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The on-road operation of Diesel Particulate Filters

Abstract: The problem in engine tests stand investigations lies in their difficult analysis in comparison to the on-road, real traffic investigations. The same problem occurs in the case of diesel particulate filters. A variety of papers have been published related to the topic of DPF investigations on engine and chassis dynamometers and still the conclusions from these investigations do not entirely reflect the actual status quo in this matter. This forced the engineers to begin a complex on-road testing of the DPF. The paper present an analysis of the operation of DPF and basic investigations into DPF under real operating conditions in an urban, extra urban and expressway cycles on selected vehicle types. The investigations comprised the measurement of the gaseous exhaust components and particulate matter along with the measurement of their concentration and size distribution while recording the operating parameters of the vehicle in motion.

Key words: *exhaust gases emission, diesel particulate filter*

Eksploatacja filtra cząstek stałych w warunkach rzeczywistej eksploatacji

Streszczenie: Podstawowym problemem badań stanowiskowych pojazdu jest utrudniona analiza w odniesieniu do badań w rzeczywistych warunkach eksploatacji. Problem ten występuje również w przypadku badań filtrów cząstek stałych. Opublikowano szereg prac związanych z badaniami DPF na hamowniach silnikowych i podwoziowych jednak w konsekwencji wnioski z tych badań nie do końca odzwierciedlały rzeczywisty stan rzeczy. To spowodowało konieczność prowadzenia kompleksowych badań pracy filtrów cząstek stałych w rzeczywistych warunkach eksploatacji. W pracy przedstawiono analizę działania oraz badania podstawowe filtrów cząstek stałych DPF w rzeczywistych warunkach eksploatacji w cyklu miejskim, pozamiejskim i autostradowym na wybranych typach pojazdów. Badania obejmowały pomiar emisji gazowych składników spalin i cząstek stałych oraz ich koncentrację i rozkład wymiarowy z jednoczesną rejestracją parametrów pojazdu w ruchu.

Słowa kluczowe: *emisja gazów wylotowych, filtry cząstek stałych*

1. Introduction

Particulate matter generated by diesel engines is an unwanted pollutant, harmful for the natural environment. The emitted PM are of different shapes and sizes. The currently applied particulate filters that are the key PM aftertreatment system enable a reduction of this component in the range of 70-95%. The critical aspects of the current DPF in use are related with the necessity to regenerate (PM oxidation). The sedimentation of PM on the filter results in a growth of the pressure upstream the filter, which again, results in a reduction of the potential from the fuel energy, leads to a reduction in the overall engine efficiency.

One of the ways of DPF filter regeneration is an effective process of oxidation of carbon-soot (a component of the PM) to CO and then to CO_2.

$$[C]+O_2 \rightarrow CO_2 \quad (1)$$

$$[C]+NO_2 \rightarrow CO_2+NO \quad (2)$$

The main PM components are the products of incomplete combustion of fuel and engine lubricant. We can distinguish two basic PM components, apart from the adsorbed gaseous part - light gaseous hydrocarbon fractions:

- Insoluble fractions,

a) organic (IOF – Insoluble Organic Fraction); carbon in the form of soot – products of incomplete combustion of fuel and oil additives,
b) inorganic (INSINOF – Insoluble Inorganic Fraction); ashes, sulfates, minute quantities of iron, phosphorus, calcium, silicon, chromium and also engine mechanical pollutants,

- soluble fraction,

a) organic (SOF – Soluble Organic Fraction); the main components are organic substances adsorbed in the soot particles,
a) inorganic (SINOF – Soluble Inorganic Fraction), generated mainly if sulfur is present in the fuel.

The basic components of the insoluble fraction are soot particles. They are characterized by a very high adsorption of products of incomplete combustion of fuel and engine lubricant. The soot having adsorbed these products (most of these products are carcinogenic) becomes particularly hazardous for the environment.

According to this definition soot generated as a result of combustion in diesel engines is composed of solid fraction – SF and soluble organic fraction SOF that is adsorbed (fig. 1).

At high engine speeds and under heavy load PM form concentric circles that are transformed into soot – graphite (fig. 2).

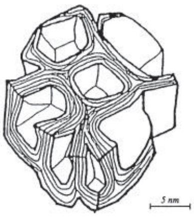

Fig. 1. A model of soot structure [8]

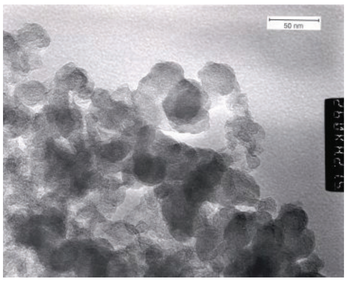

Fig. 2. Image of TEM PM obtained at high engine speeds at heavy load

The main problem related to the operation of DPF is the obtaining of sufficient temperature for the soot accumulated in the filter to burn out.

The temperature needed for the oxidation of soot is approximately 550–600ºC and additionally this process requires a sufficient amount of oxidizer – O_2 contained in the exhaust gases. Usually the temperature of the gases in the urban cycle for diesel engines does not exceed 250ºC and in extra urban cycles 400ºC.

