CATALYTIC REACTOR AS A RESISTANCE ELEMENT OF ICE EXHAUST SYSTEM

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Abstract

Selected problems connected with operation of catalytic reactors are presented. 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.

Catalytic converter can be treated as 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. Resistance number of the converter was 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 was calculated and analysed. The problem has been illustrated by results of experimental researches of three-way catalytic converter installed in exhaust system of spark ignition engine and its basic analysis.

Keywords: *internal combustion engine, catalytic converter, pressure drop, local and linear flow resistance, resistance number*

1. Introduction

Charge exchange work in internal combustion engine depends on resistance of air flow in an induction system and resistance of combustion gas in an exhaust system.

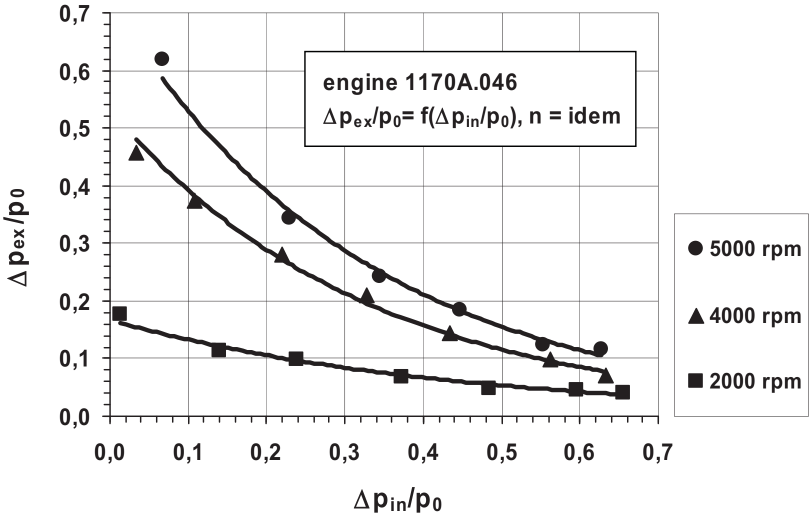

Fig. 1. Relation between pressure drop Δp_{in} of air in the induction system and pressure drop Δp_{ex} of combustion gas in the exhaust system (p_0 – ambient pressure)

Pressure drop in the systems is a measure of the flow resistance. There is accurate relation between pressure drop of air in the induction system and pressure drop of combustion gas in the exhaust system, what is illustrated in the figure 1. It was found that resistance of combustion gas in the exhaust system increases when resistance of air flow in the induction system decreases.

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

Resistance of exhaust gas flow through the catalytic converter is essential problem, because fitting the 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 [1, 3]. Therefore selected quantities of exhaust gas flow through the catalysts were determined and analysed together with their termochemical efficiency [4, 5, 7].

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

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 converter. It was confirmed that pressure drop grows when engine speed (and load) increases.

On the basis of the taken measurements resistance number ξ for the tested catalyst was calculated. For this purpose, mean values of the exhaust gas quantities within the converters and their structural parameters were used [6].

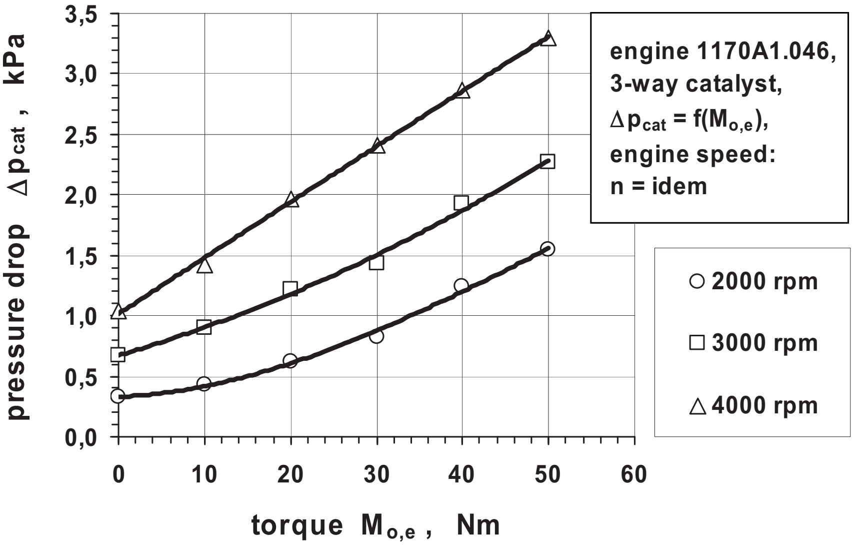

Fig. 2. Pressure drop Δp_{cat} of exhaust gas within the catalytic converter tested

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:

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

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

Using relationship (3) gas flux is expressed:

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

The average velocity of exhaust gas in the catalyst is calculated, according to 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).

