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EKOLOGICZNY ASPEKT ZIMNEGO I GORĄCEGO ROZRUCHU SILNIKA SPALINOWEGO O ZAPŁONIE ISKROWYM

THE ECOLOGICAL ASPECT OF A COLD AND HOT STARTING OF A SPARK IGNITION COMBUSTION ENGINE

Artykuł przedstawia analizę wyników pomiarów emisji wybranych składników spalin w początkowym okresie pracy silnika spalinowego o zapłonie iskrowym wyposażonego w wielowtryskowy, pośredni system zasilania oraz w trójfunkcyjny konwerter katalityczny. Pomiary zostały wykonane dla dwóch stanów cieplnych silnika, tj. dla rozruchu zimnego, gdy silnik i wszystkie jego podzespoły oraz płyny eksploatacyjne posiadały jednakową temperaturę, równą temperaturze otoczenia, a także dla rozruchu gorącego, uzyskiwanego bezpośrednio po mającym miejsce wcześniej okresie pracy silnika w warunkach równowagi cieplnej. Odczyty wyników dokonywane były z krokiem jednosekundowym i mogą być przedstawiane w postaci przebiegów czasowych obrazujących charakter zmian emisji w obserwowanym okresie. Analiza emisji w aspekcie ekologicznym uwzględnia w szczególności porównanie oraz ocenę zimnego i gorącego rozruchu pod względem wielkości emisji szkodliwych składników spalin.

Słowa kluczowe: *silnik ZI, zimny rozruch, pomiary emisji, emisja spalin, zanieczyszczenie środowiska.*

This article presents analysis of measurement results of combustion gases chosen components, obtained during initial phase of work of a spark ignition combustion engine, equipped with multi-point indirect injection system and three way catalytic converter, work. Measurements were conducted for two temperature states: for a cold start, when engine, all its components and exploitation liquids were of the same, equal to its surroundings, temperature, and for a hot start, which takes place right after proceeding it period of engine operation in conditions of thermal equilibrium. Readings were taken in one second intervals and can be presented as curves in function of time, showing character of emission changes in a given time. Analysis of emissions, with regard to its ecological aspects, embraces comparison and evaluation of the cold and hot start effect on amount of harmful substances emitted.

Keywords: SI engine, cold start, emission measurement, exhaust emission, environment pollution.

1. Introduction

The challenge in recent years and for future is constant reduction of harmful substances emission into environment. Utilization of conventional fuels limits absorption and adaptation capacity of ecosystems in a very fast pace. Unavoidable, as it seems, is a shift of world's economies towards ecological and renewable sources of energy. Care for an environment leads to introduction of new fuels and construction of new and better engines, but also puts emphasis on improvement of exploitation of already used machines. Therefore, there was a research carried out in Department of Power Engineering and Vehicles, Agricultural University in Lublin concerning exhaust gases emission during initial period of internal combustion engines work in both farm machinery and in typical car vehicles.

Usually research concerning start-up is focused mainly on possibilities of cold start in low temperatures, what enables determination of such start characteristics.

However, ecological aspect of cold starts seems to be an interesting matter as well. Review of previous research concerning this subject [1, 4, 6, 10] and previous own studies allow statement that low ambient temperature, which in fact determines temperature of an engine, all his components and liquids, favours increase of pollution emissions during initial phase of engine work.

In order to analyse this phenomenon one must realise how significant is a character of vehicle exploitation, especially frequency of a cold start and conditions in which it takes place. For example exploitation of a vehicle for everyday commuting to work leads to two starts which can be treated as cold. However, it is often that other, additional but short trips occur, during

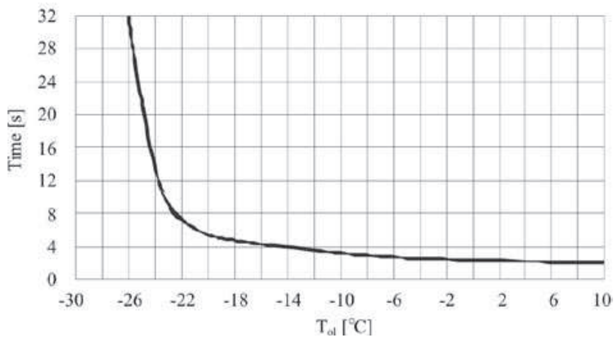

Fig. 1. Petrol feeding SI engine's (899 cm³) staritng capability [3]

which the engine and exhaust system work most of the time in temperature below optimal, thus, the processes of air-fuel mixture preparation, combustion and conversion of exhaust gases are not effective.

