RESEARCHES OF NOXIOUS COMPONENTS OF EXHAUST GASES CONVERSION OCCURS IN CATALYTIC CONVERTER DURING A START-UP OF COMPRESSION IGNITION ENGINE IN LOWERED TEMPERATURE

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Abstract

This article presents the results of the tests of catalytic reduction of carbon oxide and hydrocarbon emission during the self-ignition engine start-up. The tests were performed at the station in the climate chamber at lowered ambient temperatures: –7 ,-15 and –20^{o}C. A heated three-function platinum-palladium catalytic reactor with a metal monolith was used in the tests. The test methodology included a measurement of toxic fume concentraction upstream and downstream the catalytic reactor at simultaneous measurement of the start-up parameters and measurement of temperatures in selected engine and catalytic reactor locations. A period of the cold engine start-up is characterized by a relatively high carbon oxide and hydrocarbon emission. The level of that emissions increases as the ambient temperature gets lower. As a result of the tests the influence of heating up the reactor on its operation during the self-ignition engine start-up was identified.Carbon oxide and hydrocarbon emission during the start-up period can be reduced by initial heating up the catalytic reactor before the start-up by means of an electric heater. When heating up the reactor surface up to 400^{o}C at ambient temperature of –7^{o}C, CO concentration can be reduced by 80...90% and the hydrocarbon concentration can be reduced by app. 70% on the average.

Keywords: *engine start- up, catalytic reactor, testing station, carbon, hydrocarbon*

1. Introduction

Since some time the increasing requirements within a scope of reduction of toxic fume component emission have started to cover engine operations periods of unsteady thermal condition, especially the start-up and heating at low ambient temperature. The reason is a relatively high emission of toxic fumes during that engine operations stage. The existing technical possibilities of meeting the requirements by engines during normal operation conditions result in the increasing share in a total emission of these fume components during engine operation stages with unsteady thermal condition.

The literature concerning the problems of toxic fume emission, emission test methods and emission reduction methods is very extensive [1, 2, 3, 4]. Many research centres deal with the issues of toxicity and composition of fumes emitted by the combustion engines and the test results are published in a literature available to the public. However, considering the requirements of the existing regulations, the majority of these studies refer to the engine operation at operational temperatures so in stabilized thermal condition or started up at positive ambient temperature. Standard equipment of current cars includes devices designed to reduced that emission such as fume recirculation system, necessary to reduce nitric oxides in fumes and catalytic reactors where products of incomplete combustion are oxidized (CO, HC) and reduced (NO_x). The Engine and Mechanical Vehicle Operation Engineering Department of the Military University of Technology has been dealing with these problems since over 30 years. The current studies pay more and more attention to the examination of the engine fume composition during the engine start-up and heating at low negative ambient temperature. These are favourable conditions for very high emission of products of incomplete fuel combustion i.e. gas components and solid particles.

Recently, an increased interest of some national and foreign centres in that issue can be observed. The Scandinavian countries are especially interested in it due to severe weather conditions in that region. Moreover, they have very good natural conditions to carry out that kind of research. They promote that issue on the international forum and we can assume that testing the toxic compound emission at very low ambient temperatures will soon become obligatory. A significant limitation in dissemination of these tests is a need for a thermal-climate chamber allowing for obtaining low temperatures not only during the start-up but also during the operation for a longer period of time required to perform one full city driving cycle.

The issues of engine start-up at a low temperatures should be strictly related to the fume toxicity tests and combustion engine development. Therefore the fumes of the 4CT90 type self-ignition engine have been tested within a scope of toxic compound emission as a process which accompanies the start-up at a low ambient temperature. During the tests, an influence of the ambient temperature (and initial engine temperature) and heating up the catalytic reactor on the emission at the engine start-up stage were identified.

2. Testing station

The experimental tests at lowered ambient temperatures were carried out at the station in the climate chamber located in the Climate and Combustion Engine Testing Station of the Motor Vehicle Laboratory in the Military University of Technology (fig. 1). The cooling system of the chamber is able to lower the air temperature down to –45°C.