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

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

resistance number ξ of the catalyst is calculated by formula:

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

and presented in the whole operation range of the engine, in the figure 3. Generally, resistance number ξ depending on engine torque and engine speed is decreasing function.

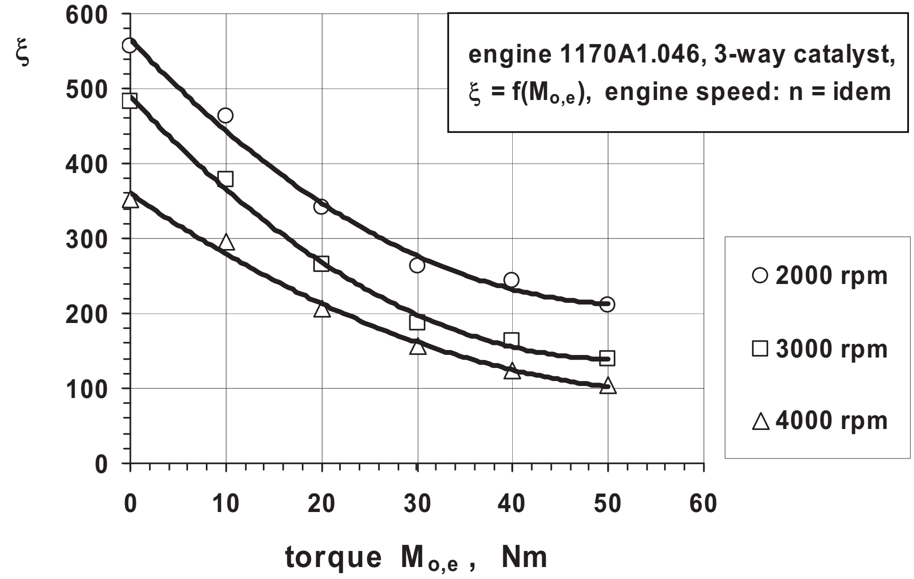

Fig. 3. Resistance number ξ of the catalyst tested

Furthermore, the mean coefficient of kinematical viscosity ν of exhaust gas within the catalyst can be calculated by formula [1]:

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

where:

$T_{ex,a}$ – average temperature of exhaust gas in the catalyst (K),

$\nu_0 = 13{,}3 \,.\, 10^{-6}$ m^2/s, $T_0 = 273$ K,
whereupon Reynolds number as:

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

where:

d – inside diameter of a catalyst (m).

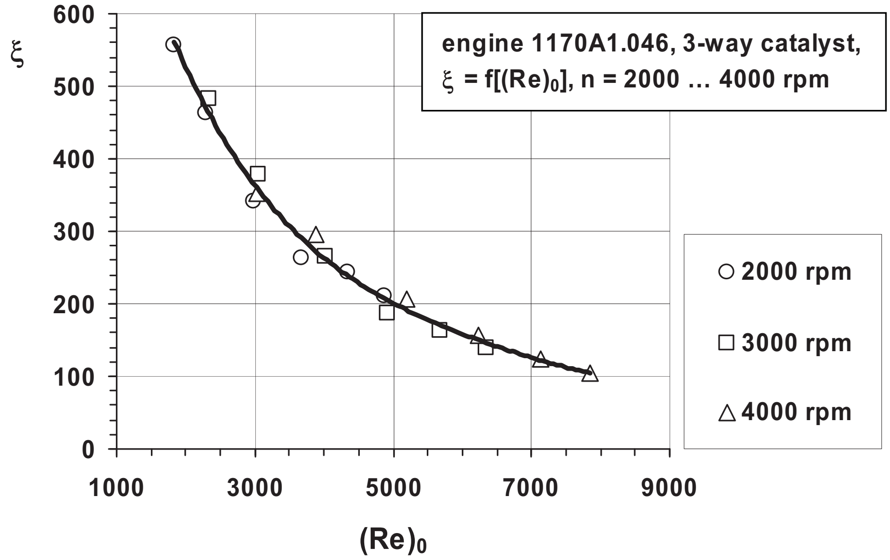

Fig. 4. Resistance number ξ of the catalyst versus Reynolds number of exhaust gas flow

Eventually, relationship of resistance number of the catalyst and Reynolds number $\xi = f[(\mathrm{Re})_0]$ can be determined (fig. 4). Resistance number ξ decreases when Reynolds number grows but, at this approach, it does not depend on engine speed.

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

In this 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 was calculated 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. An assumption was made that pressure drop is the same within each channels (fig. 2).

Exhaust gas flow in every channel can be described applying capillary approach. In this case, linear pressure change is expressed by 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 converter channel,

w_{ex} – velocity of gas flow inside of the channel (m/s) (by formula 4).