Temperature of exhaust gases emitted by spark ignition combustion engine varies from 300-400°C (573-673 K) for idle speeds of an engine up to approximately 1100°C (1373 K) for full loads. However, during cold starts in ambient temperature below 0°C (273 K), temperature of exhaust system, especially catalytic converter remains to low for its proper functioning. Relying on results of research conducted during driving tests FTP75 and NEDC it was noticed that almost 90 % of hydrocarbons and carbon oxides are emitted while engine operates in sub-optimal temperatures hence catalytic converter does not work.

To fully present the situation it can be assumed that in case of most of the cars equipped with petrol engines, distance of

1,5 – 3 km is enough to heat up the catalytic converter and to start its functioning.

An example of research confirming such thesis might be one during which volumetric participation of CO, CO_2, and O_2 in exhaust gases emitted by petrol engine installed in a vehicle undergoing NEDC test was established, what was presented in fig. 2. Correlation between CO and CO_2 which is clearly visible during the initial 50 seconds of the test, and confirmed by, presented in fig. 3, research conducted on engine working with idle speeds, should be noticed.

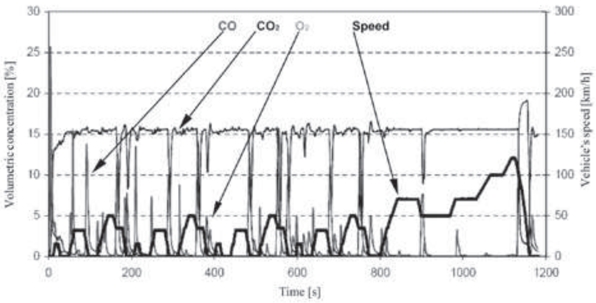

Fig. 2. Volumetric concentration changes for CO, CO_2, O_2 after the catalytic converter in NEDC drive test [5]

2. Engine's starting process in aspect of exhaust gases emission

One of many criteria used for evaluation of an engine usability is its reliability, which can be positioned next to low exploitation costs and low emission of exhaust gases containing harmful substances. Reliability may also be considered as a wider problem, but without a doubt one of its most important parameters is ability to undertake work, what becomes especially important when temperature of surroundings is low (blow 0°C (273 K)).

Low temperature is a source of many negative phenomena occurring during startup. In most cases it causes prolongation of time necessary to start an engine. Internal resistance which increases with increase of, temperature related, density of engine oil, is a very important factor [10]. Calculations based on Newtonian model of liquid prove that losses related to friction between piston and cylinder may range from couple watts to couple kW [3]. Moreover, these aren't the only places responsible for the friction occurrence. Among other, friction in crankshaft bearings must be taken into consideration.

Prolongation of engine starting has also its cause in changes of fuel properties such as loss of liquidity, turbidity and precipitation of aromatic and paraffin hydrocarbons as well as water dissolved in fuel. All that affects negatively fuel flow through a fuel system, fuel spray and hence quality of air-fuel mixture.

Greater resistance of an engine movement and decrease of battery capacity causes also slows crankshaft's rotational speed while starting. That leads to prolongation of compression time in cylinders which, potentially increases losses of pressure caused by blow-byes, and at the same time lowers temperature of the last stage of compression, speed of air flow and degree of it turbulence. All these, together with mentioned above, changes of fuel quality lead to improper preparation of fuel-air mixture and impede its ignition [11].

It shows that engine's starting is an energy consuming process, which requires increased amount of fuel to be injected, to enable absolute increase of smaller drops number, required for a successful start-up. Furthermore, greater amounts of fuel delivered into cylinder, only part of which is properly prepared for combustion, implicate creation of significant amounts of harmful substances, which during initial phase of engine work, cannot be in converted because of low catalytic reactor temperature [1, 4, 8].