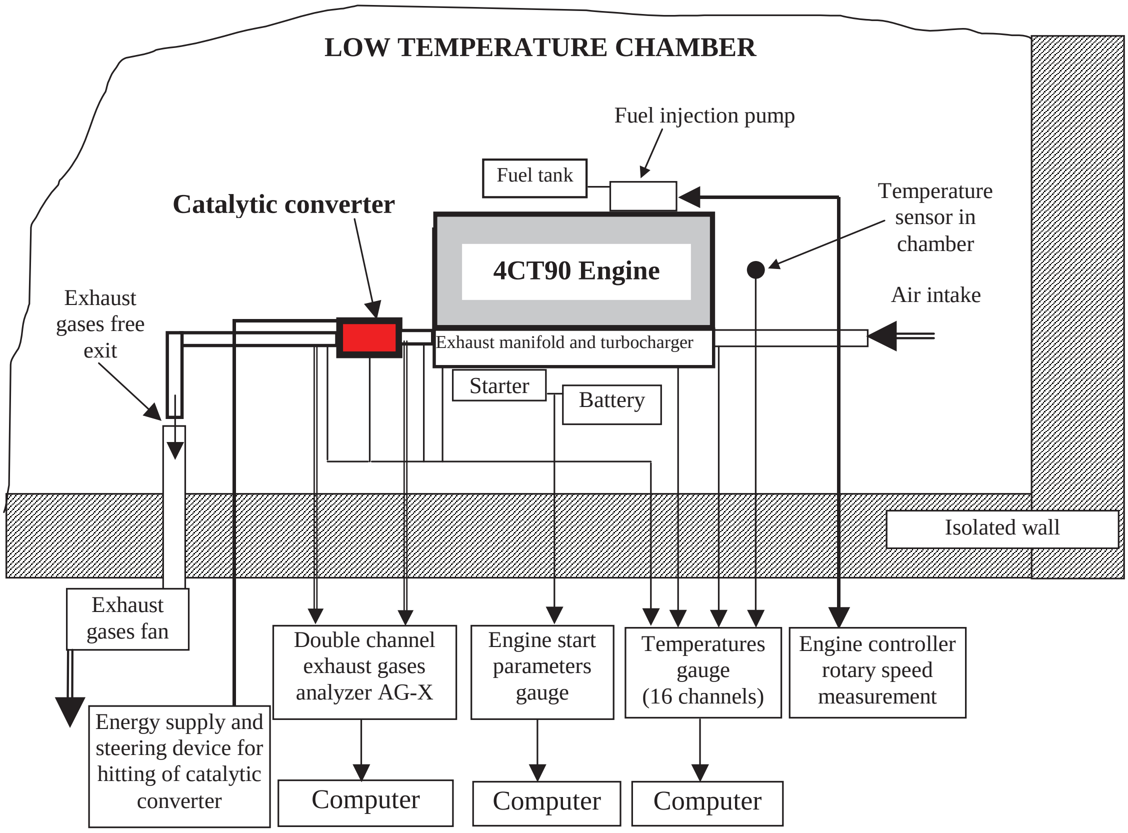

Fig. 1. Testing station in the climate chamber

The tests were performer on the turbo-charged 4CT90-1 self-ignition engine manufactured by “ANDORIA” S.A. Diesel Engine Manufacture. This is a four-cylinder engine with an indirect fuel injection to the swirl chamber (RICARDO COMET VB) made in the engine head.

Basic technical data of the engine are as follows:

- cubic capacity: 2417 cc;
- piston stroke / cylinder diameter: 95mm/90mm;
- compression ratio: 21.1;
- rated power: 66kW at 4100 rpm;
- maximum torque: 195Nm at 2500 rpm;
- injection pump: in-line, small piston type with own drive equipped with dosage corrector and pneumatic dosage corrector;
- initial injection angle adjuster: automatic, mechanical;
- turbo-charger: radial with fume release valve, charging pressure: 60-80kPa within an engine speed of 2000 – 4100 rpm.

This engine met the requirements of EURO II and had no emission reduction system during a cold start-up and heating stage.

Due to the scope of the tests, a special modular exhaust system structure was developed and built. It allowed for proper configuration of the catalytic converter location in the system. The main exhaust system includes a catalytic converter, two measurement module and two distance modules. Each module was finished with a flange allowing for easy connection of these elements. The probes for drawing the fumes and a thermocouple for the fume temperature measurement and measurement of operating area of the catalytic converter monoliths were installed in the measurement modules. The use of measurement modules allowed for the replacement of catalytic converters during measurements without a need to disassemble the measurement systems. A modernized catalytic converter, allowing for initial heating up the reactor monolith before and during the engine start-up by means of electric heaters, was used for the tests.

Concentration of selected gas components of the fumes was measured by means of a two-channel AG-X type fume analyzer (with two integrated IR type detection modules and oxygen sensors) designed especially for the needs of that testing project. The analyzer allowed for the measurement of concentration of individual components upstream and downstream the catalytic reactor and it allowed to define a conversion ratio of the toxic fume components in the reactor. The fumes were taken from the fume drawing probes, installed in the measurement modules of the exhaust system, and delivered to the analyzer. The analyzer operation was controlled by a computer. The computer analyzer set allowed for a digital record of measurement results from individual cycles in a form of text files including the following data:

- measurement date and time;
- carbon oxide concentration [ppm];
- carbon dioxide concentration [ppm];
- hydrocarbon concentration [ppm];
- oxygen concentration [%].

Nitrogen oxide concentration was not recorded because its concentration in the fumes amounts to a very low level at the cold start-up conditions [3].

