COMPREHENSIVE APPROACH TO THE WORK OF CATALYSTS IN ENGINE EXHAUST SYSTEMS

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Abstract

The use of a catalytic converter is aimed first of all at reduction of the incomplete combustion products emission. Conversion rate of harmful substances is the principal parameter of catalyst work in respect of ecology. However, resistance of exhaust gas flow through the catalytic converter is also essential problem, apart from its chemical efficiency because fitting the catalyst in exhaust system alters flow characteristic of this system significantly. Thus, there was general purpose of the carried out experiments – determination of interdependence between operating parameters of engine work and conditions of exhaust gas flow through the selected catalysts tested. Flow resistance generated by converter is considered as a local resistance. Resistance number of the catalyst was calculated using Darcy model. Inquiries into relationship between flow and structural parameters of the converters were also made. Comparison of flow resistances for the tested converters is presented.

Keywords: diesel engine, catalytic converter, conversion rate, flow resistance, porosity

1. Introduction

Emission abatement is essential problem of present automotive engineering on account of considerable environmental pollution contribution of transport, especially road transport. Nowadays, 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 the reduction 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 are the most perfect and in common use devices in exhaust systems of passenger cars. They are also increasingly fitted on heavy duty vehicles, motorcycles and off-road engines and vehicles. Catalysts, firs of all, lower significantly toxic gaseous emission: CO, HC, NO_x (three way converters) or only incomplete combustion products: CO, HC (oxidation converters). They reduce also particulate mass in diesel engine exhaust gas by up to 50%, by destroying the organic fraction of the particulate [1, 3].

Total emission of the harmful constituents depends, among other things, on a flux of consumed fuel. Nowadays the cause of fuel consumption reduction by internal combustion engines used to driving cars is taken especially seriously. This problem is directly connected with vehicle operating costs as well as with toxic substances emission. It is also necessary to decrease greenhouse gases emission, first of all carbon dioxide CO_2.

It is widely indicated that big potentiality for considerable fuel consumption reduction is inherent in better organization of charge exchange process. Generally, the charge exchange process is composed of:

- fresh charge (air or combustion mixture) cylinder filling,
- exhaust gas outflow from cylinders to environment.

In order to decrease the charge exchange work, flow resistance of the fresh charge filling and exhaust gas outflow should be reduced. In exhaust system, flow resistance of the catalytic converter is of great importance.

Exhaust gas treatment is the principal aim of catalytic converter application. However, installation of catalyst in exhaust system of an engine is of essential consequence for its operation considering introduction of additional resistance and thereby change of exhaust gas flow conditions. Next, flow resistance of the converter depend on engine working point as well as structural parameters of the catalyst itself, in particular its porosity and void cross-sectional area.

2. Conversion efficiency of incomplete combustion products

In order to selection of the suitable oxidation catalytic converter for diesel engine SW400, experimental researches of number of catalysts were carried out. Specification of some of them is presented in the table 1. Within the framework of investigations, flow resistances and efficiency of oxidation of incomplete combustion products were especially taken into consideration.

Table 1. Specification of the oxidation catalytic converters tested

Property	Type of converter			
	Baildon	MINE-X DC6	SZOP 07	MINE-X DQ8A
Substrate material	metal	metal	metal	metal
Cell density, cells/cm^2	40	31	56	31
Wall thickness, mm	0,1	0,04	0,1	0,04
Substrate volume, dm^3	2,12	1,07	1,93	2,14
Void cross-section area, cm^2	153,2	111,7	160,4	223,5
Porosity	0,85	0,94	0,87	0,94

Conversion rate η_i of i-th harmful constituent within a catalyst can be defined using molar fractions or e.g. relative emission indices. The specific emissions were investigated in the whole operation range of the engine before and after the converter. Changes of the emission indices within the catalysts and conversion rates of the toxic substances (CO and HC) were determined. Application of an oxidation catalytic converter in diesel engine is aimed at reduction of the incomplete combustion products in the range of mean and high engine loads because 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 or activation temperature). During diesel engine operation at low loads, temperature of exhaust gas leaving cylinders is considerably lower than during nominal load. This causes decrease of the toxic constituent conversion efficiency within the catalyst. Efficiency of the converters is presented on the example of carbon monoxide conversion rate (Fig. 1).

