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Investigations of fume emissions of combustion engines

Key word

Combustion engines, toxic fume components, environmental protection.

Słowa kluczowe

Silnik spalinowy, składniki toksyczne, zagrożenia środowiska.

Summary

The results of the investigations of the post and exploitation emissions of the harmful components of the fumes of engines from ZS were introduced in the work. Obtained results were subjected to a statistical study according to new computer procedures. Qualitative and quantitative reports were established for the level and kind of emission in reference to the changes of the state of studied engines.

1. Introduction

The assumption for the research of this work was the performance of the analysis of the influence of the starting phase and engine warming on the harmful emission at these states of engine work, especially concerning climate conditions in Poland. In the range of research, the analysis of the emission of

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harmful compounds was performed during the first few minutes after the start-up of a cold and warmed-up engine in the neutral gear at different temperatures of the environment.

The conducted research was conducted on the work of high-pressure engines of different destination. Exploitation generally takes place in changeable unsettled conditions, which considerably influences the general emission of harmful components of fumes.

The contribution of harmful components of fumes of ZS engines into total atmosphere pollution is as follows: There are mostly solid particles (PM) and nitro-oxides (NOx) in fumes, while in smaller amounts, there is carbon oxide (CO) and unburned hydrocarbons (HC).

The results of laboratory and exploitation tests on a chosen group of ZS engines allow the determination, practically and cognitively, of important premises in the field of toxic effects of ZS engines on the environment.

2. Research objects

The research of his work, in the field of recognising toxic components generated by ZS engines for different modelled technical states and changeable external temperature, were performed on a stationary engine S-359 in the laboratory UTP. The practical verification of the results of the research in the range of quality changes of the toxic components of fumes in operation conditions of S-359 engines was performed over 2 years of exploitation on the group of 20 vehicles with such engines – Fig. 1.

Fig. 1 General view of test stations
Rys. l. Ogólny widok stanowisk pomiarowych

The object of research in this work was S-359 engine with self-acting fusion whose basic technical data is presented in Table 1. It is an engine of a wide practical application, and characterised by small unitary fuel use, good dynamic characteristics, and high durability.

Table 1. Basic technical data of the engine S- 359 [105]
Tabela 1. Podstawowe dane techniczne silnika S- 359 [105]

Cylinder formation	row, vertical
Number of cylinders	6
Cylinder diameter	110 mm
Piston stroke	120 mm
Swept capacity	6.842 dm^3
Compression degree	17
Order of cylinder work	1-5-3-6-2-4
Maximum Power	110 KW with 2800 min^{-1}
Maximum turning moment	438Nm with 1800-2100min^{-1}
Minimum unitary fuel use	224 g/kWh
Statistical angle of pumping beginning	18.5^{0}OWK before GMP
Injection system	Direct
Injection pump	P-76G10
Injection pressure	22MPa

The engine is the driving unit for trucks: Star 200 – street, Star 266 – cross-country, produced in Starachowice (at present: Star Trucks Sp.z o.o). These cars are widely used in the national industry, as well as military service.

Fig. 2 shows the chosen elements of the test station in the laboratory and at the exploitation test station, together with elements of the measuring set.

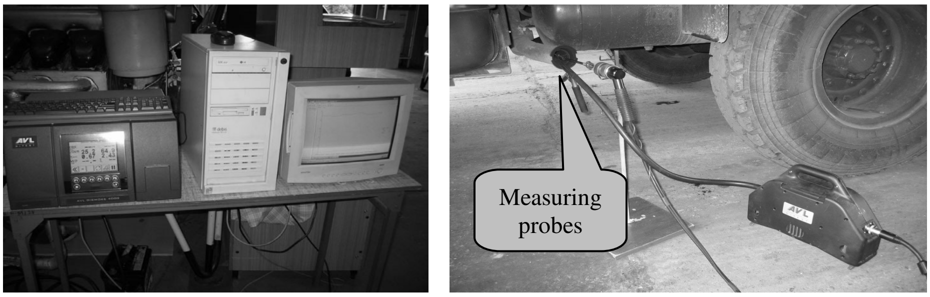

Fig. 2. Research objects and measuring instruments at the test station
Rys. 2. Obiekty badań i aparatura pomiarowa

The tested combustion engines belong to the group of exploitation objects used in difficult training conditions of military service. Large and changeable loads of engines implied by inexperienced drivers diversified their technical state, which for the research of his work posed a challenge in the preparation of the experiment, its proper realisation, and the careful statistical work.

3. Testing stations

Stationary tests were performed in a laboratory of combustion engines located inside laboratory rooms in order to obtain natural environment conditions. It was important to consider the acquisition of different temperatures in which the engine S-359 was thermally stabilised and the temperature of the air used for running the engine.

Before proceeding with the tests, the following were checked and regulated:

a. The technical state of the engine;
b. The injection pump at the probing station, type PW-8, predestined for testing fuel equipment of high-pressure engines with regard to dosage and performance, according to BN-88/1301-16 velocity characteristics of fuel injection;
c. The injectors used for the tests were checked and regulated on an injector probe type PRW-3, performing the evaluation of the pressure of the injector's opening, tightness and trickling of the sprayer, and the correctness of fuel spraying;
d. Intake and exhaustion valves – according to the manufacturer's suggestions.
e. During the test, the following were registered:
f. The multi-component composition of exhausted fumes of the engine,
g. The smoke of fumes with a smokemeter AVL.

Fume tests concerning the quantity of toxic substances were performed with the use of a multi-component analyser of fumes LANCOM, whose general image is presented In the Fig. 3. The analyser, LANCOM, enables the measurements of: CO, CH, NOx, SO2, fume temperature, and environment temperature.