In the performed tests, the measurements of individual fume component concentrations were carried out in a continuous way, recording measured concentration values in 0.68 s intervals. Thermal condition of the engine systems was defined by 15 ”K” type thermocouples. The thermocouples were connected to the computer data archiving system, which allowed for continuous measurement of temperatures: ambient, fumes, catalytic reactor, cooling fuel, cylinder liner, lubricant oil and air in the inlet system. The fume temperature was measured in the exhaust collector, behind the turbine, in the inlet and outlet of the catalytic reactor. The catalytic reactor temperature was measured:

- on the inlet area of the metal monolith I,
- on the outlet area of the metal monolith II,
- on the housing of the metal monolith.

The temperature measurement system provided a possibility of measuring the temperature simultaneously in all measurement points and allowed for continuous record of measurement results in a form of a digital data on a computer hard drive with a possibility of monitoring the measured values.

The engine start-up process was recorded by means of a special computer measurement kit allowing for continuous measurement of current intensity drawn by the starter, current intensity drawn by the heater plugs and the voltage in the engine electric system.

2. Test methodology

The methodology of the tests performed during the engine start-up and at the engine heating stage included a measurement of the fume component concentration in the fumes flowing into the catalytic reactor and flowing out of it, with simultaneous measurement of the start-up parameters and measurement of temperatures in selected engine systems. The data from the measurement tracks was processed in real time (in a form of text files) on three separate sets of computers.

The tests performer in order to identify the influence of heating up the catalytic reactor on the emission of toxic fume components were of comparative nature. They were performed in precisely defined measurement cycles. A measurement cycle included:

- engine and catalytic reactor preparation for the tests,
- cooling down the engine with a battery and fuel to a test temperature,
- thermal stabilization at the test temperature for 5 hours,
- heating up the catalytic reactor up to a preset monolith area temperature,
- engine start-up (switching on the pre-ignition heater plugs for 25s before the start-up and during the start-up),
- idle engine speed according to default settings for 5 minutes (or longer),
- engine operation for 10 minutes without load at a fixed engine speed increased up to 2000 rpm,
- idle engine speed according to default settings for 1 minute,
- switching off the engine.

The catalytic reactor was initially heated before the start-up up to a particular temperature of the monolith area and during the engine warm-up stage. During the tests performed at the low temperature, the exhaust system and the catalytic converter were thermally isolated by means of a 25mm thick mineral wool, with one-side layer of aluminium foil (Fig. 1). Electric fan heaters (external air blow) were used for heating up the reactors as well as an electric heater placed before the first monolithic insert of the catalytic converter. The electric heaters were fed from the external power network (voltage: 230V, frequency: 50Hz). That way of heating up the reactors allowed for changing the thermal power of the heaters by means of autotransformer in the laboratory conditions.

3. Test results

The test results presented in that publication make a small part of the test result examples from a wide testing programme. Its scope included the tests performed at the testing station in the climate chamber. Due to limited frames of this publication, it does not include the results of the previous tests performed in the engine test house (at a positive ambient temperature), where operation of tested reactor prototypes was checked at steady conditions (speed and load characteristics) and at unsteady conditions.

The tests were performed in the thermal climate chamber for three temperatures: -7, -15 and -20^{o}C for a cold engine.

A platinum-palladium catalytic reactor with two metal monoliths, placed in series in one housing, was used in the tests. Both reactor monoliths had the same structure (number of ducts: 500 cpsi, load: 1g/dm^3, ratio Pt:Pd/2:1). In order to make this publication more simply and clear the following reactor marking was used Pt/Pd.

Fig. 2. presents the results of CO and HC concentration measurement on the upstream and downstream side of the catalytic reactor during a cold start-up and engine operation at idle speed. The diagram legend includes the following indexes: **_1** – upstream concentration values and **_2** for downstream concentration values. The engine start-up time amounted to 8s. The diagrams show a characteristic increase of carbon oxide and hydrocarbon emission during the engine start-up and gradual stabilization after app. 3 minutes at idle speed at the engine speed of app. 830 rpm. A lack of catalytic reactor operation can be noticed. The carbon oxide and hydrocarbon upstream and downstream concentrations are similar. A lack of reactor activity resulted from too low fume temperature, amounting to just 80^{o}C after starting up the engine. Hydrocarbon and carbon oxide oxidation reactions occur when a temperature of the reactor monolith surface exceeds 250^{o}C. Until reaching that temperature, toxic substances generated by the engine are not converted and contribute to the atmospheric air contamination. The maximum level of the toxic substance conversion is obtained when a temperature of 300^{o}C is exceeded.