2. Methods of regeneration

The most frequently used solution for the DPF filter regeneration leading to the oxidation of soot is to increase the temperature of the exhaust gases or the mere filter. This requires a use of an additional source of energy, which, however, incurs substantial costs let alone the risk of filter damage.

A more economical and safer solution seems the utilization of passive filter regeneration that consists in a use of appropriate catalysts that reduce the oxidation temperature of soot. Currently two technologies are used for the filter regeneration. The first one is based on the continuous regeneration: CRT, CCRT, CSF and the second one uses catalysts contained on the fuel (FBC) (fig. 3-5).

The technology that consists in continuous regeneration (the catalysts are placed on the catalytic support and/or the filter) utilizes the oxidation of a sufficient amount of NO from the exhaust gases to NO_2 (using appropriate catalysts), which leads to a reduction in the temperature of soot oxidation to the range of 250–350ºC. This process is yet, extremely sensitive to the presence of sulfur in the fuel and can only be used in the case of desulfated fuels. This process is used in heavy-duty vehicles for which the ratio of the amount of NO_2 to PM is higher than 8. Additionally, we know that oxygen contained in NO_2 is more active than molecular oxygen.

Systems of continuous regeneration supported by oxidizing catalysts also reduce the emission of CO and HC. Most frequently, Pt is used for this purpose, that also causes the formation of SO_3 from SO_2 at higher temperatures. SO_3 in contact with water vapor contained in the exhaust gases may form H_2SO_4. Both the sulfuric acid and the formed sulfates may result in increased emissions of particulate matter.

The best NO_x/PM ratio in terms of the emissions in the system of continuous regeneration is 25/1, which allows proper and effective filter regeneration.

In the second method that uses fuel-borne catalysts such as Ce or Fe (transition and precious metals e.g. Pt used as fuel additives) a reduction in the soot oxidation temperature is obtained (600–400ºC) in the filter. This method still does not lead to continuous filter regeneration.

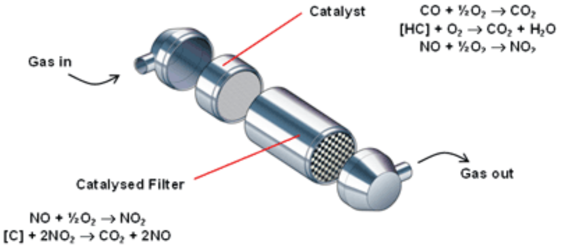

Fig. 3. CCRT system [1]

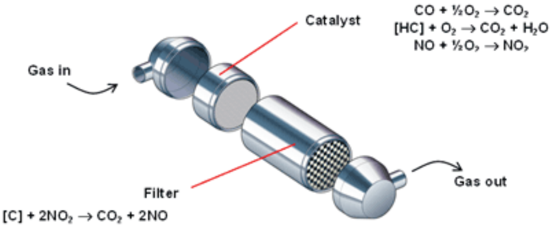

Fig. 4. CRT system [1]

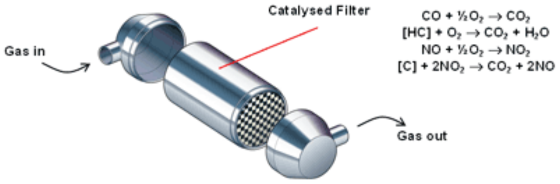

Fig. 5. CSF system [1]

If the pressure in the filter increases and is too high, an additional injection into the exhaust system is realized, which results in an additional energy leading to the growth of the exhaust gas temperature. This again leads to a more effective soot oxidation process. Unfortunately, the addition of the catalyst to the fuel generates ash that builds up in the filter cells resulting in lower filter efficiency (fig. 6) [7].

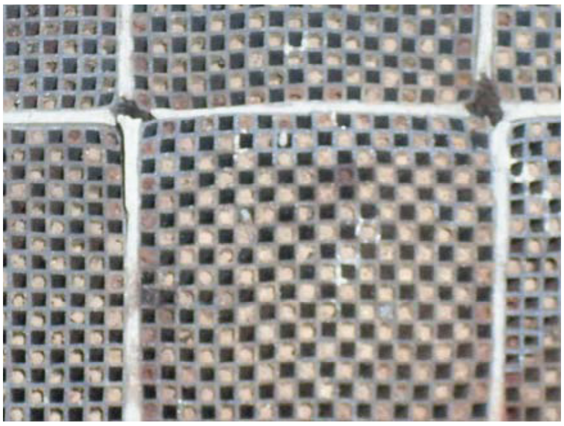

Fig. 6. Effect of FBC in DPF after 120 000 km

3. Soot oxidation

In model processes of soot burning two basic mechanisms are diostinguished. The first one is based on the reaction of oxidation-redox and the other one is called the spillover effect (fig. 7).

In the first mechanism redox takes place possible through the use of a special catalyst. This mechanism is based on the assumption that a metal containing two states of oxidation can trigger oxidation of soot thanks to the oscillations between these two states. This mechanism requires a good contact between the catalyst and the soot. If there is no physical contact the catalysts can operate as renewable donors triggering the activation of oxygen.

