INVERSE ASPECTS OF THE THREE-WAY CATALYTIC CONVERTER OPERATION IN THE SPARK IGNITION ENGINE

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Abstract

There are two sides of the catalyst operation: favourable and adverse. The positive side can be expressed by a conversion rate of harmful substances which is the principal parameter of catalyst work in respect of ecology. However, resistance of exhaust gas flow through the catalytic converter is also an essential problem. This is just the negative, adverse side of the converter operation. The catalytic converter can be treated as a local or linear resistance element of exhaust system. The first model, in which flow resistance generated by a catalyst is treated as local resistance, is more simplified. It is especially useful in case, when detailed constructional data of converter are unknown and the analysis of flow resistances in exhaust system is necessary. The basic measured quantity of flow resistance is pressure drop of exhaust gas within the catalyst. Next, on the basis of taken measurements also resistance number for the tested catalyst is calculated and analysed. Resistance number of the converter is calculated using Darcy model. In the second case, exhaust gas flow resistance through catalyst is treated as linear resistance with energy dissipation (linear frictional resistance) distributed linearly along way of exhaust gas flow. Friction number for the tested converter is calculated and analysed. The problem has been illustrated by the results of experimental researches of the three-way catalytic converter installed in the exhaust system of the spark ignition engine.

Keywords*: catalytic converter, conversion rate, flow resistance, local resistance number, friction number*

1. Introduction

There are two aspects of the catalytic converter operation [2, 10]:
- negative, energy aspect – increase of flow resistance in exhaust system,
- favourable, ecological aspect – reduction of toxic substances emission.

The 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 significantly flow characteristic of this system. Too big flow resistance makes exhaust gas outflow difficult, thereby it increases charge exchange work and reduces internal as well as effective work of an engine. Finally, effective efficiency also decreases as a consequence of flow resistance in the exhaust system [1].

Emission abatement is an essential problem of present automotive engineering on account of the 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 of carbon monoxide, hydrocarbons, nitrogen oxides 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 by up to 50%, by destroying the organic fraction of the particulate [4, 6, 10].

2. Energy aspect of catalytic converter operation

Experimental research of three-way catalytic converter, installed in the exhaust system of spark ignition engine (type: 1170A1.046) was carried out. The experiment design comprised the whole operation range of the engine (Fig. 1). The catalyst is composed of two ceramic monoliths. Selected technical specification of the tested catalyst is presented in the Tab. 1.

Tab. 1. Specification of the catalytic converter tested

substrate material	ceramic (cordierite)	total volume of substrates	851.24 cm^3
catalytic substances	platinum, palladium, rhodium	overall length of substrates	153 mm
cell density	400 $cells/in^2$	substrate equivalent diameter	83.75 mm
wall thickness	0.15 mm	cell equivalent diameter	1.12 mm
substrate cross-section	55.64 cm^2	porosity	0.78

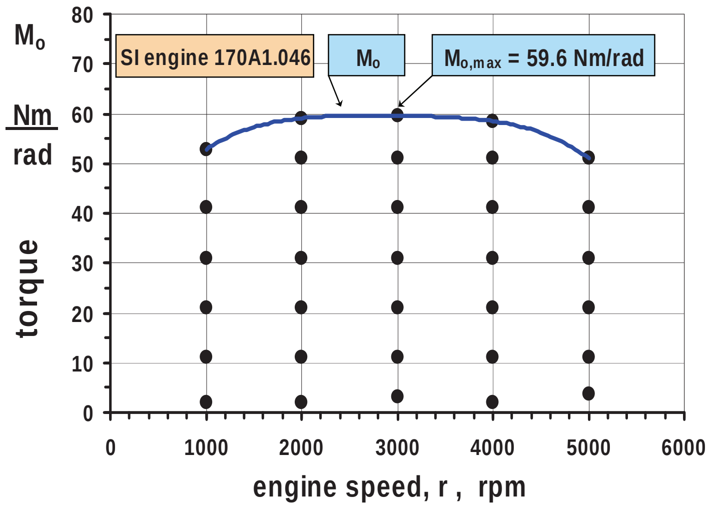

Fig. 1. Experiment design against the background of the operation range of the tested engine