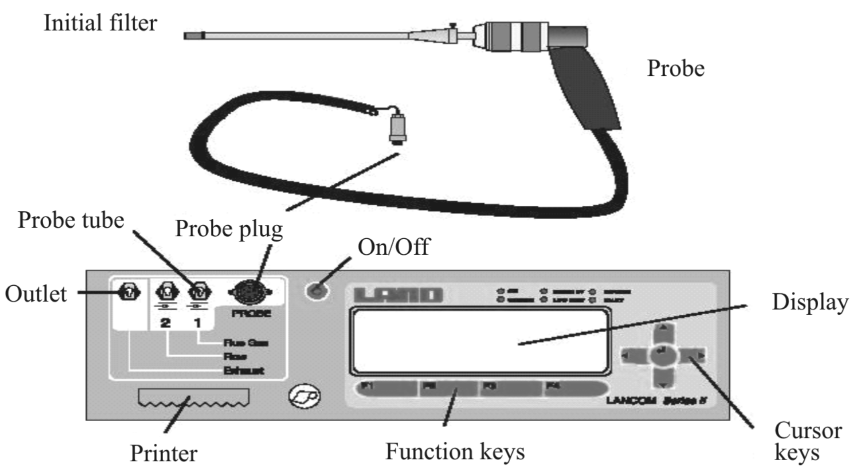

Fig. 3. General image of fume analyser, LANCOM, with fume acquisition probe
Rys. 3. Ogólny widok analizatora LANCOM II z sondą pomiarową

The measurements of the smoke degree of fumes of ZS engines were performed with the use of a smokemeter AVL-4000. For statistical processing, the measured values were recorded in a spreadsheet (Excel).

Exploitation tests were performed in real conditions on the group of 20 vehicles with the use of the same instruments and generally the same research methodology which had been used in stationary tests (Fig. 4).

Fig. 4 General view of the exploitation tests station
Rys. 4. Ogólny widok stanowiska badań eksploatacyjnych

4. Testing conditions

A. Stationary tests

In order to obtain a wide range of temperatures of engine start-up, the tests were performed over a dozen months, taking into account summer and winter months. The engine, before each test, was subjected to thermal stabilisation, thanks to which all elements of the engine and exploitation liquids and exhaust system had the same temperature, which was equal to the temperature of the environment.

The temperatures of the environment and motor oil were measured directly, prior to each measurement, and if the temperature differences did not exceed 1°C, the measurement began.

Also performed were tests in the conditions of a hot start-up, i.e. during a start-up of an engine before being warmed-up to a normal temperature (oil temp. 80°C) in certain environmental conditions. During the measurement, the following were registered (LANCOM, AVL): the contents of carbon oxides (CO), hydrocarbons (HC), nitro-oxides (NO_x) in fumes, motor oil temperature, rotational speed of the crankshaft, the temperature of the environment, and fume smoke.

Considering the aim of the work, stationary research was performed in the conditions of cold and hot start-up of the engine for the recognised seven states:

1. Apt engine (with regulation settings suggested by the manufacturer);
2. The values of the advance angle of fuel injection of 10°OWK (delayed injection – nominal advance angle of fuel injection advance, 18.5°OWK);

3. The values of the advance angle of fuel injection of 24°OWK (advance injection);
4. For the pressure of injection processes beginning in cylinders: first 20MPa, fifth 18MPa and third 16MPa (nominal injection pressure – 22MPa);
5. For the pressure of injection processes beginning in cylinders: sixth 23MPa, second 24MPa and fourth 25MPa (in the other cylinders nominal injection pressure – 22MPa);
6. For inlet valves clearings in cylinders: first, fifth and third 0.15 mm each;
7. For inlet valves clearings in cylinders: first, fifth and third 0.45 mm each (nominal inlet valves clearing – 0.3mm).

The tests were performer for two variants of the engine's thermal states: cold and hot start-up in temperatures of 5°C, 10°C and 20°C. During the tests, there was constant registration of fume emissions during work in neutral gear from the moment of starting and for the first 6 minutes of the engine operation.

B. Exploitation tests

Exploitation tests were realised in real conditions on a group of 20 randomly chosen vehicles with the engine S-359 throughout the period of 2 years in a military facility. The tests on toxic substances emission in fumes (CO, HC, NO_x and PM) of ZS engines during a hot start-up (oil and cooling liquid temperature – 70-80°C) were performed at different environmental temperatures, with a special consideration of kilometres vehicles had been driven and operation-maintenance actions carried out during breaks in tests.

The average daily usage of each car was about 70 km, sustaining the regime of car operation suggested by the manufacturer with an average of about 14000-16000 km per vehicle yearly.

5. Stationary tests results

The measurements of emissions of fumes toxic components and smoking of the engine with self-acting fuse S-359 in the laboratory were realized for specified states, at slow rotations of the crankshaft for three environment temperatures (5°C, 10°C, 20°C), with cold and hot start-up.

The further presented juxtapositions of measurements results of stationary tests on the contents of CO, HC, NO_x and smoking were obtained for cold and hot start-ups taking place In repeatable testing conditions.

The results of stationary tests in the range of estimating toxic components emissions (*NOx, CO, HC*) o fan apt engine for cold and hot start-up at environment temperatures: 5, 10 and 20°C. The coefficient of fumes smoking (*k*) for the examined conditions is given in the description of Fig. 5.

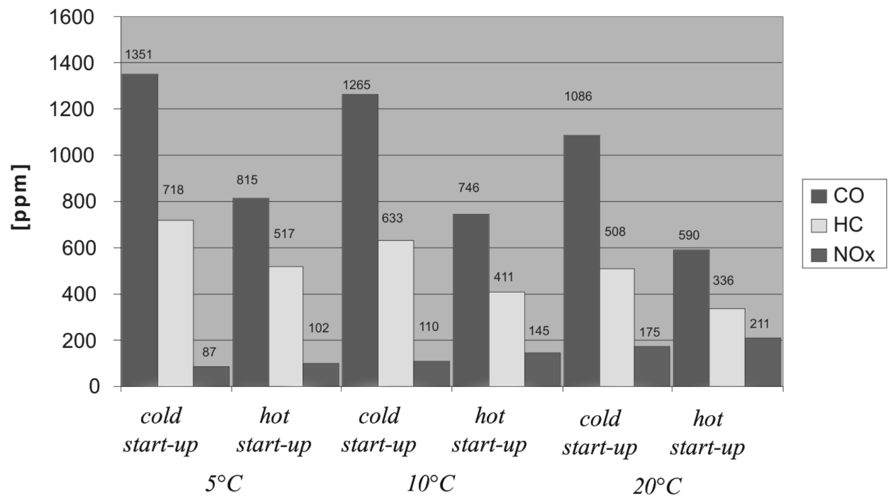

Fig. 5. Juxtaposition of emission of examined fumes components of an apt engine
Rys. 5. Zestawienie emisji badanych składników spalin silnika zdatnego

Research results of smoking of an apt engine in a cold and hot start-up are presented in the Fig. 6.