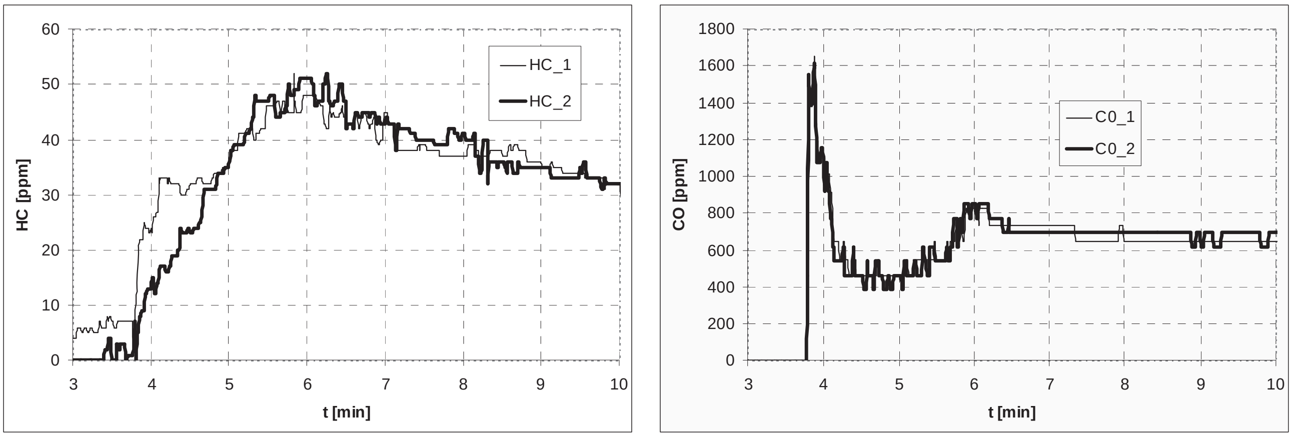

Fig. 2. Hydrocarbon and carbon oxide concentration on the upstream and downstream side of the catalytic reactor during the 4CT90 engine start-up and heating at idle speed and at ambient temperature of –7^{o}C without heating up the reactor

The palladium catalytic reactors were used in the 70's as the oxidizing catalytic converters. Then, the palladium was used together with platinum in the three-phase reactors. The palladium shows good characteristics in hydrocarbon oxidization in the fumes of oxidizing nature (fumes of self-ignition engines), and it is significant in case of emission reduction during a cold engine start-up. Therefore the catalytic reactors with a high palladium content are often suggested as a solution to reduce the emission during the cold engine start-up and heating. Initial operation temperatures of the reactors with palladium are lower by app. 50^{o}C than the reactors containing only platinum.

The engine start-up at ambient temperature of –7^{o}C took 10 seconds. The course of that start-up was presented on Fig. 3 in a form of a diagram of current intensity drawn by the starter. The start-up period was limited with A and B letters, where A means starter activation time and B means starter deactivation time. These marks were put on the fume component intensity diagrams in order to identify the engine start-up period. The engine start-up was relatively easy. The ignitions in the engine cylinders occurred as soon as after 1 second of the starter operation and they supported the starter at the following phase (current intensity reduction). During the start-up, a characteristic high increase of carbon oxide and hydrocarbon concentration in the upstream fumes during the engine start-up could be noticed. Presence of carbon oxides and hydrocarbons in the upstream fumes before the engine start-up (before point A) is a result of deposit combustion processes caused by heating up the catalytic reactor. When the starter is activated, significant changes of concentration of all measured fume components are noticed.

Reactor activation methods include heating the reactor up to a required operation temperature before the engine start-up by means of electric heaters. The diagrams on Fig. 4 present the results of HC and CO concentration measurements on the upstream and downstream side of the heated catalytic platinum-palladium reactor. The reactor was heated before the start-up up to a temperature of app. 400^{o}C, measured on the inlet surface of the first monolith. The heating was performer by means of 1500W electric fan heater. When the engine was started up, the reactor was heated further on during idle speed operation by means of 1500W electric heater.

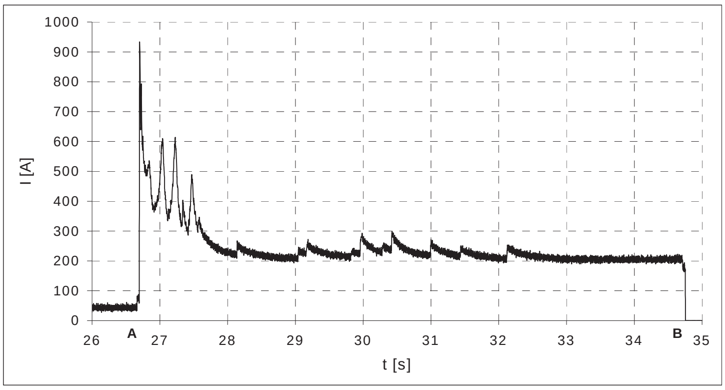

Fig. 3. A course of current intensity drawn by the starter during the 4CT90 engine start-up at ambient temperature of –7^{o}C