Modelling the problem of the exhaust gas flow resistance, the catalytic converter can be treated as local or linear resistance element of exhaust system. In both models, the basic measured quantity characterizing flow resistance is pressure drop Δp_{cat} of exhaust gas within the catalyst, which is presented in the Fig. 2 for the tested converter. It was confirmed that pressure drop grows when engine speed (and load) increases.

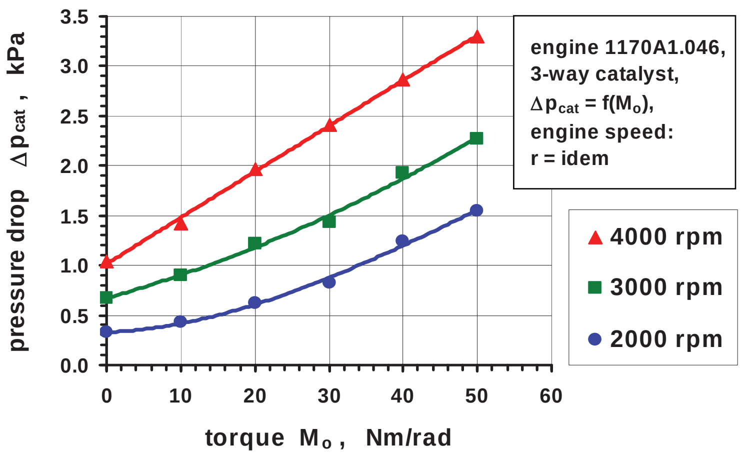

Fig. 2. Pressure drop Δp_{cat} of exhaust gas within the tested catalytic converter

2.1. Catalytic converter as a local resistance element of exhaust system

The model, in which flow resistance generated by a catalyst is treated as local resistance, is more simplified. It is especially useful in case, when detailed constructional data of converter are unknown and the analysis of flow resistance in the exhaust system is necessary.

On the basis of taken measurements resistance number ξ for the tested catalyst was calculated. For this purpose, mean values of the exhaust gas quantities within the converter and its structural parameters (Tab. 1) were used. Mass flux $\dot{m}_{ex}$ of exhaust gas can be written as follows:

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

where:

A_{ex} - void cross-section of the 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-section of the catalyst (m^2),
ε - porosity [8].

Introducing eq. (2) to the eq. (1), it is obtained:

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

where:

$$\varepsilon\, w_{ex} = w_{0,ex} \tag{4}$$

and $w_{0,ex}$ is average, face velocity of exhaust gas in the catalyst. Using the relationship (4), gas flux is expressed:

$$\dot{m}_{ex} = A\, w_{0,ex}\, \rho_{ex}\,. \tag{5}$$

The average, face velocity (Fig. 3) of exhaust gas in the catalyst is calculated, according to the formula:

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

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).

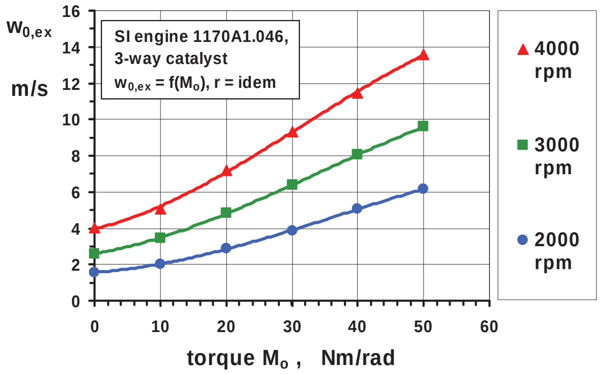

Fig. 3. Average, face velocity of the exhaust gas in the tested catalytic converter