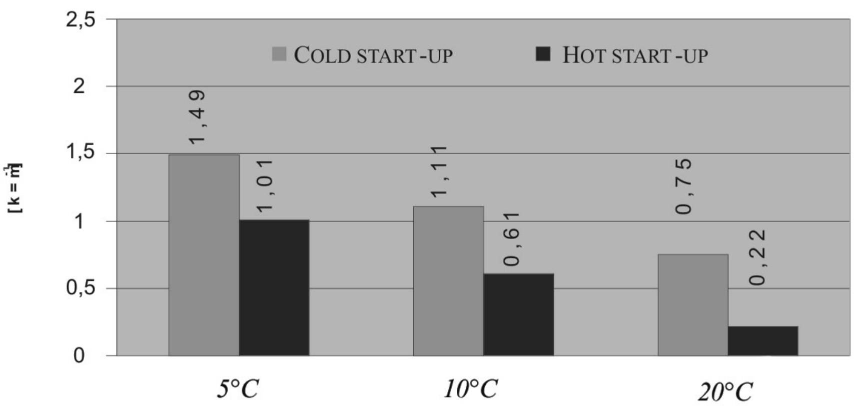

Fig. 6. Juxtaposition of coefficient values of smoking for an apt engine at cold and hot start-up
Rys. 6. Zestawienie wartości współczynników zadymienia dla silnika zdatnego przy rozruchu zimnym i gorącym

The volume of separate components of fumes and smoking for the start-up of a cold and hot engine, with a specified angle of injection advance 10°OWK (delayed injection) was shown in the Fig. 7.

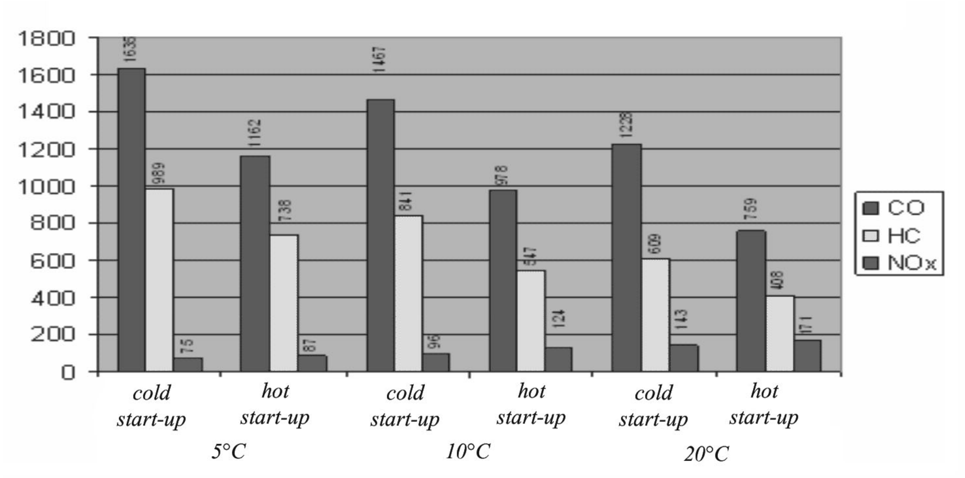

Fig. 7. Overall juxtaposition of emission of separate components of fumes and smoking for the start-up of a cold and hot engine with the angle of injection advance 10°OWK
Rys. 7. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika, przy kącie wyprzedzenia wtrysku 10°OWK

In the Fig. 8 shown below, research results of smoking of the engine for the start-up of a cold and hot engine with the angle of injection advance 10°OWK are shown.

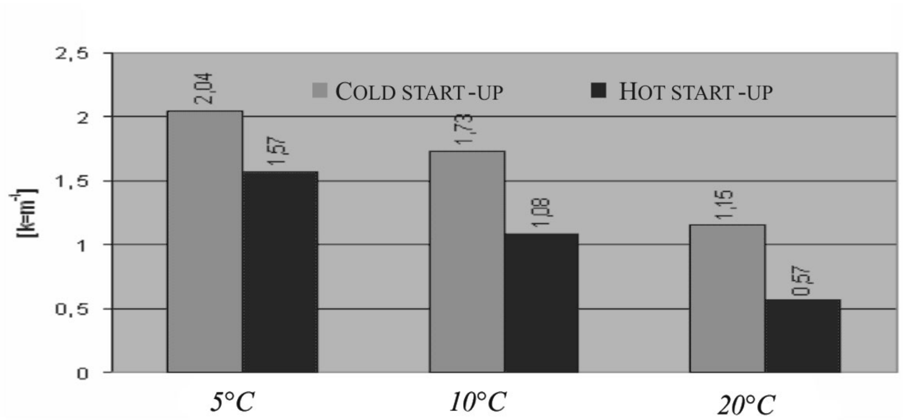

Fig. 8. Juxtaposition of results of smoking for the start-up of a cold and hot engine with the angle of injection advance 10°OWK
Rys. 8. Zestawienie wyników zadymienia podczas zimnego i gorącego rozruchu silnika dla kąta wyprzedzenia wtrysku 10°OWK

Quantity comparison of the emission of toxic components: CO, HC, NOx and smoking, during cold and hot start-up of the engine for the angle of injection advance 24ºOWK – accelerated (nominal 18,5ºOWK) is presented in the Fig. 9.

