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Basic Aspects Related to Operation of Engine Catalytic Converters

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Abstract

Experimental research on the diesel engine 6C107 equipped with selected oxidation catalytic converters was carried out. Specific emissions of toxic substances were investigated in the whole operation range of the engine before and after catalysts. Thus, changes of the emission indices within the catalysts and conversion efficiencies of the harmful substances were evaluated. Besides, temperature threshold of the catalytic action was determined too. Apart from chemical efficiency of the converters, their resistance to exhaust gas flow also is an essential problem. Therefore selected quantities of exhaust gas flow through the catalysts were determined and analysed together with their termochemical efficiency.

Keywords: Diesel engine, catalytic converter, toxic substance, conversion efficiency, flow resistance, resistance number.

1. Introduction

Dynamic increase of number of motor vehicles is noticed in Poland for the last few years. Considerable contribution to the total emission of toxic substances falls to transport, particularly to road transport. Exhaust gases from internal combustion engines contain chemical substances and compounds which have an adverse impact on our environment in the form of acidification, ozone formation, carcinogenic emissions, etc.

Reduction of toxic substances emission (components in gaseous phase: CO, NO_x, HC, SO_y, as well as solid particles: soot and condensed hydrocarbons) from combustion engines can be achieved by realisation of two groups of measures:

- primary (in other words inside-engine) measures,
- secondary (in other words outside-engine) measures (Postrzednik and Zmudka, 2002).

As primary measures many different possibilities and technical methods of reducing exhaust gas emission are used e.g.:

- combustion of lean air-fuel mixtures,
- multistage injection of fuel,
- exhaust gas recirculation,
- flue gas after-burning,
- loading (injection) of additional water into cylinder volume (as well as combustion of fuel-water mixture, humidification of recirculating flue gas or supercharging air).

Nowadays, as secondary measures, in automotive exhaust aftertreatment processes a range of advanced technologies is applied based on oxidation and three-way catalyst: adsorption, storage and filtration processes. This enables reduction of the carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x) and particulate emissions from a gasoline or diesel engine, to meet the demands of current and future exhaust emission regulations. Catalytic converters lower significantly toxic gaseous substance emission as well as particulate mass in diesel engine exhaust gas up to 50%, by destroying the organic fraction of the particulate (Searles, 1998).

Advanced technology of the catalysts and their substrates ensures high conversion efficiency. Cell density of ceramic substrates has increased from 200 cpsi (cells/in^2) of cross-section to as high as 900 cpsi. Wall thickness has reduced from 0,3 mm to almost 0,05 mm. Metallic substrates allow higher cell density to be achieved. Complex internal structures can be developed with a wall thickness of 0,02 mm and cell density of 1600 cpsi. This progress is very beneficial. A larger catalyst surface area allows better conversion efficiency and durability. Thin walls reduce thermal capacity and pressure losses. Comparison of the typical metallic and ceramic substrates is presented in the TABLE I (Searles 1998, Garrett 1991, Maus 2001).

TABLE I. TYPICAL METAL AND CERAMIC SUBSTRATE MATERIALS COMPARED

Property	Metal	Ceramic
Wall thickness mm	0,04 *0,02**	0,2 - 0,15 *0,05**
Cell density cells/in^2	400 *1600**	400 *900**
Clear cross section %	91,6	67,1
Specific surface area m^2/dm^3	3,2	2,4
Thermal conductivity W/(m K)	14 – 22	1 – 1,08
Specific heat kJ/(kg K)	0,5	1,05
Density g/cm^3	7,4	2,2 – 2,7
Thermal expansion ΔL/L 10^{-6} K	15	1

* *the most advanced technology*

2. Experimental Tests of Selected Oxidation Catalytic Converters

Experimental research on three oxidation catalysts, installed in exhaust system of diesel engine 6C107 (6 cylinders, capacity 6540 cm^3, power $N_{e,max} = 98$ kW, $M_{max} = 380$ Nm, compression ratio $\varepsilon = 16$), was carried out. Fitting a suitable catalyst to this type of engine was a goal of the investigations. The use of the oxidation catalyst aims at reduction of the incomplete combustion products in the range of mean and high engine loads. Specification of the tested catalyst is presented in the TABLE II.

The converters were assembled in the exhaust system as close to the engine as possible, immediately after the exhaust manifold, in order to fast warm-up to a temperature of their activation.

For evaluation of the engine with regard to the content of toxic substances in exhaust gas, molar fractions and relative indices e_i (specific emissions) of noxious pollutants emission were used (Zmudka et al. 2000). The specific emissions were measured in the whole operation range of the engine before and after the catalysts. Changes of the emission indices within the converters and conversion efficiencies of the toxic substances (CO and HC) were determined.