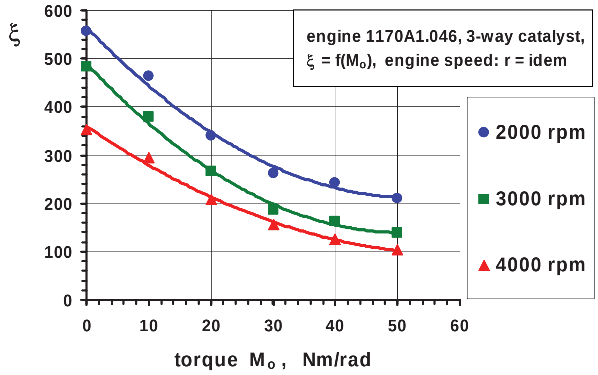

Fig. 4. Local resistance number ξ of the tested catalytic converter

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

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

resistance number ξ of the catalyst is calculated by the formula [9]:

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

and presented in the whole operation range of the engine, in the Fig. 4. Generally, resistance number ξ depending on engine torque and engine speed is a decreasing function.

Furthermore, the mean coefficient of kinematical viscosity ν of exhaust gas within the catalyst can be calculated by the formula [9]:

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

where:
$T_{ex,a}$ - average temperature of exhaust gas in the catalytic converter (K),
$\nu_0 = 13.3 \, . \, 10^{-6}$ m^2/s, $T_0 = 273$ K,
then face Reynolds number as (Fig. 5):

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

where d – inside diameter of the catalyst (m).

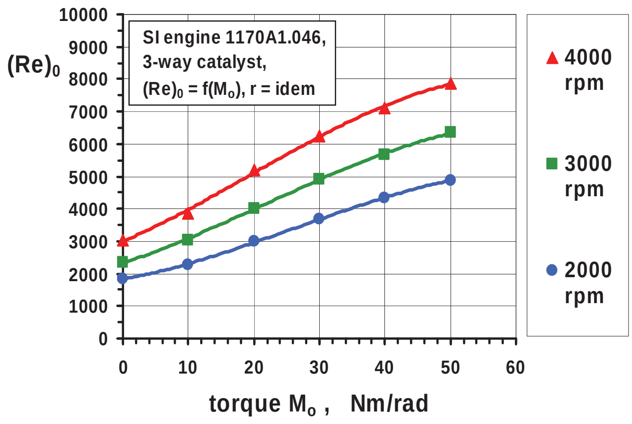

Fig. 5. Face Reynolds number of the exhaust gas flow into the tested catalytic converter

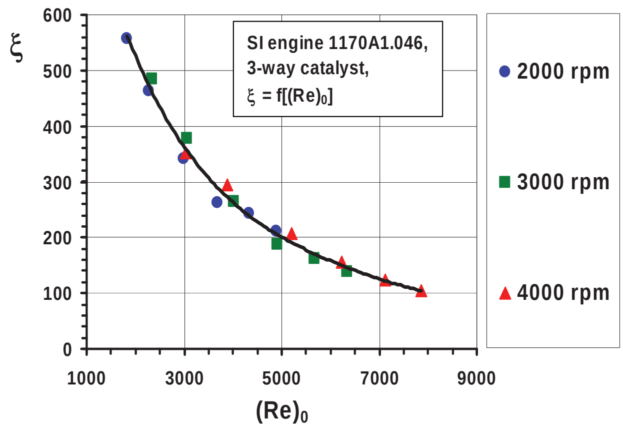

Fig. 6. Resistance number ξ of the catalytic converter versus Reynolds number of exhaust gas flow

Eventually, generalising problem and research results, resistance number of the catalytic converter can be expressed as a function of the face Reynolds number $\xi = f[(\mathrm{Re})_0]$ (Fig. 6). This is a generalisation for the whole operation range of spark ignition engines.