The activated oxygen gets recombined very quickly (within its own molecules) in the gaseous phase before it gets to the surface of carbon. In the case o catalysts set on the support, active oxygen migrates through the support layer to the surface of the built-up soot (carbon) – spillover theory (fig. 8).

In this theory the catalyst triggers dissociation of molecular oxygen and a supply of active atoms of oxygen to the soot to enable a non-catalytic oxidation process. Pt catalyst generates spillover that leads to the process of oxidation. In this process NO is oxidized to NO_2 (NO_2 is a better oxidizer than O_2). The reaction between NO_2 and soot leads to a non-catalytic soot oxidation.

Catalytic activity occurs in the gaseous phase e.g. acceleration of the conversion from NO to NO_2 that triggers soot oxidation (effect of continuous regeneration) or assists the process of CO oxidation (generated during the carbon thermal oxidation) and the formation of CO_2. The process of thermal and catalytic soot oxidation is currently investigated by many scientific centers and automotive concerns. It seems quite clearly defined but the mechanism of the catalytic process of soot oxidation is not as yet fully explained.

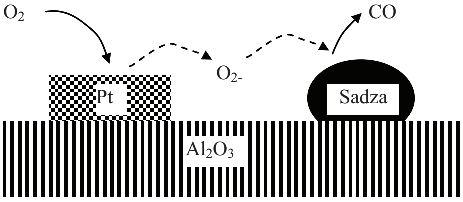

Fig. 7. Spill-over mechanism

Two mechanisms are proposed for the explanation of the catalytic soot oxidation. The first one tackles the problem on the atomic level based on the mechanism of electron transport. This mechanism consists in the activation of carbon (soot) by an appropriate catalyst that boosts the soot ability to oxidize. This theory is based on the change of the electron distribution in the structure of carbon, which in fact has not been experimentally confirmed.

The other mechanism consists in supplying active oxygen and is by most of the scientists accepted as the main mechanism of carbon (soot) oxidation. According to this theory a catalyst is perceived as a donor for oxygen activation.

In the macroscopic scale both mechanisms are based on sufficient contact between the catalyst surface and carbon (soot).

Most of the catalysts require good contact with carbon-soot for the reaction to properly take place – direct catalysis. In this respect we can distinguish two types of reactions between the surface of the catalyst and soot: a formation of a channel (channeling) and edge recession (fig. 8).

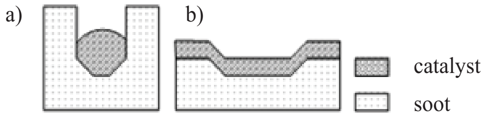

Fig. 8. The comparison of the reactions: a) channeling; b) edge recession

The first type of reaction occurs when the inter-phase bonds between the surface of the catalyst and the surface of carbon–soot are too weak and then the channeling effect takes place.

The second type of reaction (edge recession occurs when the inter-phase (solid-solid) bonds are very strong (the bonds between the surface of the catalyst and the surface of carbon).

The atoms of metal that adsorb the dissociated oxygen and form oxides through strong inter-phase bonds lead to edge recession. The atoms of metal that adsorb the undissociated oxygen and remain in the – unoxidized ‘precious’ state do not form strong bonds and this leads to the effect of channeling.

4. Fracture

One of the main issues related to the durability of catalytic supports and diesel particulate filters is fracturing that may occur during the thermal regeneration of the system.

The glasslike structure of the highly porous SiC sinters used as filter supports does not allow permanent anchoring of the nanoparticles of the catalyst due to very smooth surfaces of the pores. It is possible to modify these surfaces in order to obtain the required parameters. One of the methods to do that is surface etching that takes place in hydrogen and steam. Wet chemical etching is also possible here.

The surface of the SiC support in the temperature of T= 330°C in hydrogen decomposes into a SiC – Si composite (fig. 9) and the deep pores developed in this process allow fixing the catalyst grains or clusters onto the SiC support (applying nanopaste).

The silicon present on the surface of SiC forms low temperature eutectics, with most of the metals and their oxides. This results in a major improvement of the physical and chemical parameters of the support. Wide research has been conducted in this matter.

Structures of nanometric spheres are formed that enable the boosting of the durability of the catalytic supports. The obtained nanometric structures of the spheres (Ti_4O_7, TiO_2 – RuO_2) result in a significant development of the smooth surface of SiC and reduce the possibility of fracture of the SiC surface [2].

In the case of Ti_4O_7 fixed into the glasslike structure of SiO_2, on the surface of SiC, a composite structure develops ($SiC–SiO_2–Ti_4O_7$) thus enabling the said reduction of the risk of fracture on the SiC surface [2], [3].