3. Methodology

With the end of 1998, the directive 98/69 was accepted in Europe. It introduced measurement of emission in temperatures below 0°C (273 K) into homologation process. It is conducted with dynamometer testbed in climatic chamber enabling measurements in temperature -7°C (266 K). The test comprises of four basic cycles of European NEDC cycle, embracing determination of CO and HC emissions during cold starting and heating of an engine [8]. It should be noticed that such method of carrying out the measurements is expensive, therefore, own research utilized simplified method, not embracing the climate chamber. However, in order to take such an important factor as temperature into account, investigation of exhaust emissions were conducted after prior period of temperature stabilization on exterior stand. Standards concerning starting procedures serve various temperature stabilization periods, from 6 hours (norm FIAT 7.11063/01) up to 12 hours (BN-74/1345-09 and BN-81/1374-10). It is assumed that shorter periods are adequate for car engines characterizing with lower weight and heat capacity [9].

Therefore, the engine (vehicle) had undergone the thermal stabilization process, which lasted not less than 8 hours. It can be assumed that all elements of the engine and of the exhaust system had same temperature as surroundings. Temperature of surroundings and engine oil was determined, both for cold and hot start, prior to each of measurement. Research was conducted with the engine working with idle speed, and directly after its startup. Measurements for hot start were conducted right after completion of cold start ones. Warmed up engine, which temperature stabilized, was stopped and started again in surrounding conditions the same as for the cold start.

Time of measurement duration was chosen so that, engine working with idle speed, reached stable level of particular compounds of exhaust gasses and stable work temperature. Throughout this time, engine oil temperature, crankshaft rotational speed as well as volumetric participation of: carbon oxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NOX) and oxygen (O_2) in emitted gases were determined and registered.

Exhaust gasses composition was investigated by means of exhaust gasses analyzer Multigas 488 Plus, which is classified to class I analyzers according to OIML (Organization Internationale Metrology Legal). Analysis of carbon dioxide, carbon oxide and hydrocarbons were conducted by means of method based on infrared radiation absorption (NDIR), while content of oxygen and nitrogen oxides was conducted by means of electrochemical method. Characteristic, for this research, is utilization of typical diagnostic analyzer, which software enables registration of results on a personal computer.

Object, on which the research was carried out, was GA-16DE spark ignition combustion engine installed in a vehicle which mileage reached 50 thousand km, in a very good condition, right after periodical check-up. Chosen characteristics of the engine were presented in table 1.

During work of an engine in road conditions, its control system receives signals from various sensors (position and

Tab. 1. Chosen technical data of a GA16DE engine

Number and cylinders layout, valves per cyl.	*4, row, 4*
Engine cubic capacity	*1597 cm³*
Maximal power	*73 kW (100 KM)/6000 min⁻¹*
Maximal torque	*136 Nm/4000 min⁻¹*
Compression ratio	*9,8 : 1*
Camshaft	*DOHC*
Ignition	*SI, distributor*
Feeding system	*multi-point injection system EGI*
Exhaust gas treatment	*three way catalyst*
Fuel	*petrol, EUROSUPER 95*
Lubricant oil	*Mobil 1 (5W/40)*

rotational speed of camshaft, weight of fresh air, coolant temperature, oxygen content in exhaust gasses, throttle position, vehicle speed etc.). Relying on simultaneous comparisons to data in memory, proper duration of injection and moment when signal is sent to ignition coil are chosen. In case of an engine working with idle speed, sudden acceleration and during engine startup and its heating, ignition angle is set according to separate data gathered in memory of a control unit. In these situations readings from lambda sensor are not considered by the control unit, which steers without feedback.

4. Analysis of GA16DE engine exhaust gasses emission

Initial period of the engine work, when maximal rotational speed is reached, should be presented more closely. For cold start temperature of –5°C (268 K), maximal rotational speed is reached after approximately 65 seconds from the start-up. Delay is dependent on temperature in which engine is to be started [6]. It is caused by increased internal resistance of an engine and non optimal process of combustion in low temperatures. For temperatures below +5°C (278 K) an idle air valve is fully open, therefore crankshaft rotational speed, right after starting an engine, greatly depends on inner movement resistance, decreasing with subsequent work cycles. Therefore, initially increase of rotational speed is observed. Gradual increase of the engine temperature and decreasing resistance cause changes of signals sent from control unit and closing idle air valve hence reduction of, delivered to cylinder, amount of air-fuel mixture and decrease of rotational speed.