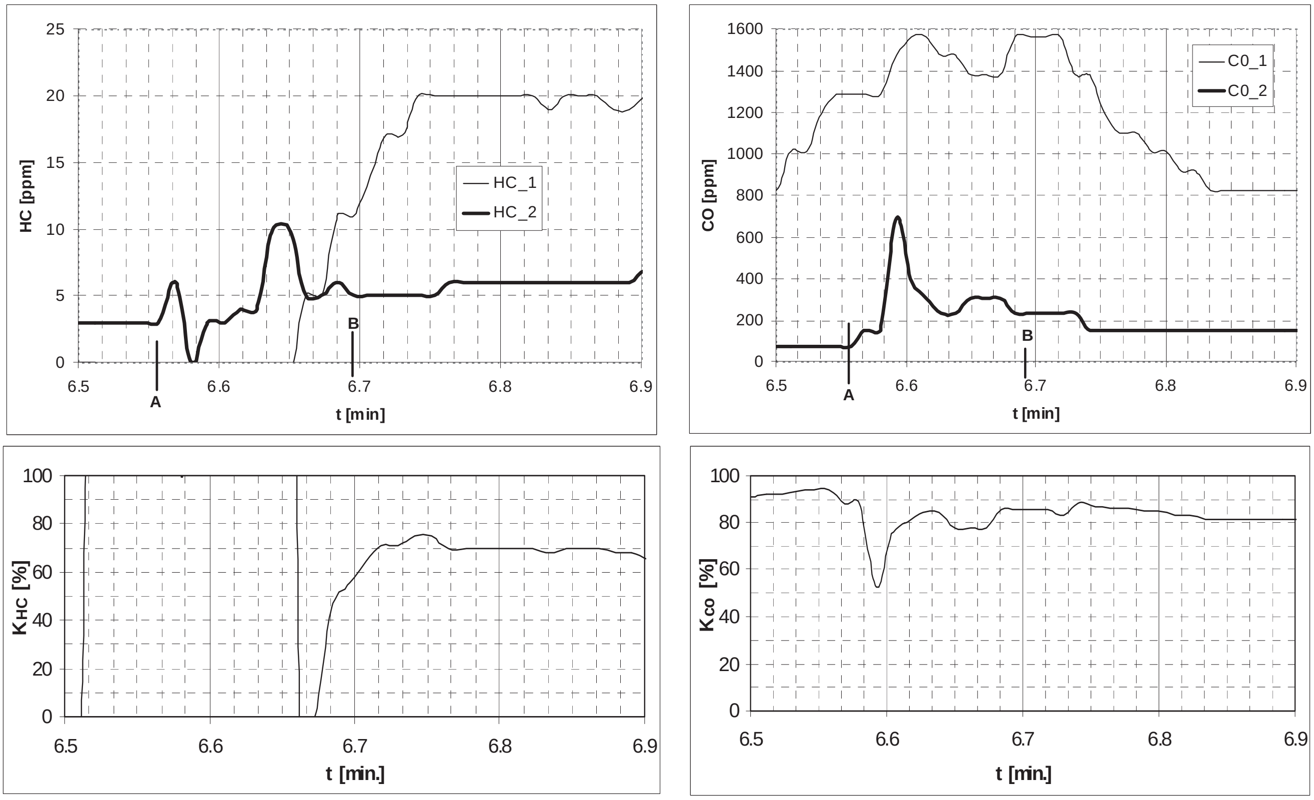

Fig. 4. Concentration of hydrocarbons HC, carbon oxide CO, on the upstream and downstream side of the Pt/Pd catalytic reactor (initially heated up to 400^{o}C) and conversion level (K_{HC} and K_{CO}) during the 4CT90 engine start-up and at ambient temperature of –7^{o}C

During the idle speed operations, the level of emission of these components was reduced and stabilized at a fixed level. Significant reduction of carbon oxide and hydrocarbon concentration on the downstream side of the catalytic reactor indicate fume oxidation reactions in the reactor.

A course of the oxidation reaction is indicated by the higher carbon dioxide concentration on the downstream side of the reactor than on the upstream side. The concentration on the upstream side amounted to app. 40000ppm, and on the downstream side it amounted to 65000ppm. The highest carbon dioxide concentration occurred during the engine start-up. As the engine was getting hot the carbon dioxide concentration was reduced. A significant reduction of the carbon oxide concentration in the fumes, from the level of app. 1600ppm to the level of app. 300ppm, can be clearly noticed. When the engine was started up the hydrocarbon level was reduced from 20 to 5ppm.

As the ambient temperature lowered the engine start-up time got longer. The engine was started up in 22 seconds at ambient temperature of –15^{o}C, but at ambient temperature of –20^{o}C the engine was started up in 84 seconds. The nature of these start-up is presented on Fig. 5 and 7.