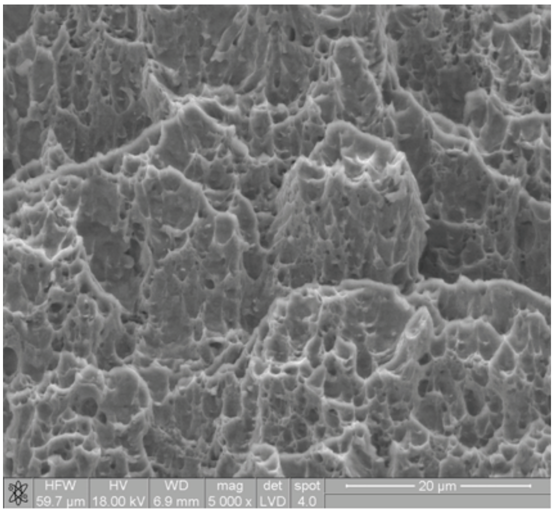

Fig. 9. The surface of the porous SiC sinter after hydrogen etching

Fracture occurring during thermal shocks can be eliminated by the application of surface blending of the Ti_4O_7 nanosphere. In figure 10 one of the examples has been presented of the fracture elimination through the Ti_4O_7 blended into the surface of $SiC–SiO_2$.

The Ti_4O_7 nanosphere on the surface of SiO_2–SiC glasslike materials in the thermal investigations during thermal shocks in the temperature range of T = 25–1250°C, is not destroyed but only deformed due to its elastic nanostructure: Ti_4O_7 sphere – glass –SiO_2–SiC [4], [5].

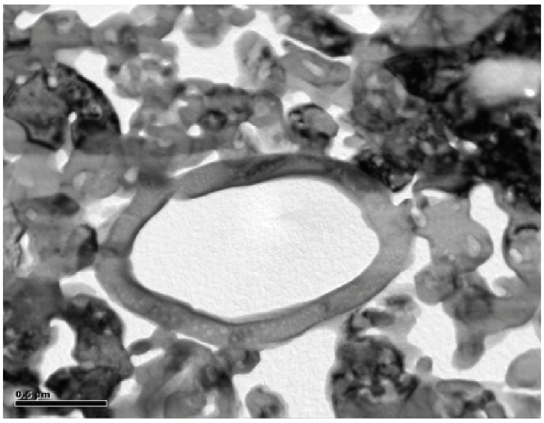

Fig. 10. Transverse microsection of composite – glasslike structure $SiC–SiO_2–Ti_4O_7$

5. The analysis of the physical chemical properties of the DOC-DPF system

One of the most important elements of the catalytic systems modeling is proper selection of the DOC operating parameters. The systems should be designed so as to have appropriate dimensions and have the right catalytic components that ensure high system efficiency.

The task of an aftertreatment system is to minimize all the exhaust emissions generated during the process of combustion:

$$\text{Min } [f= HC_{emission}+ CO_{emission}+ NOx_{emission} + PM_{emission}] \qquad (3)$$

This function is for the minimization of the emission to the level of currently applicable and future standards i.e. [6]:

$$\text{Min } f = W_{HC}\left[\frac{HC_{emission}}{HC_{regulation}}\right] + W_{CO}\left[\frac{CO_{emission}}{CO_{regulation}}\right] + W_{NOx}\left[\frac{NOx_{emission}}{NOx_{regulation}}\right] + W_{PM}\left[\frac{PM_{emission}}{PM_{regelation}}\right] \qquad (4)$$

When selecting the parameters of the catalytic systems we need to consider many variables including the geometrical parameters: length, cross-section, support wall thickness, number of cells and porosity. Also, an important aspect is the kind of material used for the construction of the catalytic systems (type of catalyst and the way it was applied on the support). A well-selected composition of the active layer should allow for the processes and conditions that take place during the operation of the vehicle. An important parameter of this system is also its mass that, to some extent, limits the thermodynamic parameters including its thermal inertia and the operating range of the catalytic converter. The mass of the catalytic support is defined as a function of two variables: the thickness of the walls and the cells (channels) that come in a given unit of area.

The use of the DPF filter including its regeneration requires the operation of additional elements such as the DOC in particular. The mutual cooperation of these devices requires a selection of their proper volumes, which ensures the afterburning of the accumulated PM and soot. The process of regeneration needed for long-life filter operation is also necessary to prevent an adverse and uncontrolled backpressure increase when the DPF filter gets clogged. This could lead to a reduction in engine power output through a limitation of the charge exchange efficiency in the cylinders. The backpressure is also very disadvantageous for the operation of the turbocharger i.e. supercharging level, which directly translates into the quality of the combustion process.

The temperature that enables the afterburning of PM (soot) in the filter oscillates around 500–600^{o}C. From many tests that have been performed it results that the temperature above 600^{o}C can occur during high (extreme) engine loads and only in such conditions the filter regeneration would be possible. In the temperature range of 500–600^{o}C and higher the oxidation of PM does take place but it does not guarantee full filter regeneration. In the driving cycle sufficiently high engine loads in a sufficiently long period of time do not occur for the proper regeneration to complete (fig. 11). In an appropriate selection of the DPF regeneration strategy the following play a significant role:

a) engine operating parameters,
b) injection parameters,
c) thermodynamic conditions of the engine-exhaust system pair,
d) the possibility of selecting appropriate configuration in terms of widely understood physical chemical parameters DOC-DPF and DOC/CRT.