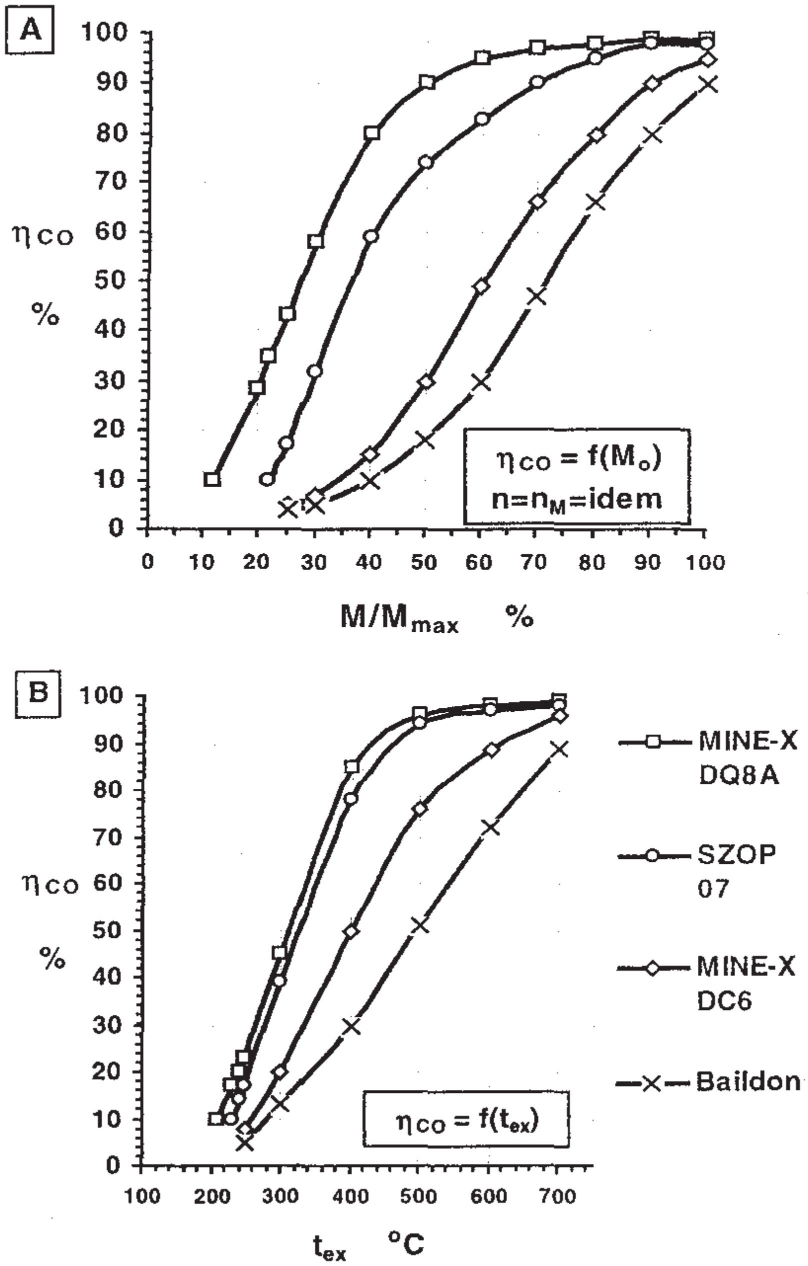

Fig. 1. CO conversion rate η_{CO} within the oxidation catalytic converters tested versus engine load (A) and exhaust gas temperature t_{ex} (B)

It was found that the catalytic converter MINE-X DQ8A reaches the highest efficiency in the whole operation range of the engine. Its maximum rate of CO conversion is 98%. The catalyst achieves satisfactory effectiveness ($\eta_{CO} > 60\%$) at relative engine load of 30% (Fig. 1A). For the load above 50%, efficiency of CO oxidation exceeds 90%. Likewise temperature threshold of this catalyst operation is the lowest and amounts about 320°C (Fig. 1B).