In order to present the emission differences related to hot and cold start, rough results of measurements were shown in fig. 3 and 4. The figure presents volumetric concentrations of particular compounds (carbon oxide, carbon dioxide, hydrocarbons, nitrogen oxides, engine rotational speed), registered for both cold and hot start in ambient temperature –5°C (268 K).

As it is visible in fig. 3, during a cold start and process of investigated engine heating, volumetric participation of particular compounds have been changing significantly for initial 800 seconds, while later, their values remained constant. When hot engine is started (fig. 4) period of increased emission is ten times shorter. Moreover, observed peak values are several, and in case of CO even a dozen or so, times lower than for a cold start [6].

Period of increased emission noticed for a cold start can be divided into two sub-periods. During first one, emission of investigated compounds is especially high, what results from two appearing simultaneously factors. Initially, cold walls of cylinder, according to its significant heat capacity, absorb heat. Low

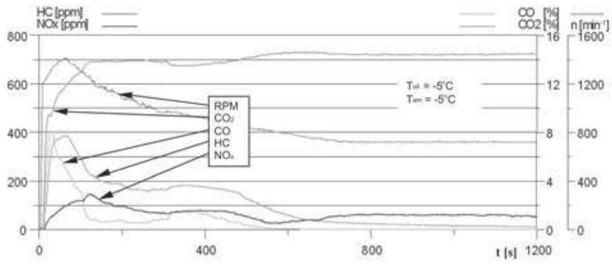

Fig.3. Volumetric concentrations of CO, CO_2, HC, NO_x in fumes & shaft's speed for the cold starting and idling of a GA16DE engine at ambient temperature –5°C

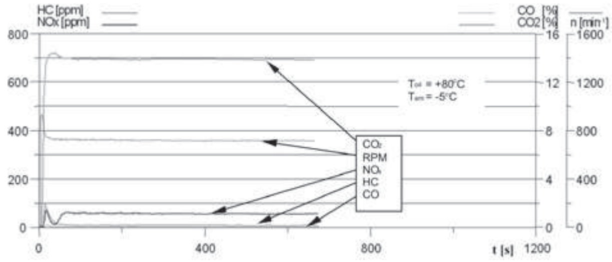

Fig.4. Volumetric concentrations of CO, CO_2, HC, NO_x in fumes & shaft's speed for the hot starting and idling of a GA16DE engine at ambient temperature –5°C

temperature impeding fuel vaporization, as well as wall and gap effects are significantly affecting combustion during this initial period thus conditions are unfavourable for creation of homogeneous air-fuel mixture. Additional factor, resulting from too low temperature, is lack of catalytic converter operation.

With increase of cylinder walls temperature formation of air-fuel mixture becomes more effective and CO emission decreases to 0,7 % and in case of HC level of 200 ppm is reached. Almost simultaneously emission of nitrogen oxides decreases to 70 ppm. It results from a fact that, as engine heats up, less air-fuel mixture is delivered, thus initially higher combustion temperature decreases. Lower energy of CO and HC oxidation reaction activation, when compared to reaction of nitrogen and oxygen, is related to decrease of volume of oxygen, which cold be bonded with nitrogen.

Emission of presented compounds is not yet at its minimal level, which is reached when catalytic converter is heated up to proper work temperature (so called 'light-off') [8], which in case of engine working in road conditions should be reached after approximately 3 minutes [7]. In the research this moment is delayed because engine works with idle speeds and with no external load. After approx. 9 minutes participation of CO and HC lower reaching 0,01 % and 15 ppm respectively. Decrease of nitrogen oxides is also observed than. However, after less than a minute a slight increase of these values, resulting from a change in steering mode, is noticed. Control unit sets parameters as for idle speed with no exterior loads, but for a hot engine. In such conditions signals from lambda sensor are not used, an engine works without feedback combusting air-fuel mixture, which is leaner than required by a catalytic converter ($\lambda \approx 1{,}037$). Thus, incomplete conversion of NO_X takes place. Proportions of particular substances in exhaust gasses (CO, CO_2 and NO_X) result from availability of oxygen and can be easily observed in fig 3.