The exploration of the DPF regeneration parameters is important from the point of view of:

- the improvement of the operation efficiency of DPF through a better control of the PM emission during the filter regeneration,
- extension of the filter life,
- the possibility of the control of the engine operating parameters – ensuring appropriate thermodynamic parameters,
- the possibility of control of the amount of consumed fuel.

The presented preliminary analysis leads to conclusions that for the improvement of the filter regeneration it is necessary to:

- reduce the mass of the aftertreatment system, including the thermal inertia:
  a) of the DOC support,
  b) of the DPF support:

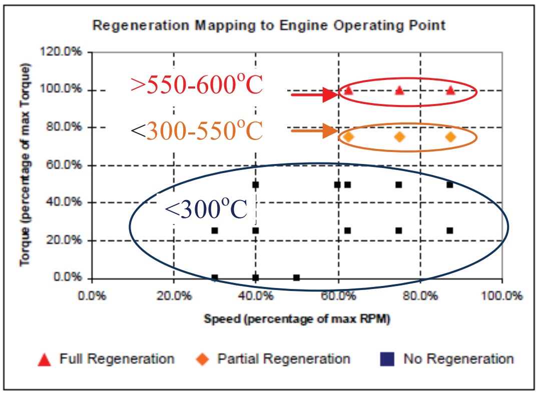

Fig. 11. The regeneration map of regular CI engine operating points according to ESC cycle w/o added additional energy or additives [6]

- select the most normalized parameters in terms of efficiency and cost; according to the following dependencies have been proposed based on the consultation with the DPF manufacturers (USA):
  - normalized DOC mass = DOC mass / (150% x DOC standard mass),
  - normalized DPF mass = DPF mass /(150% x DPF standard mass),
  - normalized system mass = system mass /(150% x standard system mass) (coefficient 150% was selected based on the manufacturer declarations regarding the possible cost increase acceptance against the obtained efficiency).

In order to ensure proper efficiency of the DPF filter regeneration the following parameters should also be considered:

- minimization of the fuel consumption:
  - fuel economy = the fuel mass used during the filter regeneration;
  - normalized fuel economy = the fuel mass used/10% of the total mass of fuel in the process.

Because of the increase in the efficiency of PM conversion i.e. the obtainment of the maximum level of PM oxidation the parameters of the regeneration process itself are also taken into account:

- regeneration capability = number of successful regenerations /number of regeneration trials;
- regeneration efficiency = the mass of the burnt particles /the mass of the particles before the regeneration.

The regeneration efficiency is thus calculated as the ratio of the mass of the oxidized particles and the particles built up in the filter before the regeneration for each point at which the regeneration process occurs.

In terms of design, the ratio of the length of the DOC and DPF systems to their diameter should be considered (fig. 12). Appropriate selection of these parameters conditions the operation of the whole aftertreatment system: lower thermal inertia, better heat transfer between the cells, better surface extension and growth in the active catalytic centers. Higher A/R ratio is more advantageous.

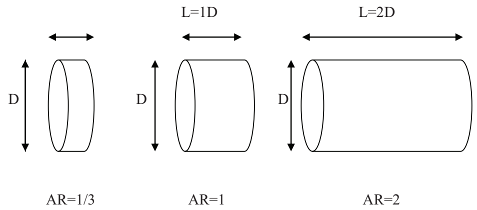

Fig. 12. Selection of the design parameters of DOC and DPF [6]

This allows a higher share of the cells that change the parameters most quickly depending on the thermodynamic states in the exhaust system. Besides, it guarantees more time for the reactants to diffuse into the catalytic layers and ensures a higher probability of active ion clash.

The efficiency of the whole DPF filter also depends on the unit values of the thermal expansion coefficient of the materials of the individual components. This is important due to the temperature distribution depending on the dynamically changing parameters of the exhaust gases (temperature and pressure) but most importantly it influences the filter durability. Various values of the thermal expansion coefficient lead to propagation of cracks in the catalytic support and this leads to a change in the number and kind of open pores that are the direct filtering material.

Variants of the ratio of DOC to DPF length are considered. In this case we distinguish three groups:

- DPF – long/small diameter +DOC – smaller/greater diameter;
- DPF – small/ great diameter +DOC – longer/ small diameter;
- DPF – much smaller/great diameter +DOC – much longer / small diameter (fig. 13).

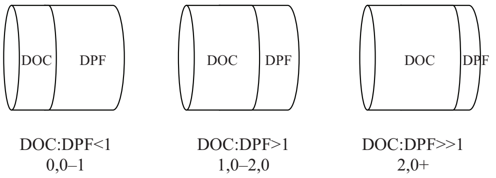

Fig. 13. Design of DPF-DOC with different volume factor of DOC/DPF [6]

The AR coefficient (fig. 12) for DOC and DPF assuming D = constant is equal to the quotient of the length of both of these systems as per the dependence [6]:

$$\frac{DOC_{AR}}{DPF_{AR}} = \frac{\left(\frac{DOC_L}{DOC_D}\right)}{\left(\frac{DPF_L}{DPF_D}\right)} = \frac{DOC_L}{DPF_L}. \qquad (5)$$

for DOC_D = idem and DPF_D = idem

To date, the effective DPF continuous passive regeneration has not been possible. The main issue is low temperature of the exhaust gases thus low temperature of DPF.