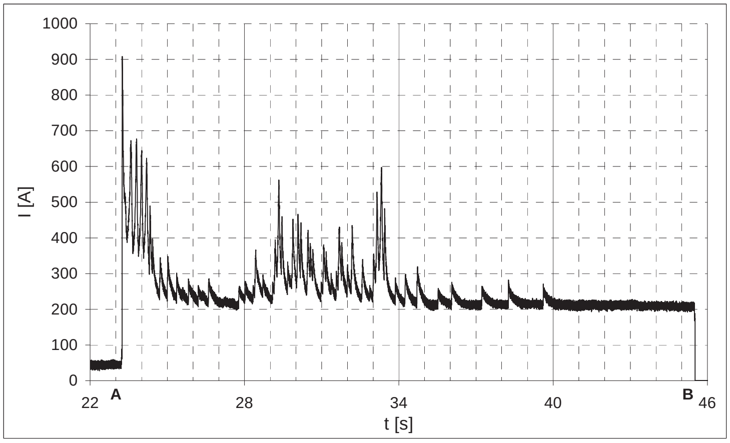

Fig. 5. A course of current intensity drawn by the starter during the 4CT90 engine start-up at ambient temperature of –15^{o}C

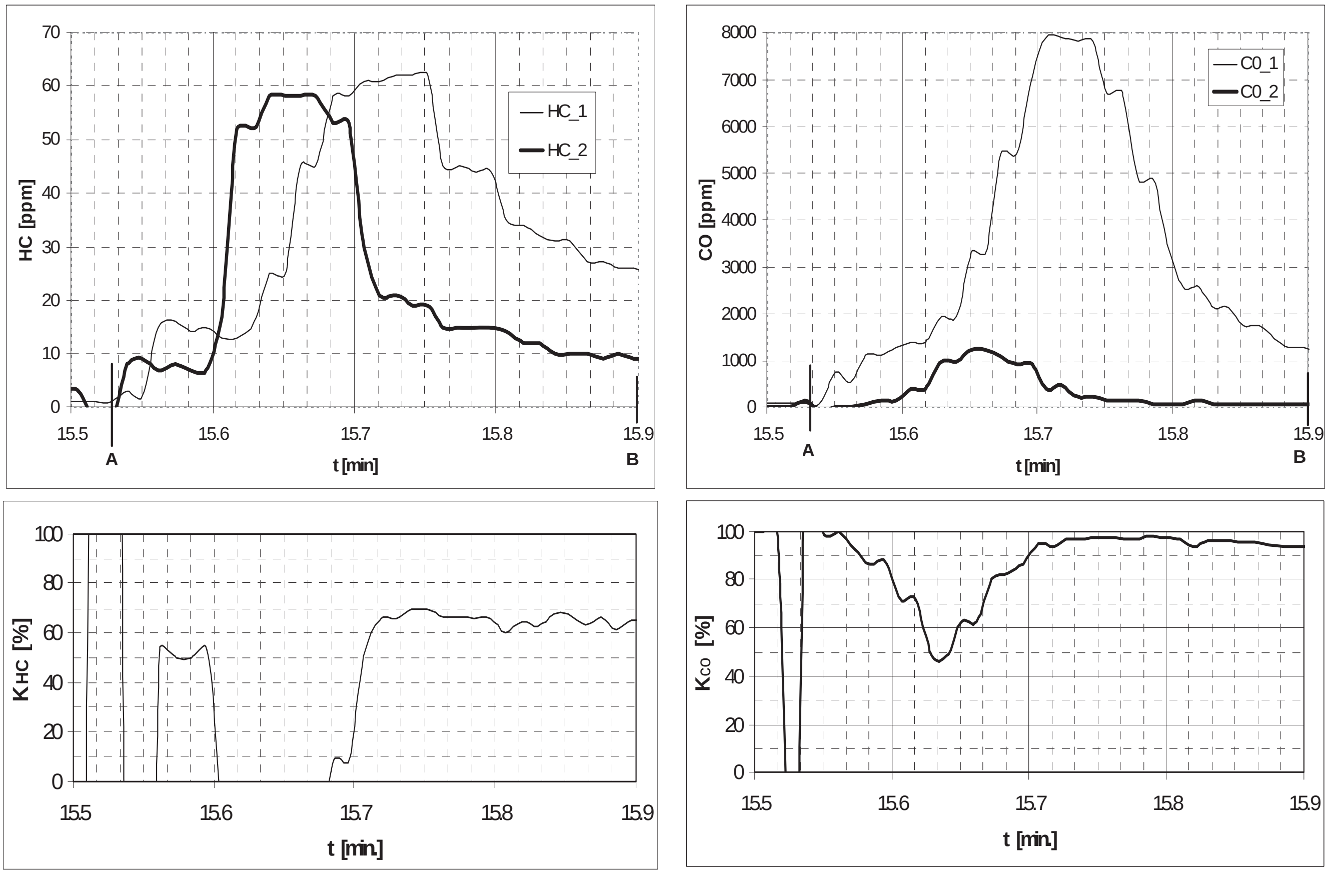

Fig. 6. Concentration of hydrocarbons HC, carbon oxide CO on the upstream and downstream side of the Pt/Pd catalytic reactor (initially heated up to 400^{o}C) and conversion level (K_{HC} and K_{CO}) during the 4CT90 engine start-up and at ambient temperature of –15^{o}C