TABLE II. SPECIFICATION OF THE OXIDATION CATALYTIC CONVERTERS TESTED

Property	Type of converter		
	Baildon	SZOP 07	Ekomot. KS 0325
Substrate material	metal	metal	ceramic
Cell density, cells/cm^2	40	56	30
Wall thickness, mm	0,05	0,1	0,30
Substrate volume, dm^3	2,16	1,93	2,41
Void cross-section area, cm^2	176,3	160,4	133,3

Exhaust gas composition was analysed by means of gas analyser INFRALYT EL, which measures molar fraction of five constituents in dry exhaust gas with the following accuracy (absolute error):

$$\Delta[CO_2] = \pm 0{,}1\%;\ \Delta[O_2] = \pm 0{,}1\%;$$

$$\Delta[CO] = \pm 0{,}01\%;$$

$$\Delta[HC] = \pm 5\text{ppm};\ \Delta[NO] = \pm 10\text{ppm}.$$

Conversion efficiency η_i of i-th noxious constituent can be defined as:

$$\eta_i = \frac{e_{i,1} - e_{i,2}}{e_{i,1}} \quad (1)$$

where: $e_{i,1}$ and $e_{i,2}$ are specific emission of i-th substance before and after catalyst respectively [e.g. g/kg fuel].

Characteristics of CO conversion efficiency for the tested catalysts are presented in the *Figure1*.

It was found that the catalytic converter SZOP 07 reached the highest efficiency in the whole operation range of the engine. Its maximum efficiency of CO conversion is 98%. The catalyst achieves satisfactory effectiveness ($\eta_{CO} > 60\%$) at relative engine load of 40%. For the load above 70%, efficiency of CO oxidation exceeds 90%.

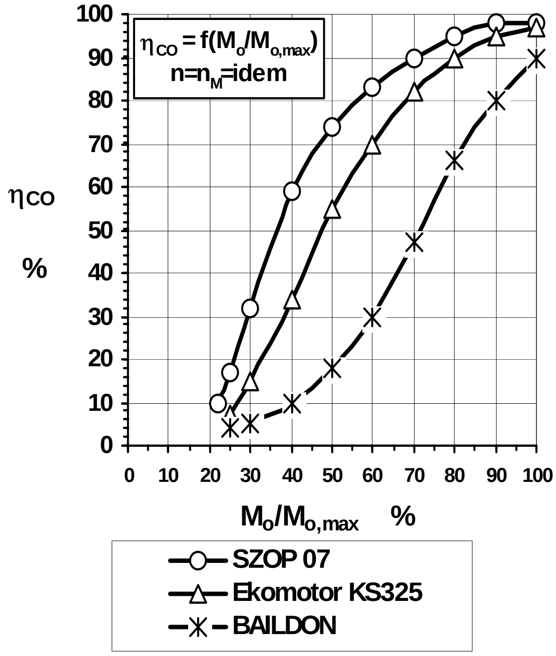

Figure 1. CO conversion efficiency η_{CO} of the oxidation catalytic converters tested – versus engine relative torque (load)

Likewise temperature threshold of the catalyst SZOP 07 operation is the lowest and amounts about 320°C (*Figure 2*).

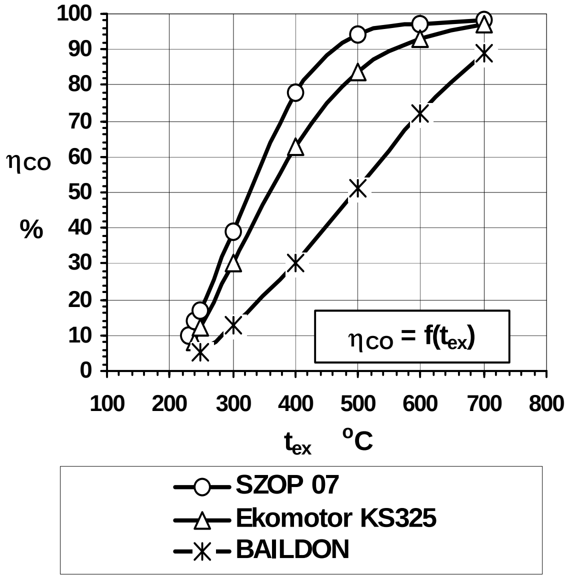

Figure 2. CO conversion efficiency η_{CO} within the oxidation catalytic converters tested – versus exhaust gas temperature t_{ex}

Speed characteristic of hydrocarbons conversion efficiency for the catalyst SZOP 07 is presented in the *Figure 3*.

Idle running, operating characteristic and selected values of engine load have been taken into consideration. Thus, the performance of the converter is shown also in the whole operation range of the engine. Conversion efficiency of hydrocarbons exceeds 90% at engine speed above 1700 rpm for operating characteristic of the engine.

