawalnictwa 8/2012, s. 3–6.
10. https://www.dieselnet.com/standards/eu/nonroad.php.
11. Idzior M., Borowczyk T., Karpiuk W., Stobnicki P.: Możliwość badania stanu technicznego nowoczesnych wtryskiwaczy silników o zapłonie samoczynnym. Logistyka, Poznań 03/2011.
12. Kwiatkowski K., Żółtowski B.: Ekologiczne aspekty oddziaływania silników wysokoprężnych. Diagnostyka'26, s. 107–109.
13. Kadota T., Yamasaki H.: Recent advances in the combustion of water fuel emulsion. Prog Energy Combust Sci 2002; 28: 385–404.
14. Asad U., Kelly C., Wang M., Tjong J.: Effect of Intake Air Humidity on the NOx Emissions and Performance of a Light – Duty Diesel Engine. ASME 2012 Internal Combustion Engine Division Fall Technical Conference. Paper No. ICEF2012-92027, pp. 235–242.
15. https://alnar.pl/kipor-kde-6700-ta3-agregat-pradotworczy-p-7599.html.
16. http://www.spectra-shop.de/mikroskop-trinokular/motic-smz-143-n2led-trinokular-zoom-stereo-mikroskop.html.
17. http://odpadyblog.pl.