Characteristic of HC conversion rate for the catalyst MINE-X DQ8A has been presented in [5]. Conversion rate of hydrocarbons exceeds 70% at engine speed above 1800 rpm for operating characteristic of the engine.

3. Flow resistance of the catalytic converters tested

Resistance of exhaust gas flow through a catalytic converter is essential problem, apart from its chemical efficiency because fitting a catalyst in exhaust system alters flow characteristic of this system significantly. Too big flow resistance makes exhaust gas outflow difficult, thereby it increases work of charge exchange. Therefore selected quantities of exhaust gas flow through the catalysts were determined and analysed together with their termochemical efficiency.

The basic measured quantity of flow resistance is pressure drop Δp_{cat} of exhaust gas within the catalyst, which is presented in the figure 2 for the tested converters. It was confirmed that pressure drop grows when engine speed (and load) increases. Obviously, the values of the pressure drop and its gradient depend on type of the catalyst.

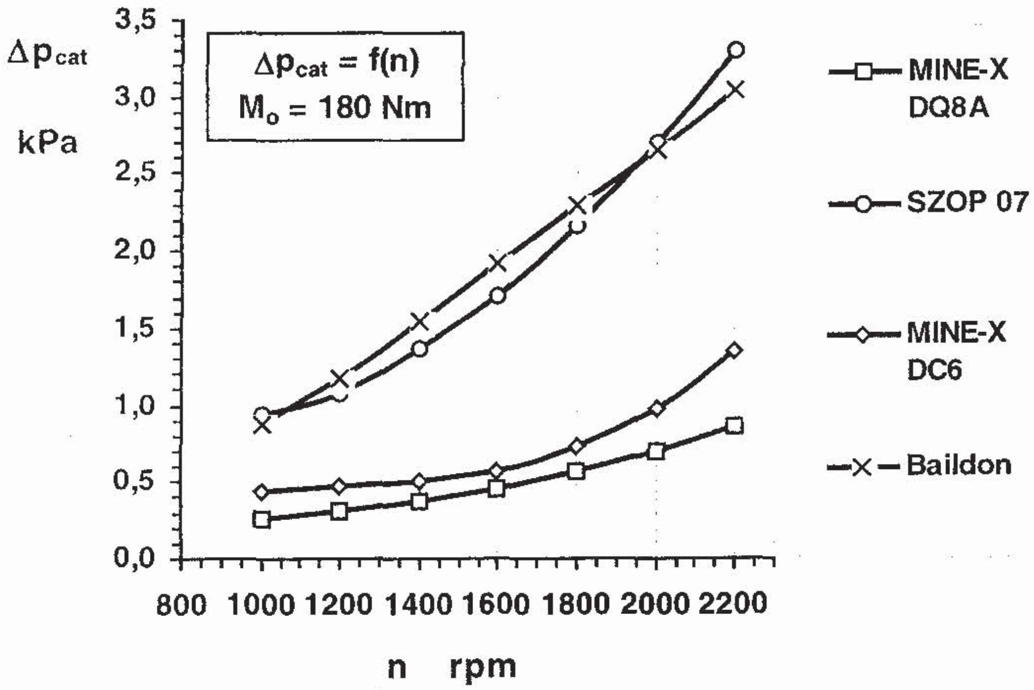

Fig. 2. Pressure drop Δp_{cat} of exhaust gas within the catalytic converters tested versus engine speed

On the basis of the taken measurements also resistance number ξ for the tested catalyst were calculated. For this purpose, mean values of the exhaust gas quantities within the converters and their structural parameters were used [4].