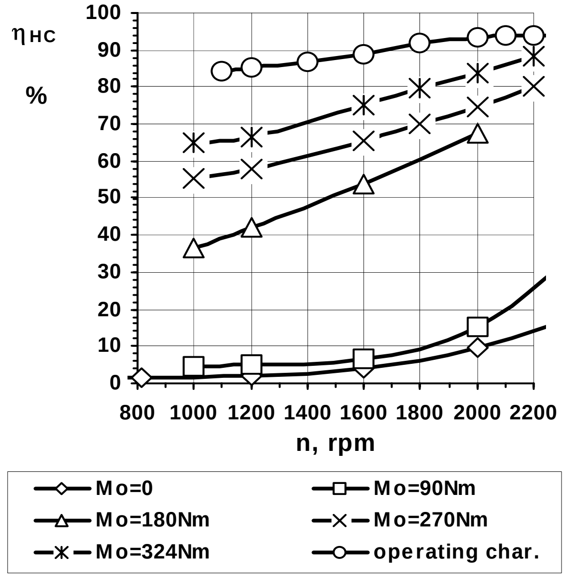

Figure 3. Speed characteristic of HC conversion efficiency for the catalyst SZOP 07 – versus engine speed (M_o = idem)

3. Flow Resistance of Catalytic Converter

Resistance of catalytic converter to exhaust gas flow also is an essential problem, apart from its chemical efficiency because fitting a catalyst in exhaust system alters flow characteristic of this system significantly. Too high flow resistance makes exhaust gas outflow difficult, thereby it increases the work consumed during charge exchange. Therefore selected quantities of exhaust gas flow through the catalysts were determined and analysed together with their termochemical efficiency. For this purpose, mean values of exhaust gas parameters within the catalyst were used.

Mass flux $\dot{m}_{ex}$ of exhaust gas can be written as follows:

$$\dot{m}_{ex} = A_{ex}\ w_{ex}\ \rho_{ex} \tag{2}$$

where: A_{ex} – void cross-sectional area of a catalyst [m^2],
w_{ex} – velocity of gas flow [m/s],
ρ_{ex} – exhaust gas density [kg/m^3].

The void cross-sectional area A_{ex} of the catalyst can be expressed as:

$$A_{ex} = \varepsilon\ A \tag{3}$$

where: A – total cross-sectional area of the catalyst [m2],
ε – porosity.

Introducing (3) to (2), one obtains:

$$\dot{m}_{ex} = A\ \varepsilon\ w_{ex}\ \rho_{ex} \tag{4}$$

where

$$\varepsilon \, w_{ex} = w_{0,ex} \tag{5}$$

$w_{0,ex}$ is average velocity of exhaust gas in the catalyst.

Using relationship (4) gas flux is expressed:

$$\dot{m}_{ex} = A \, w_{0,ex} \, \rho_{ex} \tag{6}$$

The average velocity of exhaust gas in the catalyst is calculated, using (6), according to formula:

$$w_{0,ex} = \frac{\dot{n}_{ex} \, M_{ex}}{A} \, v_{ex} \tag{7}$$

where: $\dot{n}_{ex}$ – molar flux of gas [kmol/s],
M_{ex} – molar mass of humid exhaust gas [kg/kmol],
v_{ex} – average specific volume of exhaust gas within the catalyst [m^3/kg].

Flow resistance by converter is considered as a local resistance. Using Darcy model:

$$\Delta p = \xi \, \frac{w_{0,ex}^2}{2 \, v_{ex}} \tag{8}$$

resistance number ξ of the catalyst is calculated by the equation:

$$\xi = \frac{2 \, v_{ex} \, \Delta p_{cat}}{w_{0,ex}^2} \tag{9}$$

The *Figures 4-6* are illustrative of the results of experiments and calculations for the catalytic converter SZOP 07 in the whole operation range of diesel engine 6C107.

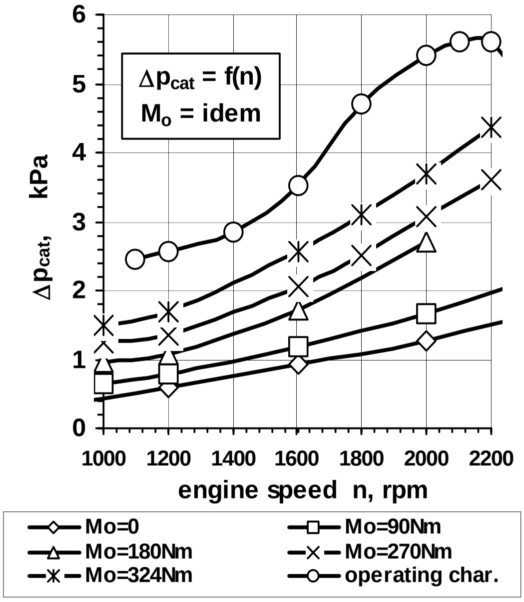

Figure 4. Pressure drop Δp_{cat} within the catalytic converter SZOP 07 – versus engine speed

It was found that depending on engine load and speed, pressure drop Δp_{cat} is within the range from 0,4 kPa to 5,5 kPa (*Figure 4*).