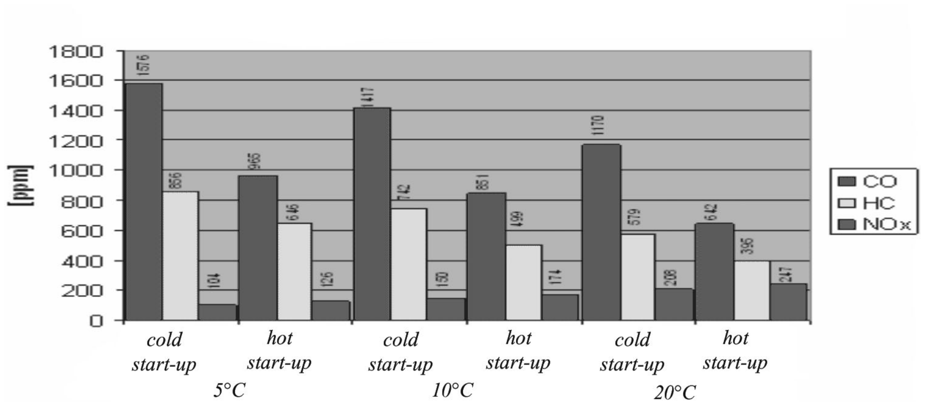

Fig. 9. Overall juxtaposition of the emission of separate fumes components for cold and hot start-up of the engine at the angle of injection advance 24°OWK
Rys. 9. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika przy kącie wyprzedzenia wtrysku 24°OWK

Next Fig. 10 presents research results of smoking of the engine for cold and hot start-up At different environment temperatures (5°, 10°, 20°C), at the angle of injection advance of 24°OWK.

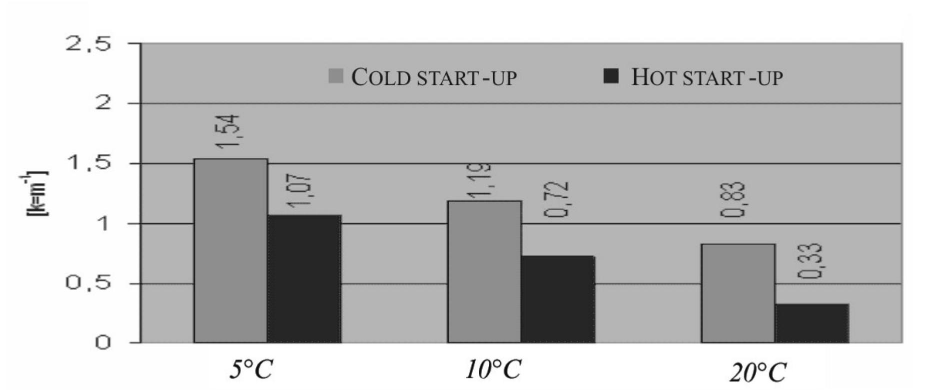

Fig. 10. Smoking juxtaposition during cold and hot start-up of the engine for the angle of injection advance 24°OWK
Rys. 10. Zestawienie zadymienia podczas zimnego i gorącego rozruchu silnika dla kąta wyprzedzenia wtrysku 24°OWK

The volume of the emission of separate fume components at the start-up of a cold and hot engine for the injection pressure of 20MPa, 18MPa, 16MPa in cylinders 1, 5, 3, with sustaining nominal values of pressure (nominal 22MPa) in the other cylinders, is shown in the Fig. 11.

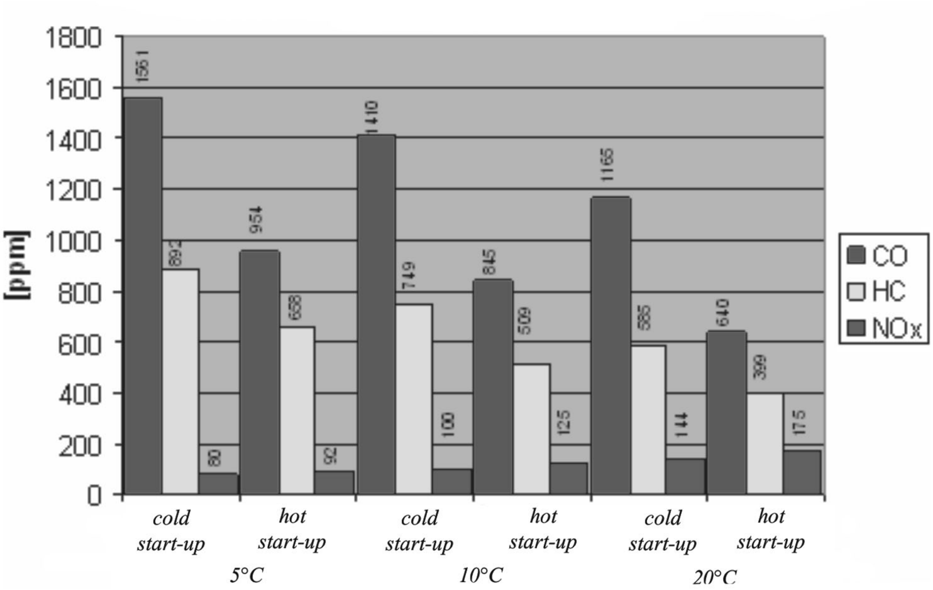

Fig. 11. Overall juxtaposition of emissions of separate fume components for a cold and hot start-up of the engine at injection pressure of 20MPa, 18MPa, 16MPa In cylinders 1, 5, 3
Rys. 11. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika przy ciśnieniu wtrysku 20MPa, 18MPa, 16MPa w cylindrach 1, 5, 3

Overall juxtaposition of results of smoking tests of the engine at cold and hot start-up at different temperatures of the environment for modeled injection pressures in cylinders 1, 3, 5 is shown in the Fig. 12.

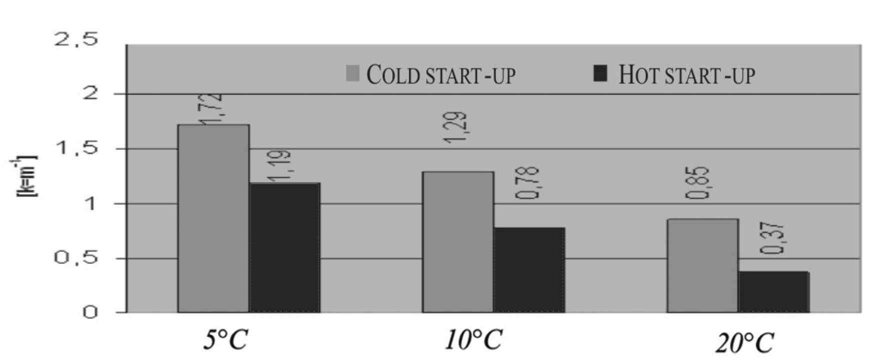

Fig. 12. Juxtaposition of smoking results at cold and hot start-up of the engine for injection pressure In cylinders: 1-20MPa, 5-18MPa, 3-16MPa
Rys. 12. Zestawienie wyników zadymienia podczas zimnego i gorącego rozruchu silnika dla ciśnienia wtrysku w cylindrach: l-20MPa, 5-18MPa, 3-16MPa

The contents of separate fume components and smoking at the start-up of a cold and hot engine at injection pressure of 23MPa, 24MPa, 25MPa in cylinders 6, 2, 4 (in the other cylinders nominal 22MPa) is shown in the Fig. 13.