6. On-road DPF testing

6.1. The characteristics of the conditions and the test objects

The tests on the filters were performed in order to compare the parameters of vehicle and engine operation under real operating conditions in terms of the possible regeneration occurrence.

The tests were performed in city traffic (Skoda), extra urban cycles and expressway cycles (Audi).

The Skoda vehicle was fitted with a 2.0 dm^3 engine (tab. 1). The vehicle mileage when the test initiated was 12 434 km. The vehicle was operated in city traffic throughout the whole test. The engine was fitted with catalyzed soot filter (CSF) (fig. 14, 15).

Fig. 14. View of the DPF fitted in Skoda exhaust aftertreatment system

Table 1

Skoda technical data

Engine typ	in line, turbodiesel
Cylinder number/valve number	4/16
Volume (cm^3):	1968
Max. power (KM/rpm):	170/4200
Max. torque (Nm/rpm):	350/1800
Fuel consumption : extra urban/urban (l/100 km)	4,5/7,7

The Audi vehicle was fitted with a 1.9 dm^3 engine (fig. 16, tab. 2). The vehicle mileage when the test was initiated was 47 330 km. Until this time the vehicle was mostly operated in the city traffic.

Similarly to Skoda it was fitted with a catalyzed soot filter (CSF) (fig. 17).

Fig. 15. View of the vehicle (Skoda) used in the test in real operation

Fig. 16. View of the Audi vehicle used in the test in real traffic operation

Fig. 17. View of the DPF fitted in the Audi exhaust aftertreatment system

The on-road tests were performed with the use of a portable exhaust emission analyzer at the same time reading the actual on-road parameters:

- Semtech DS (measuring CO, CO_2, HC, NO, NO_2; reading Ne, M, GPS),
- Engine Exhaust Particulate Sizer (PM size distribution).

When selecting the urban route two parameters reflecting the NEDC test under traffic conditions were considered: average vehicle speed and route length. The said test is composed of the urban and extra urban cycle. Both parts are characterized by different maximum vehicle speeds (52 km/h and 120 km/h). That is why the route (fig. 18) was selected for the tests so that it simulated both parts of the NEDC homologation test:

– S2 – S = 11,96 km, $V_{śr}$ = 37 km/h (fig. 18).

Table 2

Audi technical data

Engine typ	in line, turbodiesel
Cylinder number/valve number	4/16
Volume (cm^3):	1897
Max. power (KM/rpm):	115/4000
Max. torque (Nm/rpm):	285/1900
Fuel consumption : extra urban/urban (l/100 km)	4,5/7,2

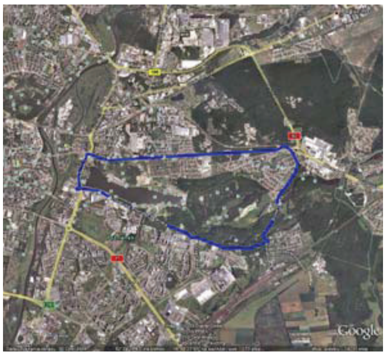

Fig. 18. S2 cycle

The second route, extra urban and expressway, marked A2 was preceded by a four-hour vehicle operation in the afternoon city traffic in order to build up the PM mass in the filter. The filter buildup was monitored with dedicated software. When the level of soot content in the filter reached 30% extra urban cycle was initiated in order to create conditions for filter regeneration.

A2 – S = 126 km, $V_{śr}$ = 75 km/h (fig. 19).

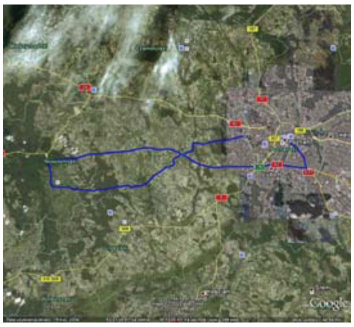

Fig. 19. A2 cycle

6.2. The S2 route test results

Based on the obtained measurements an analysis has been performed of the values of selected emissions in terms of parameters of the occurrence of DPF passive regeneration and a possible initiation of the active regeneration by the engine control unit.

On the route marked S2 the following were obtained:

- minimum vehicle speed V = 0 km/h (stops at intersections/ high traffic congestion),
- maximum vehicle speed V = 112 km/h,
- minimum engine load M = 0% (idle speed),
- maximum engine load M = 98%.