The engine start-up was more difficult at ambient temperature of –15°C than at –7°C. There were cyclic self-ignitions in the engine cylinders during the most of the start-up time. Not until the end they allowed the engine to start its independent operation. The start-up was performed at continuous starter operation and pre-ignition heater plugs switched on. That start-up process resulted in high hydrocarbon emission (up to 60ppm) and carbon oxides (up to 8000ppm), as presented on Fig. 6. Differences between concentrations of individual components on the upstream and downstream side of the catalytic reactor indicate that the reactor was active. Conversion level of HC and CO is variable during the start-up time and it depends on the course of the start-up. The highest one occurs between 34 and 40 seconds of the start-up course (Fig. 5), where regular ignitions in the cylinders took place. The CO concentration was reduced from 8000 to 100ppm, and the HC concentration was reduced from 60 to 20ppm. A characteristic increase of the HC concentration at the first engine start-up phase can be noticed. It could be caused by vaporization of some diesel oil drops in the reactor. A similar phenomenon occurred in all start-up tests.

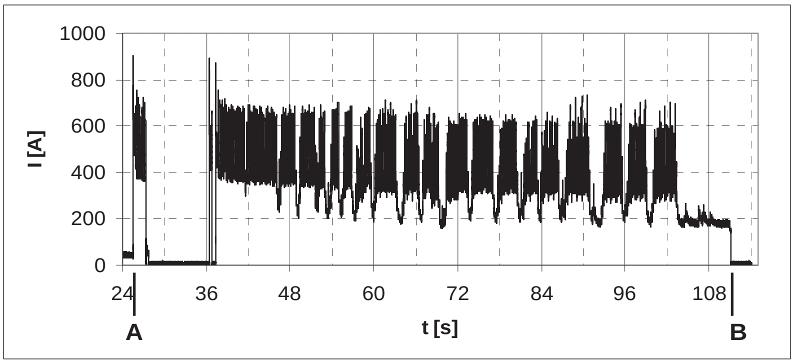

Fig. 7. A course of current intensity drawn by the starter during the 4CT90 engine start-up at ambient temperature of –20°C