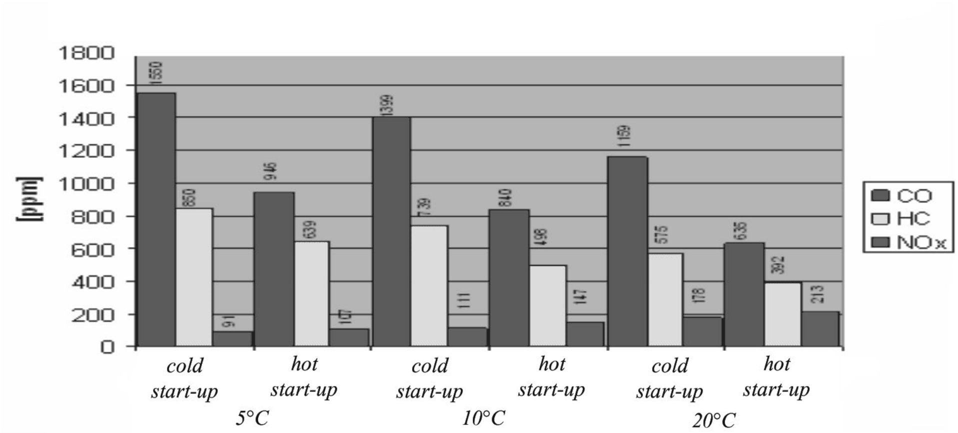

Fig. 13. Overall juxtaposition of emission of separate fume components for cold and hot start-up of the engine at injection pressure 23MPa, 24MPa, 25MPa In cylinders 6, 2, 4
Rys. 13. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika przy ciśnieniu wtrysku 23MPa, 24MPa, 25MPa w cylindrach 6, 2, 4

The values of fume smoking at cold and hot start-up of the engine for modeled injection pressures in cylinders: 6, 2, 4 at different temperatures of the environment, is shown in the Fig. 14.

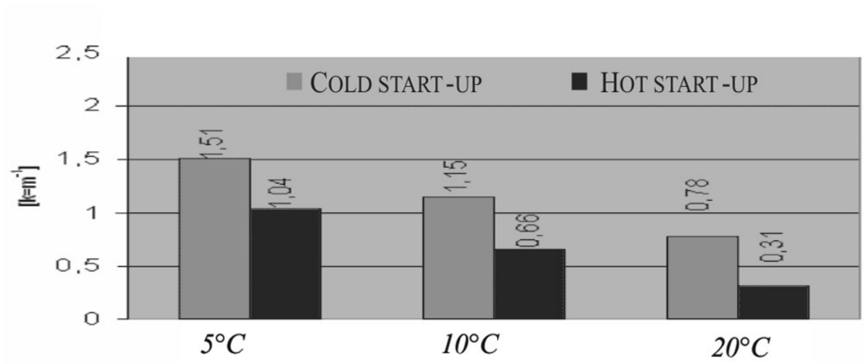

Fig. 14. Juxtaposition of smoking At cold and hot start-up of the engine for the injection pressure In cylinders: 6-23MPa, 2-24MPa, 4-25MPa
Rys. 14. Zestawienie zadymienia podczas zimnego i gorącego rozruchu silnika dla ciśnienia wtrysku w cylindrach: 6-23MPa, 2-24MPa, 4-25MPa.

The contents of emissions of separate fume components and smoking at the start-up of a cold and hot engine for clearing of inlet valves of 0.15 mm in cylinders 1, 5, 3 (nominal clearing 0.3 mm) at different temperatures of the environment, is shown in the Fig. 15.

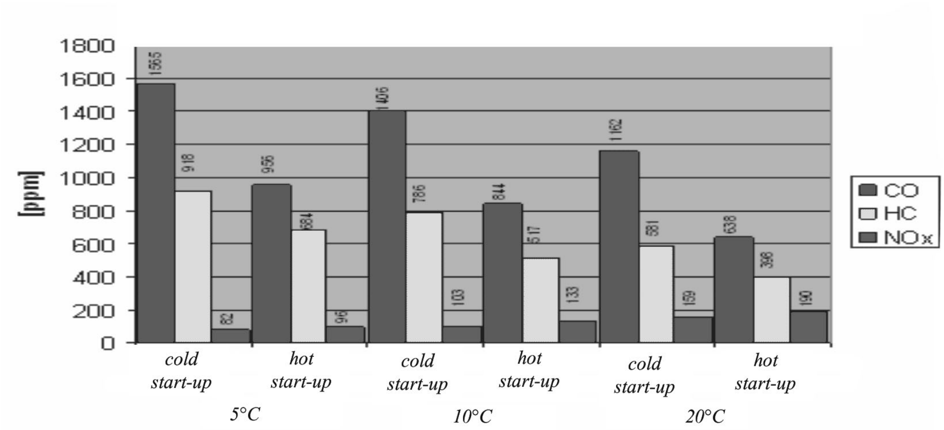

Fig. 15. Overall juxtaposition of emissions of separate fume components for cold and hot start-up of the engine with assumed clearings of inlet valves of 0.15mm in cylinders 1, 5, 3
Rys. 15. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika przy założonych luzach zaworów dolotowych 0,15mm w cylindrach 1, 5, 3

The values of fume smoking at cold and hot start-up of the engine for modeled valve clearings in cylinders: 1, 5, 3 at different environment temperatures is shown in the Fig. 16.