Average velocity $w_{0,ex}$ of exhaust gas in the converter varies from 4 m/s to 24 m/s (*Figure 5*).

Resistance number ξ of the catalyst is presented in the *Figure 6*. This parameter depends also on engine speed as well as on torque. Generally, resistance number decreases (from 120 to 60) when speed increases.

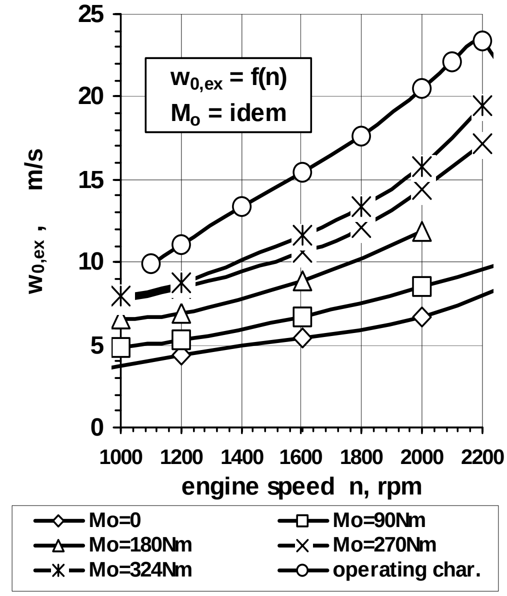

Figure 5. Average velocity $w_{0,ex}$ of exhaust gas in the converter SZOP 07 – versus engine speed

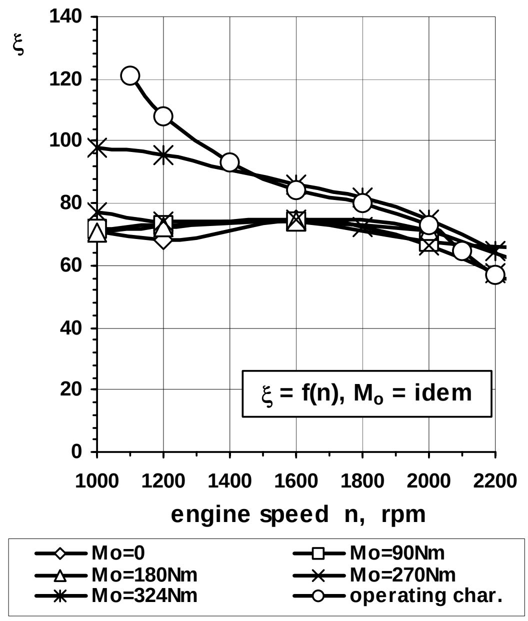

Figure 6. Resistance number ξ of the catalyst SZOP 07 – versus engine speed

4. Conclusion

Investigation of three oxidation catalytic converters was carried out within the range of conversion efficiency of the incomplete combustion products and flow resistances. It was found that the most suitable catalyst for mating with the tested diesel engine 6C107 is the converter SZOP 07 in consideration of the high efficiency. Moreover, its temperature threshold is the lowest.

Unfortunately, efficiency of the catalyst is sufficiently high only above boundary value (minimal) of load. This is conditioned by suitable temperature level of the catalyst (so-called temperature threshold). During diesel engine operation at low loads, temperature of exhaust gas leaving cylinders is considerably lower than during nominal load. As a result temperature of the catalyst also decreases. This causes reduction of the toxic constituent conversion efficiency within the catalyst. Therefore additionally, to reduce CO and HC emission at idling and low loads the other methods should be applied. It can be e.g. fuel supply cut-off to selected cylinders technique (Zmudka et al. 2000).

A second problem in diesel engines is reduction of nitrogen oxides (NO_x) emission. Reduction of NO_x emission can be achieved e.g. by proper control of fuel injection advance angle or exhaust gas recirculation.

By these methods, the complex solution of the problem of toxic substances emission from diesel engine can be attained.

It was also confirmed that operating parameters of engine influence flow resistance significantly that decrease engine effective work.

Nomenclature

A	cross-sectional area [m^2]
e	specific emission [g/kg fuel]
M_o	torque [Nm]
$\dot{m}$	mass flux [kg/s]
$\dot{n}$	molar flux [kmol/s]
p	pressure [Pa]
v	specific volume [m^3/kg]
w	velocity of gas flow [m/s]
ε	porosity
η	toxic substance conversion efficiency
ξ	resistance number
ρ	gas density [kg/m^3]

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