2.2. Catalytic converter as a linear resistance element of exhaust system

In this model, exhaust gas flow resistance through catalytic converter is treated as linear resistance with energy dissipation (linear frictional resistance) distributed linearly along way of exhaust gas flow. Friction number λ_k for the tested converter was determined and analysed.

Substrate of the catalytic converter is treated as a bank of parallel, straight channels with length

L and equivalent inside diameter d_k each (Fig. 7). An assumption was made that pressure drop is the same within each channels (Fig. 2).

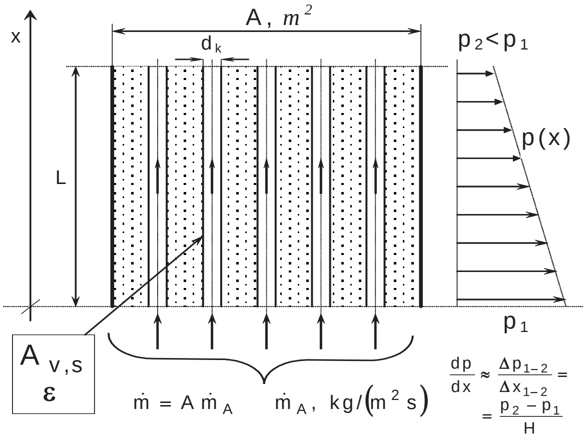

Fig. 7. Model and basic parameters of the tested flow system (catalytic converter)

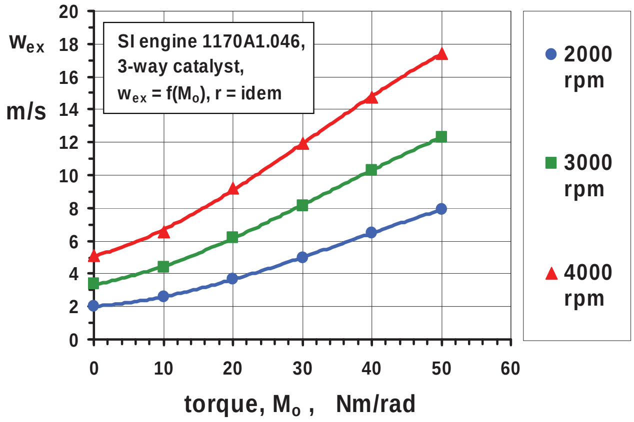

Fig. 8. Velocity of exhaust gas flow inside of the converter channels

Exhaust gas flow in every channel can be described applying a capillary approach [5, 9]. In this case, linear pressure change is expressed by the formula:

$$\frac{dp}{dx} = -\lambda_k \frac{w_{ex}^2}{2\,d_k}\rho_{ex}, \qquad 0 \le x \le L\ , \tag{11}$$

where:
λ_k - friction number (of linear resistance) in the converter channel,
w_{ex} - velocity of exhaust gas flow inside of the channels (m/s) (by the eq. 5), (Fig. 8).

After integration of the equation (11), it is obtained (averaging on channel L):

$$\Delta p_{1-2} = \left(\lambda_k \frac{L}{d_k}\right)\frac{w_{ex}^2}{2}\rho_{ex}. \tag{12}$$

The expression (λ_k L/d_k) is a dimensionless criterion of linear flow resistance in the converter channel. On the basis of the results of experimental investigation, the value of the criterion of linear flow resistance (λ_k L/d_k) can be determined first, then the value of the friction number λ_k (knowing geometric dimensions: L, d_k). Calculation results of the friction number λ_k for the whole operation range of engine are presented in the Fig. 9.