Figure 4 presents the course of investigated compounds emissions for the hot start taking place in surroundings conditions same as for the cold start. In this case, similar character of emission as in case of the cold start can be observed, except for clear influence of the catalytic converter, which is fully heated and hence do not affect increased emission. On the other hand, starting an engine itself, right after a start, is bonded to a delivery of rich starting mixture into a cylinder and leads to occurrence of local extremes of investigated compounds. In such case distinct becomes a stage when control unit shifts from starting settings to ones for idle speed with no load. As it was mentioned above, it is bonded with an engine working in open system (with no feedback from λ sensor) on slightly leaner mixture. It is expressed through decrease of carbon dioxide participation, which right after startup reaches 14,3 %, and dozen or so seconds later stabilizes on about 13,9 %. Oxygen, not bonded with carbon, reacts with nitrogen thus decrease of air-fuel mixture amount expresses in increase of nitrogen oxides participation (up to 65 ppm after 50th second of measurement) what is related to their incomplete reduction in the catalytic converter.

Registered results of volumetric participation measurements of particular compounds and of velocity and temperature of exhaust gasses enable calculation of weight or volume of emitted gas compounds [6].

Visualization of utilized results is similar, nevertheless, one can notice significantly higher emission during initial stage of the engine work, related to increased fuel consumption and greater rotational speed of the engine, what, when only volumetric participation is taken into consideration, is not clearly visible.

Results representing total emission of chosen compounds of the exhaust gasses, both for the cold and hot start, expressed in volumetric units and corresponding to initial 800 seconds from the engine start, were presented in following figures (fig. 5).

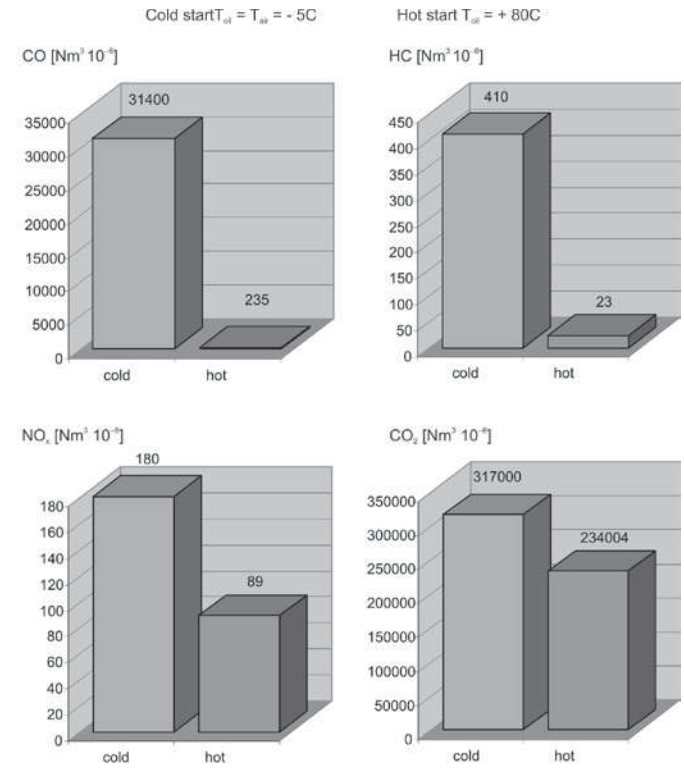

Fig. 5. Total emission of CO, HC, NO_X and CO_2 for the cold starting and worming up of the GA16DE engine and for the hot starting and idling during the same time as worming up (800 seconds) at ambient temperature –5°C

Period of 800 seconds was chosen for this comparison because it was time after which emission levels of particular compounds had stabilized. This period was interesting because of variations in emission and for purpose of this research can be considered as time of the engine heating, however such statement is not entirely precise. After investigated period, emission of exhaust gasses is not different from one observed for the engine which reached fully stable temperature, and limiting only to 800 seconds enables more distinct comparison of the cold and hot start, taking harmful substances into consideration.

Discussion of particular compounds comparison can be started with analysis of carbon oxide emission. Great, not observed in such degree in case of other compounds, difference concerning the hot start can be noticed here.