The maximum concentration of NO_2 in the S2 cycle was 302 ppm (t = 338s) and the minimum was 60 ppm (t = 918s). The obtained vehicle speed was within the range of 0–112 km/h. The share of the vehicle speed V = 0 km/h was 8% in the whole driving cycle (in time t = 93s). The share of the lowest engine load M = 0% (idle speed) was 10% (in time t = 116s). The maximum engine load M = 99% was recorded in t = 860–865s of the test. The literature analysis indicates that the soot accumulated in the filter in the amount close to 45–50% of the total filter capacity results in an EGR switch off, at the same time allowing an additional fuel injection in the exhaust stroke (post injection – 35^o past TDC). This action results in the exhaust gas temperature of T = 600ºC whose value is sufficient for the triggering of the soot afterburning process with O_2. In this same moment an adaptation of the charging pressure takes place in order to ensure a continuous engine power output. This state, however is difficult to reach in the case of driving in a mixed mode (stop-and-go prevalent in the urban driving cycle). In such a case and in the case of relatively low vehicle speeds the regeneration process is interrupted or does not occur at all.

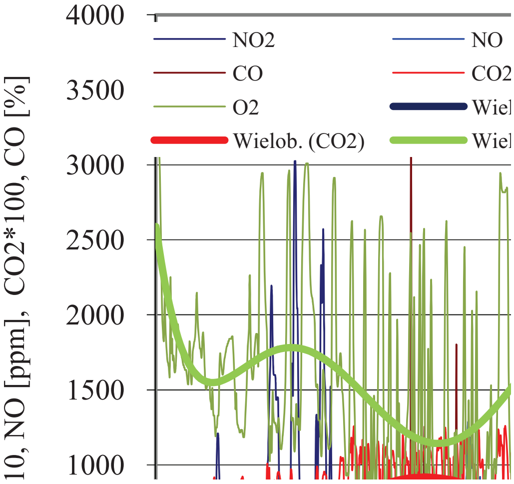

Fig. 20. Concentration of NO_2, NO, CO_2, CO, O_2 in S2 cycle

Based on the performed analyses, the authors concluded that the vehicle speed above 60 km/h constituted 11% (t = 132 s) of the test and, yet, the regeneration process was not initiated by the engine control unit.

Based on the concentration of NO_2 and CO_2 in time t = 255–463s peaks of NO_2 combined with peaks of CO_2 (fig. 20) were recorded. It is noteworthy that the concentration of CO_2 is a result of an increased fuel consumption triggered by the increase in vehicle speed V or engine load M. In the discussed part of the test the parameters change dynamically, which could be the reason for an increased CO_2 concentration. The visible peaks of NO_2 and O_2 concentration can be a result of a change in the level of exhaust gas recirculation, which leads to a growth in the concentrations of the said exhaust components (fig. 20).

At the same time the growth in the component concentration led to passive regeneration (as per (6-8)), which is evidenced by continuous changes in the size distribution of PM in the further part of the test (fig. 21, 22).

$$NO + \frac{1}{2} O_2 \rightarrow NO_2 \text{ (NO oxidation)} \tag{6}$$

$$NO_2 + C \rightarrow NO + CO \tag{7}$$

$$NO_2 + C \rightarrow \frac{1}{2} N_2 + CO_2 \tag{8}$$

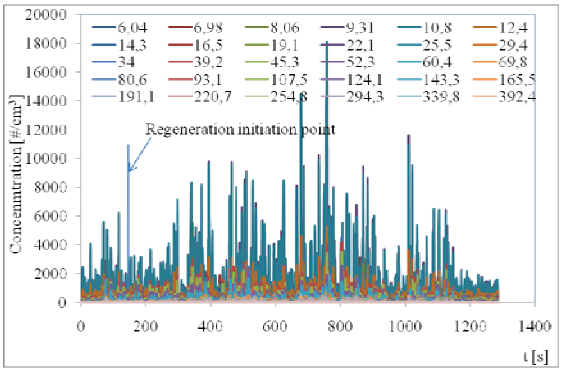

Fig. 21. Particulate matter size distribution in the S2 cycle

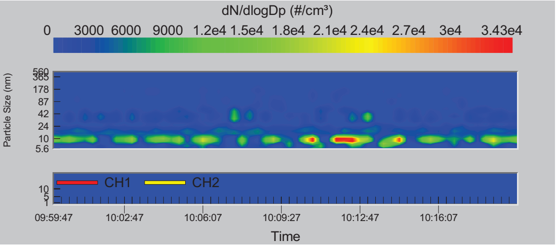

Fig. 22. Particulate matter concentration with particulate matter size distribution during passive regeneration

6.3. The A2 route test results

The A2 route was an urban, extra urban and expressway driving cycle. The route length was 126 km (fig. 19). The first part of the route was a road portion between Poznań and Nowy Tomyśl (urban and extra urban cycle), the second one was Nowy Tomyśl – Poznań (expressway cycle). The cycle was initiated with a partially filled (30%) DPF filter. The average speed in the first part of the route was $V_{śr}$ = 46 km/h and the maximum was V_{max} = 76 km/h. The conditions that, according to the literature analysis, constitute a basis for the initiation of the active regeneration process (V > 60 km/h) occurred in time t = 32 min.