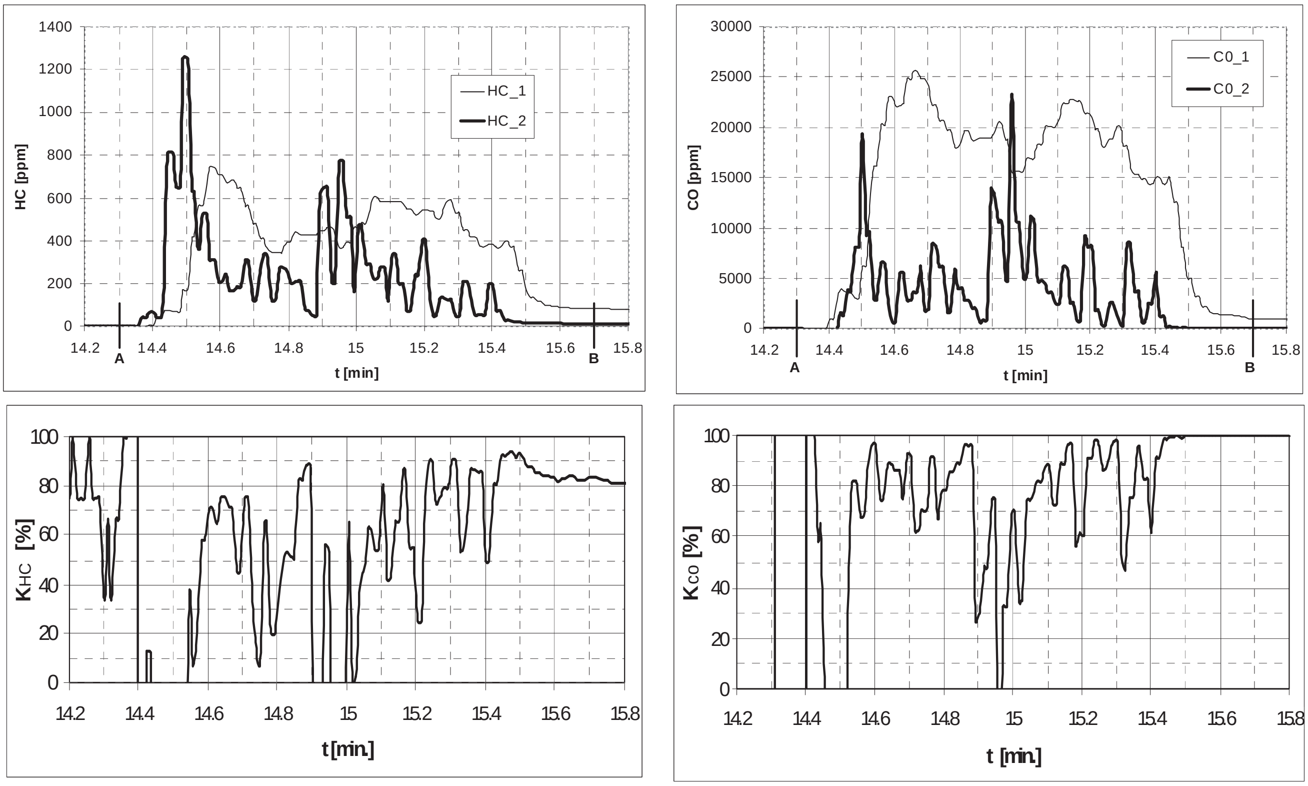

Fig. 8. Concentration of hydrocarbons HC, carbon oxide CO on the upstream and downstream side of the Pt/Pd catalytic reactor (initially heated up to 400°C) and conversion level (K_{HC} and K_{CO}) during the 4CT90 engine start-up and at ambient temperature of –20°C

The engine start-up at ambient temperature of –20°C was very difficult and prolonged. Recorded start-up parameters (crankshaft time and speed) indicated limited possibilities of starting up the engine at ambient temperatures below –20°C. After 2 seconds of operation the starter was switched off due to too low crankshaft speed. However after an eight-second break it was decided to continue the start-up process until the engine starts its own independent operation. Single irregular self-ignitions in the engine cylinders, supporting the starter, occurred during the most start-up time.

That very difficult start-up process resulted in very high carbon oxide emission (up to 25000ppm) and hydrocarbon emission (up to 700ppm), as shown on fig. 8. The diagrams clearly show the reduction of carbon oxide and hydrocarbon concentration on the downstream side of the catalytic reactor and it indicates oxidation reactions in the reactor. The beginning of the reactor operation is visible after app. 6 seconds. A reduction of HC and CO concentrations on the downstream side of the reactor can be clearly noticed. A significant reduction of oxygen concentration and increase of carbon dioxide concentration on the downstream side of the reactor indicate a very high reactor activity. Concentration diagram courses indicate very high pulsation of the fume component values on the downstream side of the reactor. It was higher than on the upstream side of the reactor. The reactor activity was determined by a course of the start-up process, as indicated by the comparison of diagrams presented on the figures. More frequent ignitions resulted in the increase of the engine speed and pressure pulsation increase and it temporarily deteriorated HC and CO conversion. When there were no ignitions in the engine cylinders HC and CO conversion increased. It had a particular influence on the reactor operation.

The intensity of oxidation reaction in the catalytic reactor during the start-up is indicated by a significant increase of the carbon dioxide concentration. Concentration on the upstream side of the reactor amounted to an average level of 40000ppm, but on the downstream side it amounted to 120000ppm, i.e. it was three times higher. Analogously, the oxygen concentration was reduced from 15% to 5%, i.e. three times as well. It indicates that a significant quantity of components of incomplete fuel combustion during a prolonged engine start-up at a low ambient temperature was burnt (oxidized) in the heated catalytic reactor.

2. Summary

The tests performed in order to identify the influence of heating up the catalytic reactor on the reduction of the toxic fume emission during a cold 4CT90 engine start-up at a low ambient temperature allowed to make the following conclusions:

1) A period of the cold engine start-up is characterized by a relatively high carbon oxide and hydrocarbon emission. The level of that emissions increases as the ambient temperature gets lower. The engine start-up time is getting longer.
2) During the cold start-up time and at the idle speed engine heating stage the applied catalytic reactor does not work due to a low fume temperature (80°C in the reactor inlet at the end of the start-up period).
3) A characteristic sudden increase of CO and HC concentrations occurs in the initial engine start-up period. As the ignitions in the cylinders developed during the start-up, concentrations of these components decrease. During a difficult and prolonged engine start-up, CO and HC concentrations show very high fluctuation determined by a course of the start-up process.
4) Carbon oxide and hydrocarbon emission during the start-up period can be reduced by initial heating up the catalytic reactor before the start-up by means of an electric heater. When heating up the reactor surface up to 400°C at ambient temperature of –7°C, CO concentration can be reduced by 80...90% and the hydrocarbon concentration can be reduced by app. 70% on the average.
5) Heated catalytic converter starts its operation in several seconds since the starter activation moment.

6) Heating up the catalytic reactor during the engine start-up makes an effective method of reducing the carbon oxide and hydrocarbon emissions but it requires a significant quantity of electric power. Using a 1500W electric heater to heat up the inlet surface of the reactor monolith up to a temperature of 400^{o}C takes 2.5 minutes. That time can be reduced by increasing the power of the electric heater.

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