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

$$\dot{m}_{ex} = A_{ex}\, w_{ex}\, \rho_{ex} \tag{1}$$

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:

$$A_{ex} = \varepsilon\, A \tag{2}$$

where: A – total cross-sectional area of the catalyst [m^2],
ε – porosity

Introducing (2) to (1), it is obtained:

$$\dot{m}_{ex} = A \varepsilon\, w_{ex}\, \rho_{ex} \tag{3}$$

where

$$\varepsilon\, w_{ex} = w_{0,ex} \qquad (4)$$

$w_{0,ex}$ is average velocity of exhaust gas in the catalyst.
Using relationship (3) gas flux is expressed:

$$\dot{m}_{ex} = A\, w_{0,ex}\, \rho_{ex} \qquad (5)$$

The average velocity of exhaust gas in the catalyst is calculated, using (5), according to formula:

$$w_{0,ex} = \frac{\dot{n}_{ex}\, M_{ex}}{A}\, v_{ex} \qquad (6)$$

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

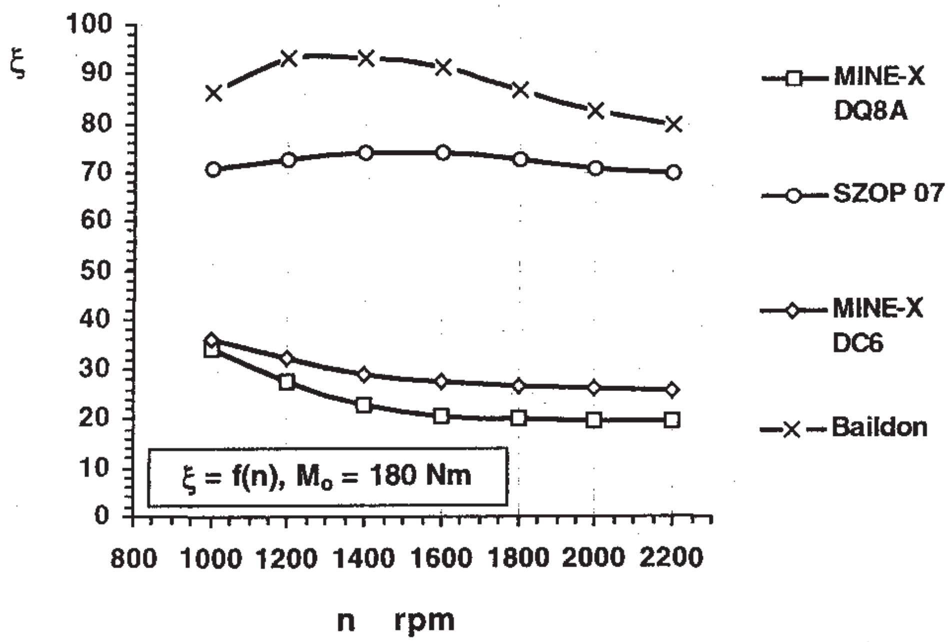

Fig. 3. Resistance number ξ of the catalytic converters tested depending on engine speed

Flow resistance generated by converter is considered as a local resistance [2]. Using Darcy model:

$$\Delta p = \xi \frac{w_{0,ex}^2}{2\, v_{ex}} \qquad (7)$$

resistance number ξ of the catalyst is calculated by formula:

$$\xi = \frac{2\, v_{ex}\, \Delta p_{cat}}{w_{0,ex}^2} \qquad (8)$$

Comparison of the resistance number ξ for the investigated converters is shown in the figure 3. Generally, resistance number depending on engine speed is decreasing function. Nevertheless, the opposite effect is noticed for two converters (Baildon and SZOP07) within the range of small speed. This situation is conditioned, in accordance with formula (8), by greater influence of pressure drop and specific volume of the exhaust gas increase on the resistance number than exhaust gas velocity rise.