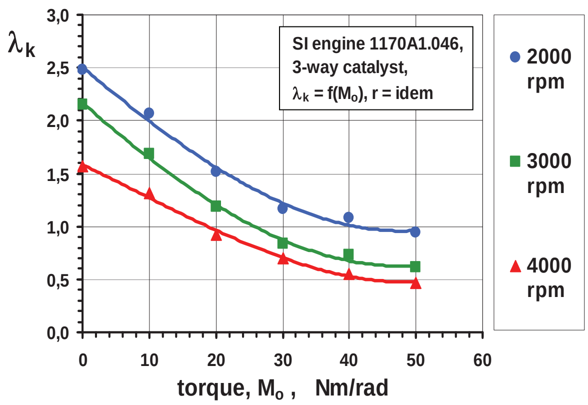

Fig. 9. Friction number λk for channels of the tested catalytic converter

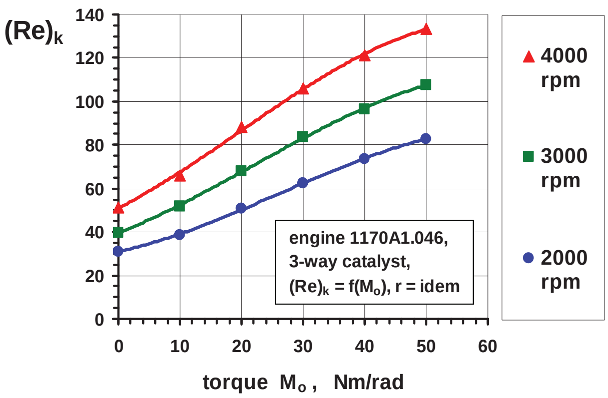

Fig. 10. Reynolds number (Re)k of exhaust gas flow through single channel of the catalyst

Friction number λ_k depends on the quality of channel surface and on flow conditions characterized by Reynolds number, in this case, expressed as:

$$(\mathrm{Re})_k = \frac{w_{ex}\, d_k}{\upsilon}. \tag{13}$$

Reynolds number $(\mathrm{Re})_k$ of exhaust gas flow through a single channel is presented in the Fig. 10. Exhaust gas flow in the converter channels is in the range of the laminar flow.
Generalising problem and research results, in this model, friction number λ_k of the catalytic converter channels can also be expressed as a function of the Reynolds number: $\lambda_k = f[(\mathrm{Re})_k]$ (Fig. 11). This is a generalisation for the whole operation range of spark ignition engines.

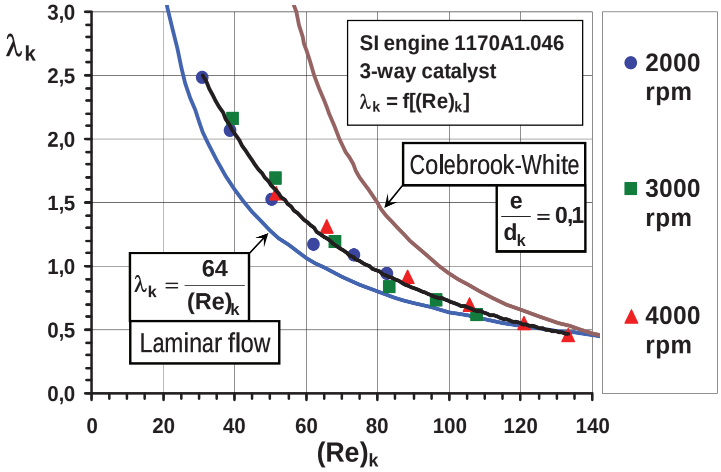

Fig. 11. Friction number λ_k versus Reynolds number $(Re)_k$ for the catalyst channels

Significant values of friction number λ_k (Fig. 9 and 11), higher than typical values, result from big relative surface roughness (e/d_k) of the converter channel walls.
The curve characterising laminar flow [9]:

$$\lambda_k = \frac{64}{(\mathrm{Re})_k}, \tag{14}$$

and the curve for Colebrook-White formula:

$$\frac{1}{\sqrt{\lambda_k}} = 2\lg\left[\frac{(\mathrm{Re})_k\sqrt{\lambda_k}}{2{,}51} - \frac{3{,}71}{\left(\dfrac{e}{d_k}\right)}\right]. \tag{15}$$

It have been drawn additionally in the Fig. 11, for comparison with experimental results. Characteristic $\lambda_k = f[(\mathrm{Re})_k]$ for the catalytic converter runs above the curve for laminar flow, which confirms that relative surface roughness (e/d_k) of the converter channel walls is much higher than relative roughness of typical pipes.