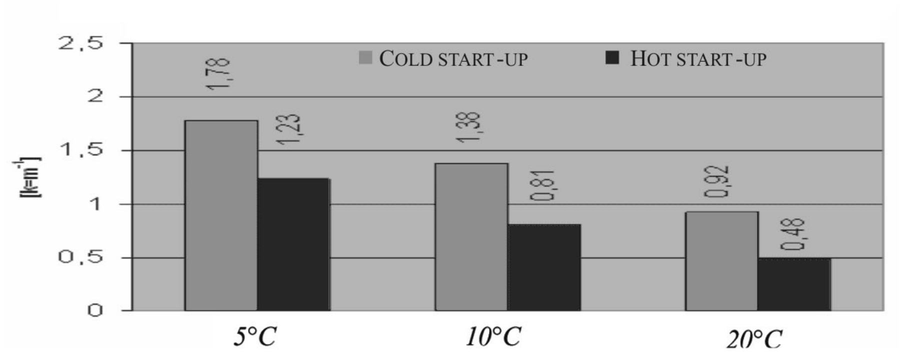

Fig.16. Juxtaposition of smoking for cold and hot start-up of the engine with assumed clearings of inlet valves of 0.15mm in cylinders 1, 5, 3
Rys. 16. Zestawienie zadymienia przy zimnych i gorących rozruchach silnika i założonych luzach zaworów dolotowych 0,15 mm w cylindrach 1, 5, 3

The contents of emissions of separate fume components and smoking at the start-up of a cold and hot engine for clearing of inlet valves 0.45 mm in cylinders 1, 5, 3 (nominal clearing 0.3 mm) at different environment temperatures is shown in the Fig. 17.

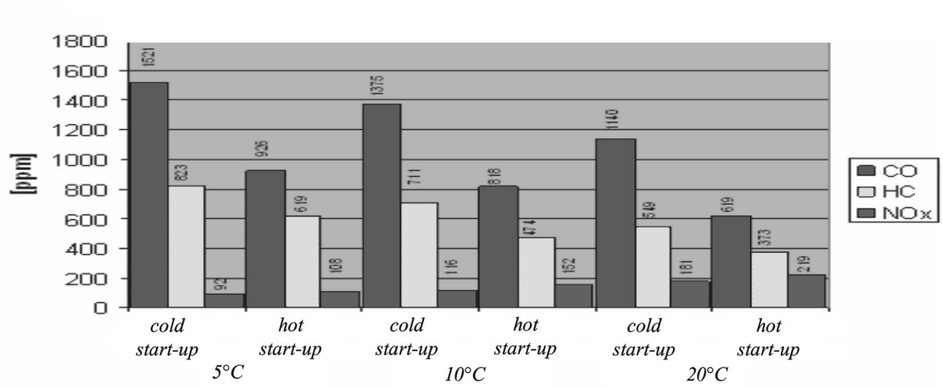

Fig. 17. Overall juxtaposition of emissions of separate fume components for cold and hot start-up of the engine for assumed valve clearings of 0.45mm in cylinders 1, 5, 3
Rys. 17. Zestawienie zbiorcze emisji poszczególnych składników spalin dla zimnego i gorącego rozruchu silnika przy założonych luzach zaworów dolotowych 0,45mm w cylindrach 1, 5, 3

The results of engine smoking tests at cold and hot start-up for different environment temperatures with modeled values of valve clearings is show in the Fig. 18.

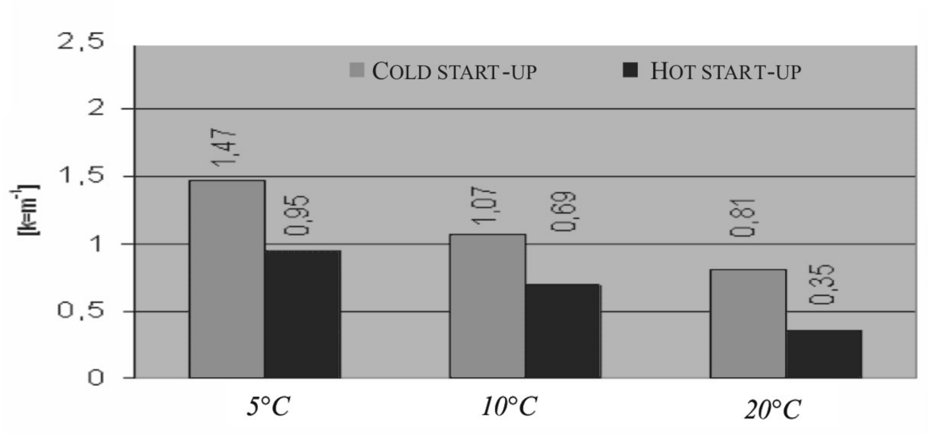

Fig. 18. Juxtaposition of smoking at cold and hot start-ups of the engine and assumed clearings of inlet valves of 0.45 mm in cylinders 1, 5, 3
Rys. 18. Zestawienie zadymienia przy zimnych i gorących rozruchach silnika i założonych luzach zaworów dolotowych 0,45 mm w cylindrach 1, 5, 3

From the examined maladjustments, the highest influence on the increase of emissions of toxic fume components compared to an apt engine, has the delayed angle of injection advance $\alpha_{ww} = 10°C$ before ZZ (nominal $\alpha_{ww} = 18{,}5°C$ before ZZ).

The second, deciding on the number of the volume of emitted toxic substances in fumes, is a maladjustment consisting in the acceleration of the injection advance angle ($\alpha_{ww} = 24°C$ before ZZ). More toxic compounds in fumes are emitted at a delayed angle of injection advance ($\alpha_{ww} = 10°C$ before ZZ) regardless the kind of the engine start-up and environment temperature.

Another maladjustment considerably affecting the volume of emitted toxic fume components is the decrease of clearing of 3 inlet valves from 0.3 mm to 0.15 mm.

The analysis of separate periods of the engine's work showed that a considerable role for a cold and hot start-up of the engine is played by the first 60–70 seconds of work, in which maximum quantities of CO, HC, NO_x and smoking are emitted.

6. Exploitation tests results

From the general number of 20 cars subjected to exploitation tests, 10 cars were chosen for the initial analysis, for which checked was the effect of the quantity of emissions of toxic fume components as well as the degree of smoking in relation to run kilometers In the testing period.