Reduction of over 99 % of CO, when compared to emission during corresponding period during the cold start, is observed. One cold start in temperature –5°C (268 K) is a source of CO amount equal to CO produced during almost 140 hot starts in same conditions. Putting it in other words, 13 minutes of heating an engine is equivalent to almost 29 hours of an engine, which reached stable work temperature, operation.

Same analogy could be used in order to present hydrocarbons emission (fig. 4) hence differences noticed for them were not that great. Observed during the cold start amount of HC emitted in temperature –5°C (268 K) is almost 18 times greater than during the hot start, for which reduction of emission reaches almost 95 %. For emission of hydrocarbons, 13 minutes of an engine's work after cold start are similar to 3 hours and 50 minutes of a thermally stable (wormed up) engine's operation.

For the cold and hot start in ambient temperature –5°C (268 K) and 800 seconds period of engine heating, while idling, 31,4 and 0,23 dm^3 of CO were emitted respectively.

The fact of the cold start causes increase of nitrogen oxides emission, although it is smaller than in above described, but the difference is significant as well. Emission of NO_X is bonded with a temperature and pressure in a combustion chamber, therefore 'only' partial reduction for the hot start is observed.

For carbon dioxide emission decrease for the

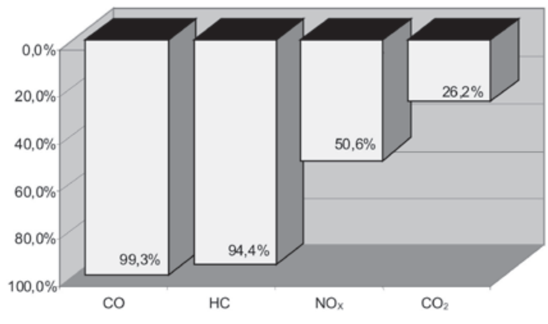

Fig. 6. Reduction ratio of total emission of CO, HC, NO_X and CO_2 for the hot starting and idling of the GA16DE engine compared with the cold starting and worming up (800 seconds) at ambient temperature –5°C

hot start, when compared to the cold one, reaches approx. 26 %. It must be noticed that this value approximately corresponds to a difference in fuel consumption. Absolute difference between the cold and hot start amounts to 83 dm^3 of CO_2 (in normal conditions). Fact of a cold start has also a great importance when CO_2 emission is considered. However, it is hard to say how it affects fuel consumption during everyday exploitation because the research focused only on measurements conducted while engine was working with idle speed. Fuel consumption in corresponding period of time, but during driving, would be several times higher. However, absolute difference resulting form a cold start would be similar. Therefore, relative change in carbon dioxide emission for a driven car is less, when one compare it to observed for an engine's work with idle speed.

5. Summary

Relying on obtained results it can be said that, when CO emission is taken into consideration, it would be better not to turn the engine off for a night, so that there would be no need to heat it up again. Naturally it applies to the engine working with idle speed and to the CO emission.

This type of analyses are undertaken more and more often, although equipment used in such research is greatly specialized, thus utilization of a diagnostic exhaust gases analyzer connected to a personal computer with proper software installed on it should be noticed.

Clearly visible is a fact, that three-way catalytic converters fulfil their function well after they reach optimal work temperature, and that they are not capable of reducing CO and HC emission in the initial stage when the engine heats up. Therefore, there should be a drive towards limiting effect of a cold start on emission. Such goal might be accomplished in many ways, among other, through introduction of additional construction changes, optimizing both process of preparation and combustion of air-fuel mixture as well as start control systems which shortening heat up time, modernization of catalytic systems and modification of fuel. The lubricant oils have also the significant effect on starting an engine. They should not be omitted because they can strongly decrease resistance during starting an engine. It was noticed that using 0W30 oils leads to 50 % lower, when compared to 10W40 oils, wear of engine's elements. Using oils lowering energy needs of a cold started engine decreases fuel consumption, and thence emission of harmful exhaust gasses components.

One of the most interesting and relatively simple solutions, which might be used in a future is crankshaft rotation without fuel delivery, carried out for a few seconds, which would lead to heating up combustion chamber by compressed air. This would enable decrease of CO, HC and PM emission during initial cycles of engine work. Other methods also rely on shortening of engine heating time, however in most cases they are related to increased energy consumption from a car battery or from external sources, what seems not to be a perfect solution.

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