Furthermore, the mean coefficient of kinematical viscosity ν of exhaust gas within the catalyst can be calculated by formula [2]:

$$\nu(T) = \nu_0 \left(\frac{T_{ex,a}}{T_0} \right)^{\frac{7}{4}} \tag{9}$$

where: $T_{ex,a}$ – average temperature of exhaust gas in the catalyst [K],
$\nu_0 = 13{,}3 \cdot 10^{-6}\ m^2/s$,
$T_0 = 273\ K$,

whereupon Reynolds number as:

$$(Re)_0 = \frac{w_{0,ex}\, d}{\nu} \tag{10}$$

where: d – inside diameter of a catalyst [m].

For the tested converters, Reynolds number $(Re)_0$ increases almost linearly depending on engine speed (Fig. 4.) and is contained within the range from 20000 till about 36000. Relationship of resistance number ξ of the catalyst and Reynolds number $(Re)_0$ of exhaust gas flow is determined in the figure 5.

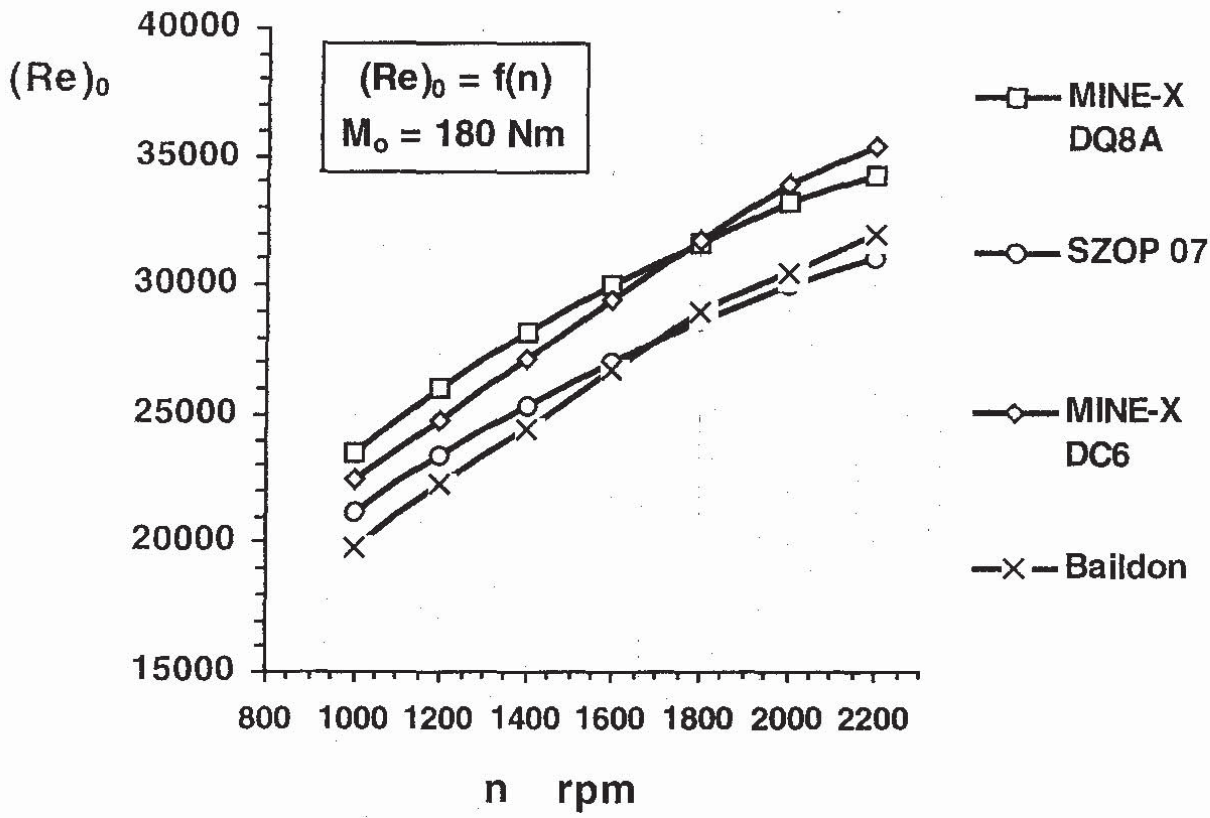

Fig. 4. Reynolds number $(Re)_0$ of exhaust gas flow versus engine speed

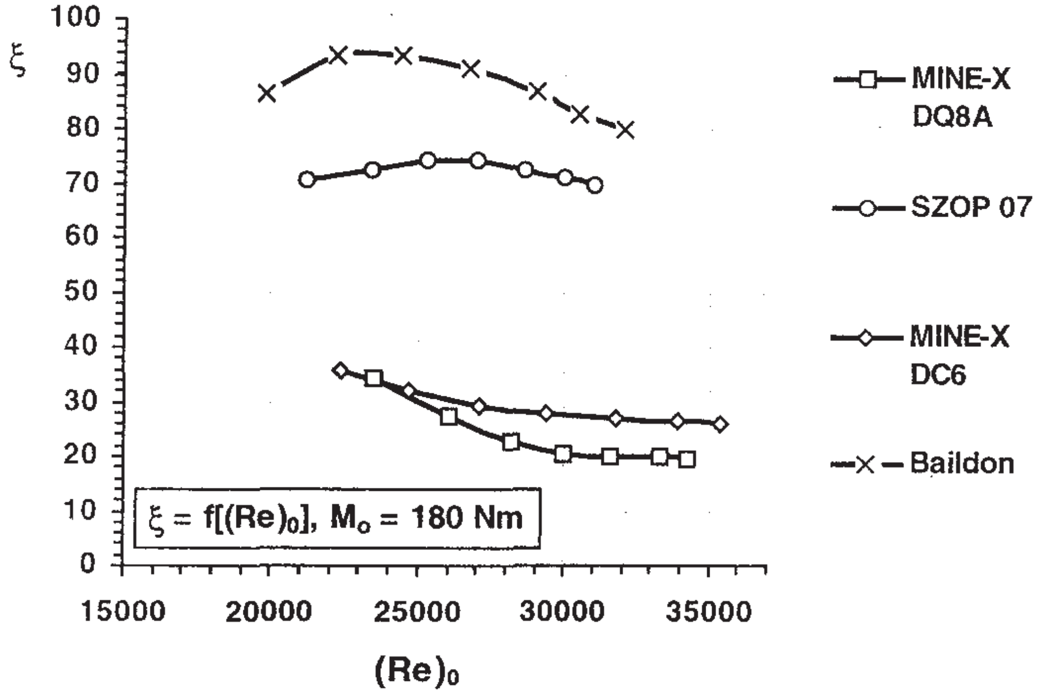

Fig. 5. Resistance number ξ of the catalytic converters tested depending on Reynolds number

Fortunately, it was found that also in consideration of the flow resistances, the catalytic converter MINE-X DQ8A is the most applicable from among the tested ones. The values of resistance number ξ (Fig. 3 and 5) as well as pressure drop Δp_{cat} (Fig. 2.) for this catalyst are the smallest.