3. Ecological aspect of catalytic converter operation

For evaluation of the engine with regard to the content of toxic substances in exhaust gas, molar fractions and relative indices e_i of pollutants emission were used [11]. The specific emissions were investigated in the whole operation range of the engine before and after the catalyst. Changes of the emission indices within the converter and conversion rates of the toxic substances were determined. The ecological aspect of catalytic converter operation is expressed by the conversion rates of harmful substances. Selected load characteristics of the basic pollutants conversion rates for the tested catalyst are presented in the Fig. 12 and 13. Effectiveness of the converter operation within the range of oxidation of the incomplete combustion products (CO and HC) exceeds 80% almost in the whole work area of the engine (Fig. 12).

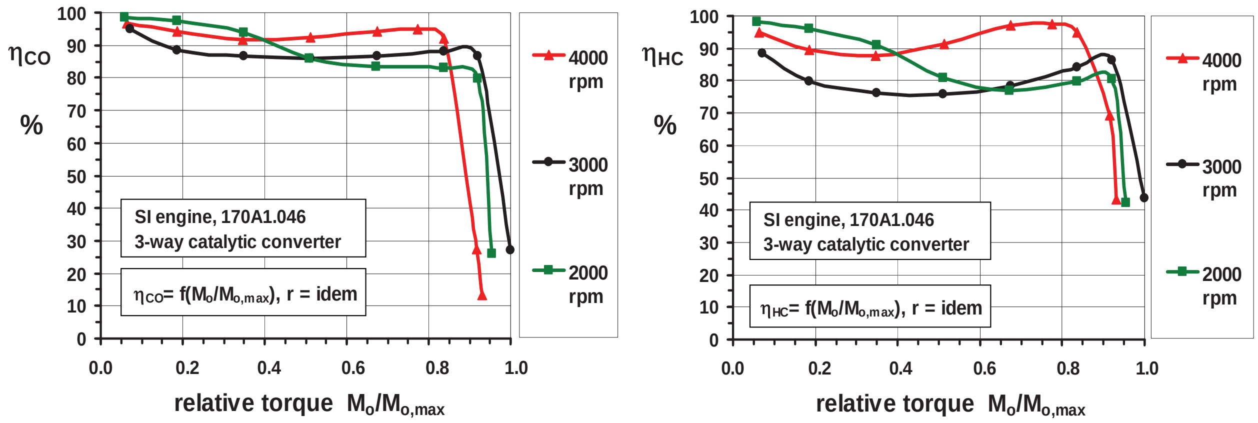

Fig. 12. Conversion efficiency of incomplete combustion products (η_{CO} – carbon monoxide; η_{CO} – hydrocarbons) within the tested catalytic converter

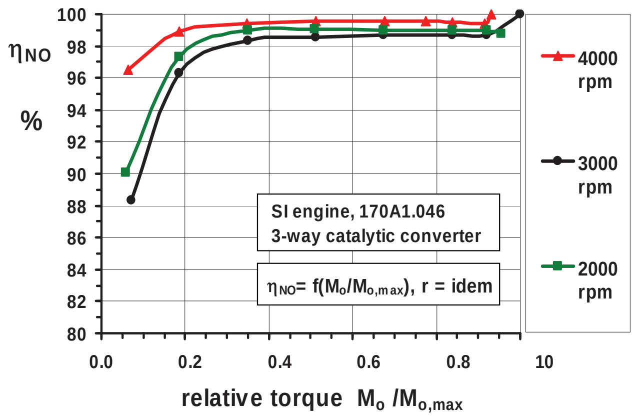

Fig. 13. Conversion efficiency η_{NO} of nitrogen oxide within the tested catalytic converter