The chosen vehicles were evaluated in respect of the contents of CO, HC, NO_x in fumes, and smoking of the hot engine, which is shown as an example in the Fig. 19.

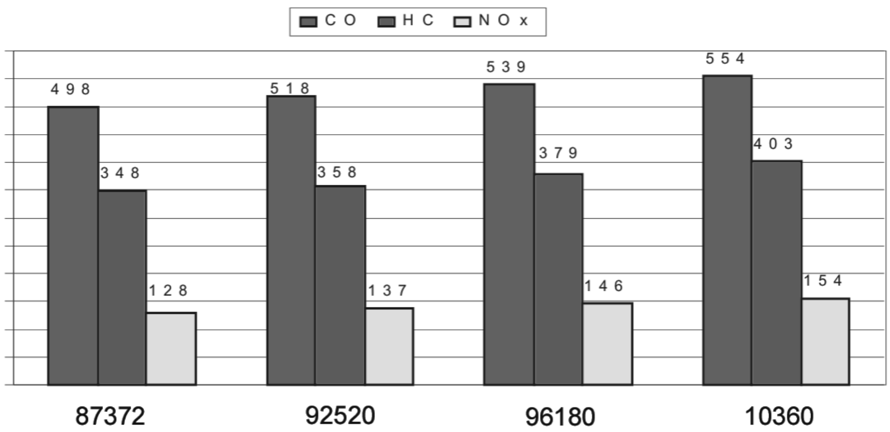

Fig. 19. Overall values of CO, HC, NO_x emissions in relation to run km
Rys. 19. Wartości zbiorcze emisji CO, HC, NO_x w zależności od przebiegu km

The following Fig. 20 presents the juxtaposition of values of engine fumes smoking for different km runs of the car.

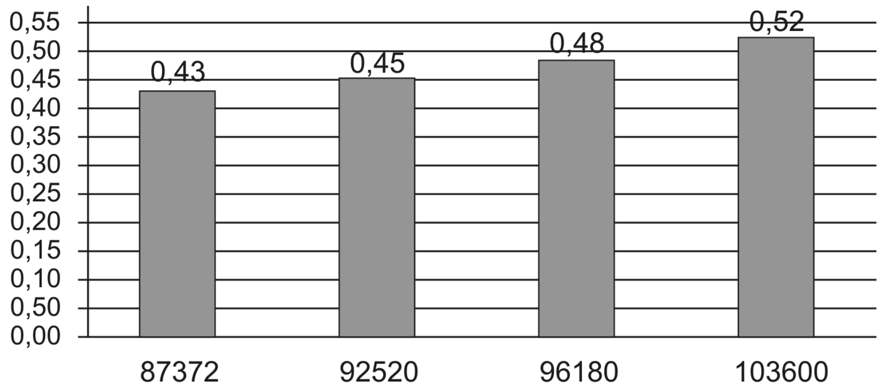

Fig. 20. Smoking of engine fumes depending on the km run
Rys. 20. Zestawienie zadymienia w zależności od przebiegu silnika

Even brie analysis of the presented results of these tests indicates a visible increase of toxic fume components and engine smoking together with increasing mileage of the car. Other test results of the whole group of 20 cars confirm it visibly. It can be stated that together with the increase of the number of run kilometers, the quantities of carbon oxide (CO), hydrocarbons (HC), nitro oxides (NO_x), and smoking go up.

7. Fume test results for engine run on BIO-D10

The possibilities to satisfy increasingly strict regulations force vehicle manufacturers to search new solutions. One of the ways is looking for new, ecologically purer, fuels, among which galenic fuels begin to play a dominant role.

Vegetable oils in their pure form, also colza oil, are not suitable for engines with self-exciting fuse, mainly because of their increased density and viscosity, low cetane number, and insufficient immunity to low temperatures. These disadvantages are absent in products of chemical processes of vegetable oils, called methyl esters, which, combined with diesel oil in appropriate proportions, are called Biodiesel.

Taking the above into account, quality comparison between diesel oil (ON) and the oil BIO-D10 was carried out during test realization. The comparison of qualities of BIO-D10 fuels with ON, used for tests, is shown in the Table 2. The characteristics of BIO-D10 fuel, produced in refinery Trzebinia, are included in the certificate No. 5100634, issued by the manufacturer.

Table 2. Comparison of chosen characteristics of test fuels of the engine S-359
Tabela 2. Porównanie wykonanych charakterystyk paliw silnika S-359

Characteristics	Unit	Diesel Oil	BIO-D10
Density at temp. 15°C	g/m^3	0,836	0,841
Kinematical viscosity at temp. 40°C	mm^2/s	2,76	2,82
Fuse temperature	°C	63,5	72
Cetane number		51,1	52,4
Sulfur contents	mg/kg	6,9	4,8
Temperature of cold filter blockage	°C	-30	-25
Remains after incineration	%(m/m)	0,002	0,003
Water contents	mg/kg	68	93

Juxtaposition for easier comparison of emissions of toxic fume components of diesel oil and BIO-D10 during cold and hot start-ups of the engine in diversified environment temperature is presented in the following figures.

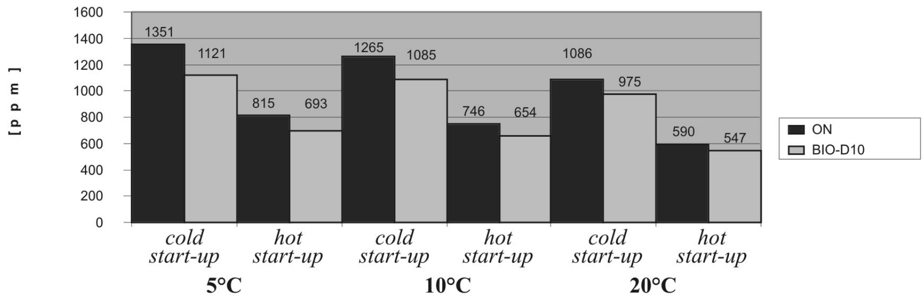

Fig. 21. Juxtaposition of CO emissions values of the engine S-359 run on ON and BIO-D10
Rys. 21. Zestawienie zawartości emisji CO silnika S-359 zasilanego ON i BIO-D10