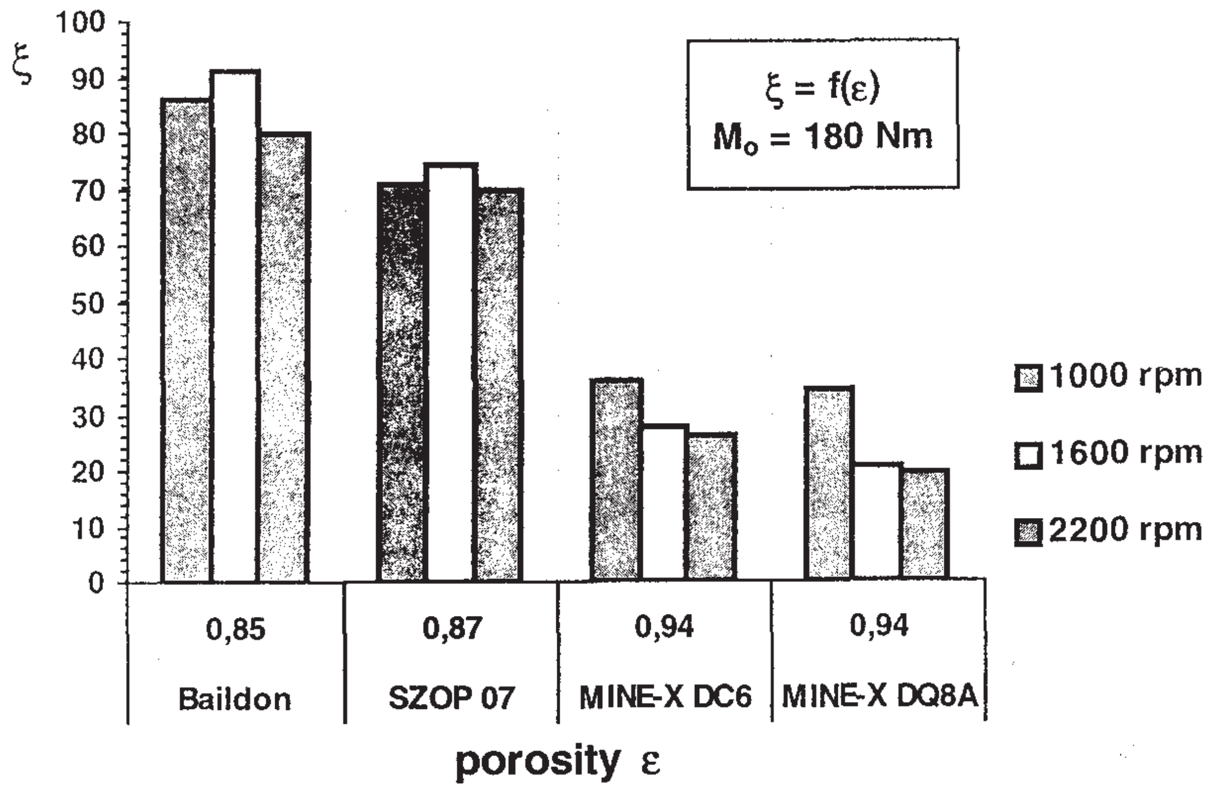

Fig. 6. Relationship between resistance number ξ and porosity ε for the converters

Flow resistances of the catalysts are also closely connected with their constructional parameters apart from operating parameters of engine and exhaust gas. On that score, porosity ε of the catalyst substrates has a significant weight. Relationship between resistance number ξ and porosity ε is noticeable, that is presented in the figure 6. The higher porosity converters attain the lower values of the resistance number. But at the same time, also the other structural parameters (e.g. void cross-sectional area) determine resistance number.

4. Conclusion

Experimental tests of heavy duty diesel engine (type SW400) equipped with several, selected oxidation catalytic converters were carried out within the range of flow resistances and conversion rate of the incomplete combustion products. It was found that the most suitable catalyst for mating with the investigated engine is the converter MINE-X DQ8A in consideration of the high efficiency and the smallest resistance number. Moreover, its activation temperature (temperature threshold) is the lowest. Use of the catalyst in the engine is aimed primarily at reduction of the harmful exhaust gas principles. However flow resistance of the converter is of great importance because it determines the charge exchange work and thereby fuel consumption and also pollutants emission. It was confirmed that operating parameters of engine influence flow resistance significantly that decreases engine effective work.

Acknowledgments

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