The exhaust gas components whose emission/concentration directly confirm the activation of the regeneration process (both passive and active) are CO, CO_2, NO, NO_2, O_2 as per 6-8. Figure 23 presents the concentration of these components throughout the whole A2 route (urban, extra urban and expressway driving cycles). We can confirm two parts of the course of the concentrations. The first one, highly variable, relates to a part of the urban and extra urban cycle where the dynamics of the change of speed V and load M was high. This also resulted in a highly variable course of concentrations of the measured exhaust components. For a better explanation of the course of the concentrations they were presented in a multinomial form. This allowed a clear confirmation of the occurrence of the active filter regeneration (fig. 23). A reduction in the concentration of O_2 and NO_2 was observed with a simultaneous increase in the concentration of CO_2, which is a result of the soot oxidation. The concentration and the size distribution of the emitted PM during the regeneration have been shown in figures 24 and 25. During the regeneration the concentration of PM in the range of diameters of 25–52 nm grew particularly high (fig. 24).

In figure 23 we can distinguish the second part of the A2 route – the expressway driving cycle in which the concentration of the measured exhaust components assumes a much smoother course. This results from the stabilized engine operating parameters. At the same time we can see the course of the active regeneration during which the drop in the concentrations of O_2 and NO_2 occurs along with the increase in CO_2 (of much lower rate though).

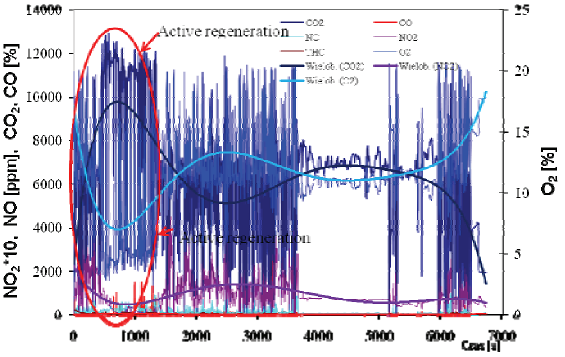

Fig. 23. Density of NO_2, NO, CO_2, CO, O_2, THC in the A2 cycle

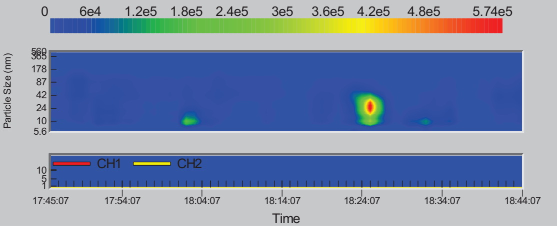

Fig. 24. Particulate matter concentration with particulate matter size distribution during active regeneration

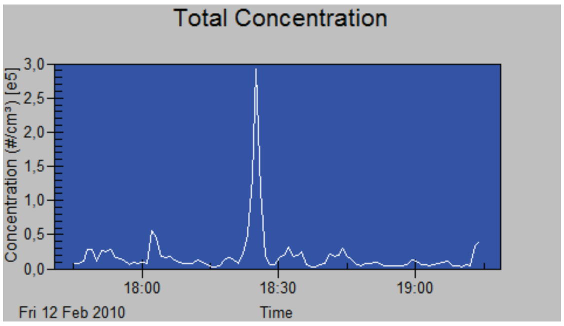

Fig. 25. Particulate matter concentration with peak during active regeneration

7. Conclusion

In the urban cycle we can state that there is a need to use fuels containing additives that will ensure the process of active regeneration or we need to apply composite materials that enable a more efficient process of passive regeneration.

The material that the DPF is composed of must have a low thermal expansion coefficient in order to prevent heat losses in the system thus preventing higher fuel consumption.

The filter material must be resistant to thermal shocks as they occur very often and lead to eutectics – local filter melting.

Due to a high PM emission of different size a system of filters of different filtering parameters is being considered (made from composite materials aiding the exothermal reactions).

For the urban cycle filter operation it is of key importance to improve the thermal conditions already in its design phase. The heat losses en route the engine and the filter in the urban cycle are significant – (lower exhaust gas temperature and frequent idle speed operation). In the extra urban cycle these heat losses are miniscule due to a sufficient amount of heat transported by the exhaust gases needed for the processes of catalytic oxidation and afterburning.

It is necessary to increase the number of regeneration cycles, hence the need to use composite structures for the construction of DOC-DPF systems.

Nomenclature/*Skróty i oznaczenia*

DPF	diesel particulate filter/*filtr cząstek stałych*
TEM	elektronowy mikroskop transmisyjny/*Transmission electron microscopy*
CRT	continuous regeneration trap/*system filtrujący o ciągłej regeneracji*
CCRT	catalysed continuous regeneration trap/*układ oczyszczania spalin z utleniającym reaktorem katalitycznym i pokrytym katalitycznie filtrem cząstek stałych*
CSF	catalysed soot filter/*filtr cząstek stałych pokryty katalitycznie*
FBC	fuel borne catalyst/*dodatki katalityczne do paliwa*
HDV	heavy duty vehicle/*pojazd ciężarowy*
PM	particulate matter/*cząstka stała*
LPG	liquified petrolum gas/*gaz skroplony*

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