Reduction rate of nitrogen oxide (NO) is still even higher – above 98% for relative torque from 0.2 up (Fig. 13). So high efficiency of the converter operation results from complying with two fundamental conditions of proper operation of a three-way catalytic converter. The first condition – keeping air excess ratio within the following range: $\lambda = 1 \pm 0>02$ almost in the whole work area of the engine with the exception of the maximal load (Fig. 14). The second condition concerns the temperature of the converter. The temperature of exhaust gas flowing into the catalyst is higher, even at idle, than the activation temperature of the converter (Fig. 14).

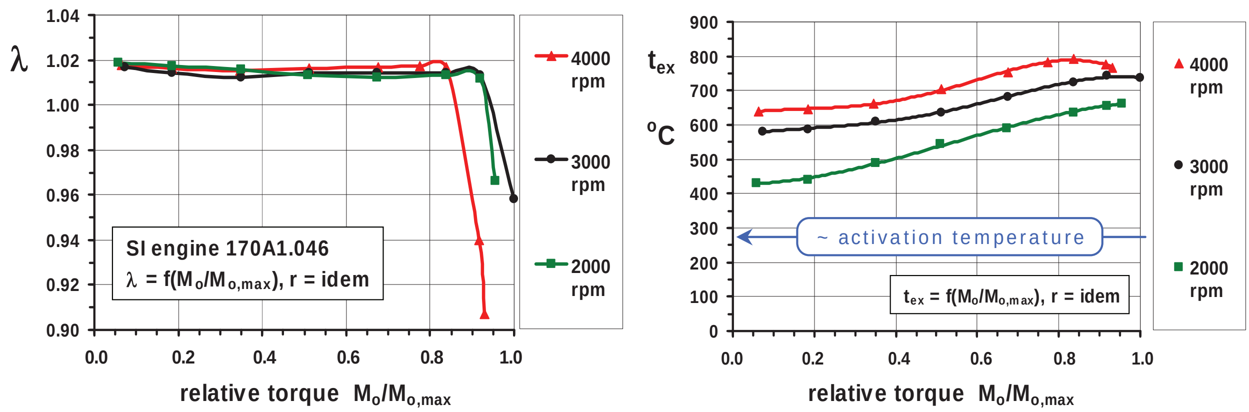

Fig. 14. Air excess number λ and exhaust gas temperature t_{ex} just before the tested catalyst

Significant decrease of the conversion rate of the incomplete combustion products (CO and HC) at maximum load is an unfavourable but typical phenomenon for spark ignition engines. This situation results from combustion mixture enrichment (air excess number $\lambda \approx 0.90 - 0.95$) in the range of the highest torque (Fig. 14).

4. Conclusion

Two aspects of catalytic converters application are very significant for charge the exchange system and engine operation. The energy aspect – negative – manifests itself by the increase of exhaust gas flow resistance, which results in the rise of charge exchange work. The catalytic converter can be treated as a local or linear resistance element of exhaust system.

The first model, in which flow resistance generated by a catalyst is treated as local resistance, is more simplified. It is especially useful in case, when detailed constructional data of converter are unknown. Resistance number of the converter can be calculated using Darcy model. Local resistance number ξ for the tested catalytic converter fluctuates in the range from 100 up to 600 depending on engine speed and load.

In the second case, exhaust gas flow resistance through the catalyst is treated as linear resistance with energy dissipation (linear frictional resistance) distributed linearly along way of exhaust gas flow. Friction number for channels of the converter can be determined applying capillary approach. Linear friction number λ_k changes in the range from 0.5 up to 2.5 and depends on the work point of the engine. Relatively high values of the friction numbers result from big surface roughness of channel walls of the tested catalytic converter.

The ecological aspect – favourable – is expressed by toxic substances emission reduction. The conversion rate of harmful substances is the principal parameter of the catalyst work in respect of ecology.

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