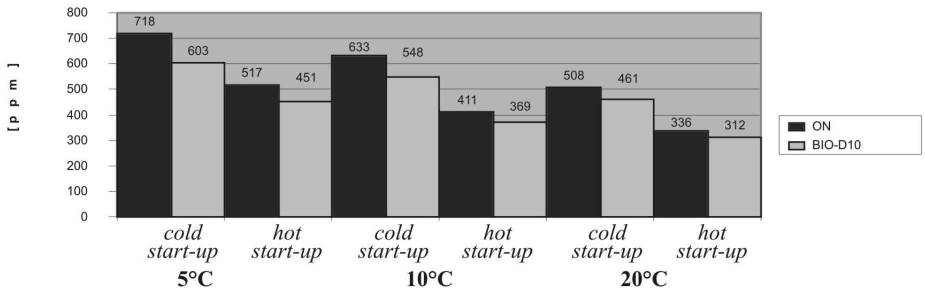

Fig. 22. Juxtaposition of HC emissions contents of the engine S-359 run on ON and BIO-D10
Rys. 22. Zestawienie zawartości emisji HC silnika S-359 zasilanego ON i BIO-D10

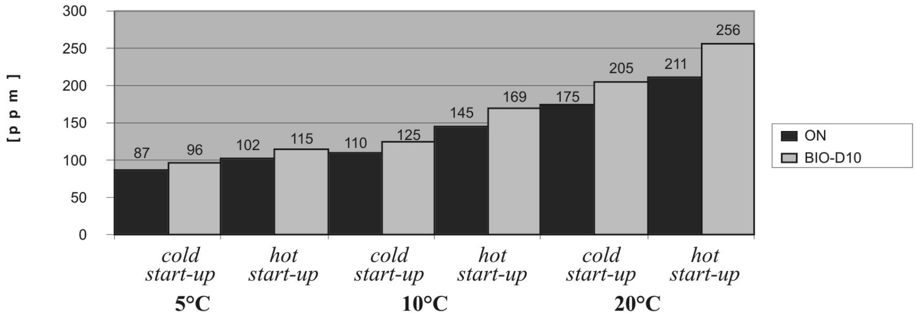

Fig. 23. Juxtaposition of NO_x emissions contents of the engine S-359 run on ON and BIO-D10
Rys. 23. Zestawienie zawartości emisji NO_x silnika S-359 zasilanego ON i BIO-D10

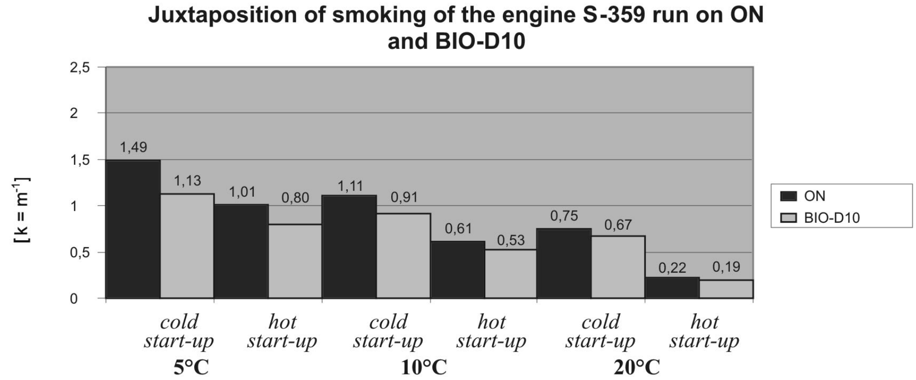

Fig. 24. Juxtaposition of smoking of the engine S-359 run on ON and BIO-D10
Rys. 24. Zestawienie zadymienia silnika S-359 zasilanego ON i BIO-D10

As the result of performed tests and result analysis, it was concluded that using the fuel BIO-D10 instead of diesel oil at cold engine start-up, at environment temperature of 5°C, causes the decrease of emissions of CO with 16%, HC with 13% and smoking with 6%. Whilst the emission of NO_x grows with 10%.

It can also be stated that with the use of BIO-D10 at cold and hot start-ups at environment temperatures of 10°C and 20°C, the contents of CO, HC and smoking in fumes decreases. Whilst the contents of NO_x go up.

The presence of oxygen in the fuel causes the increase of nitro oxides with simultaneous decrease of carbon oxide and hydrocarbons, thus giving easier possibility to regulate toxicity of fumes by delaying the angle of fuel injection initiation. Steering the combustion process can be performer in a much wider range.

8. Summary

The presented results were submitted to statistical analysis, where the methods OPTIMUM and AVD were used, as well as correlation and regression methods. It gave the possibility of quality and quantity comparison of results of fumes contents from stationary tests and exploitation researches. The results of this research allow a model (mathematical relations) determination of relations between smoking and the quantity of toxic fume components of a high-pressure engine.

The performed tests and analyses in his work's researches indicate to the conclusions:

1. In the engine of self-acting fuse (ZS), the emission of carbon oxide (CO), hydrocarbons (HC) and smoking are considerable, especially during start-up and engine warming.
2. Along with the decrease of environment temperature, the emission of CO, HC and smoking increase, whilst the quantity of NOx goes down, providing premises confirming the specified regulations of forming dangers on the side of engine fumes emission.
3. The phases of start-up and warming up of the ZS engine are characterized by increased fuel usage and increased emission of carbon oxide – CO, giving information and sensitizing vehicle users to these harmful for the engine working conditions.
4. The influence of environment temperature on the emission and smoking of fumes during hot start-ups is weaker than during cold start-ups.

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Badania szkodliwych emisji spalin silników spalinowych

S t r e s z c z e n i e

W pracy przedstawiono wyniki badań emisji szkodliwych składników spalin silników z ZS. Uzyskane wyniki podczas badań stanowiskowych i eksploatacyjnych zostały poddane statystycznej ocenie wrażliwości, przy wykorzystaniu procesur komputerowych. Jakościowe i ilościowe sprawozdania zostały odniesione do założonych zmian stanu na stanowisku laboratoryjnym oraz do pozyskanych danych w badaniach eksploatacyjnych.