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

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

Expression (λ_k L/d_k) is dimensionless criterion of linear flow resistance in converter channel. Friction number λ_k depends on quality of channel surface and on flow conditions characterized by Reynolds number, in this case, expressed as:

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

Reynolds number $(\mathrm{Re})_k$ of exhaust gas flow through single channel is presented in the figure 5. Exhaust gas flow in the converter channels is in the range of laminar flow.

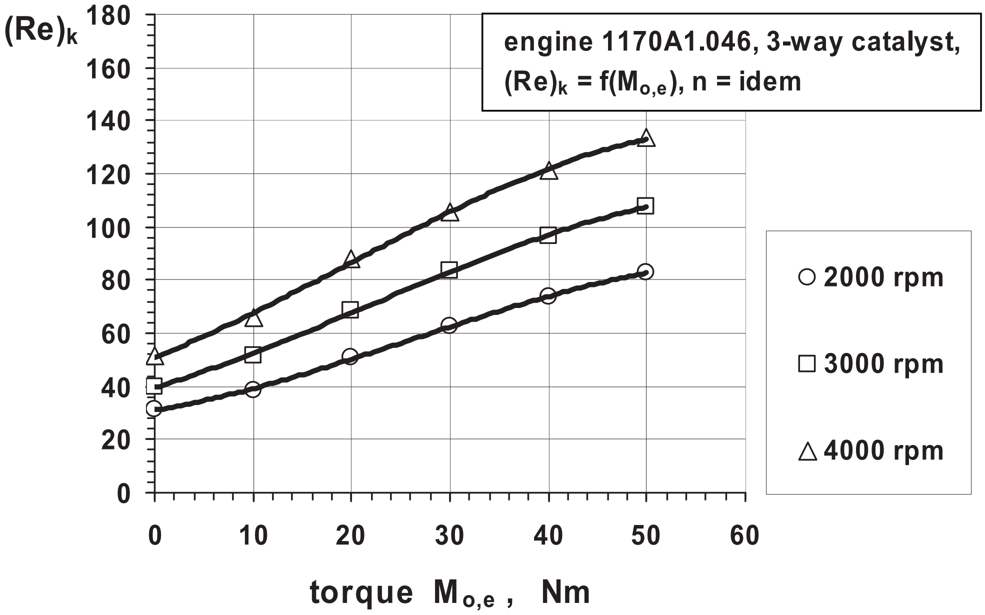

Fig. 5. Reynolds number $(\mathrm{Re})_k$ of exhaust gas flow through single channel

On the basis of results of experimental investigation, the value of criterion of linear flow resistance (λ_k L/d_k) can be determined first, whereupon the value of friction number λ_k (knowing geometric dimensions: L, d_k). Calculation results of criterion of linear flow resistance for the whole operation range of engine are presented in the figure 6.

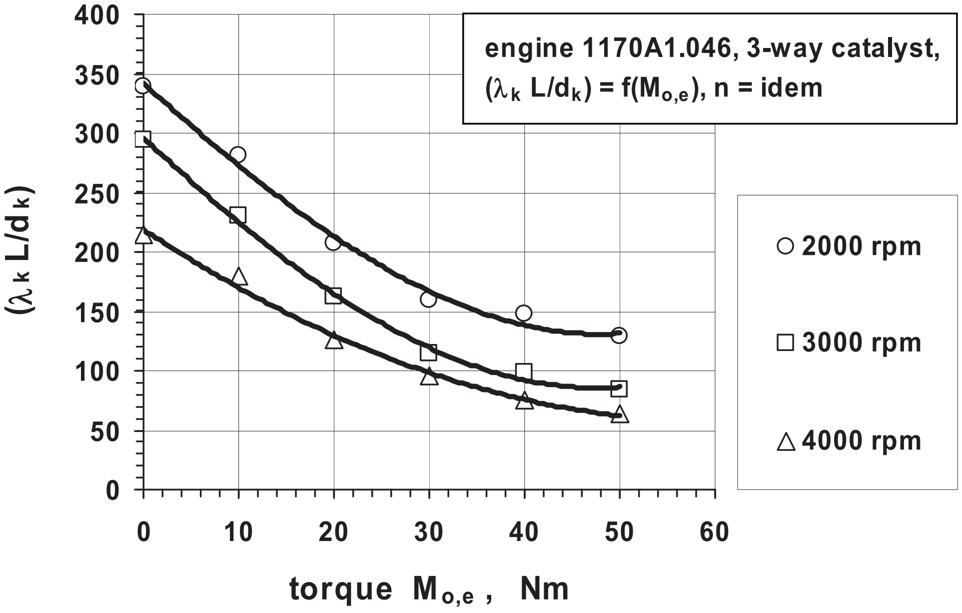

Fig. 6. Criterion of linear resistance of exhaust gas flow (λ_k L/d_k)

The value of Reynolds number $(\mathrm{Re})_k$ experts principal influence on the value of friction number λ_k, that is illustrated in the figure 7.

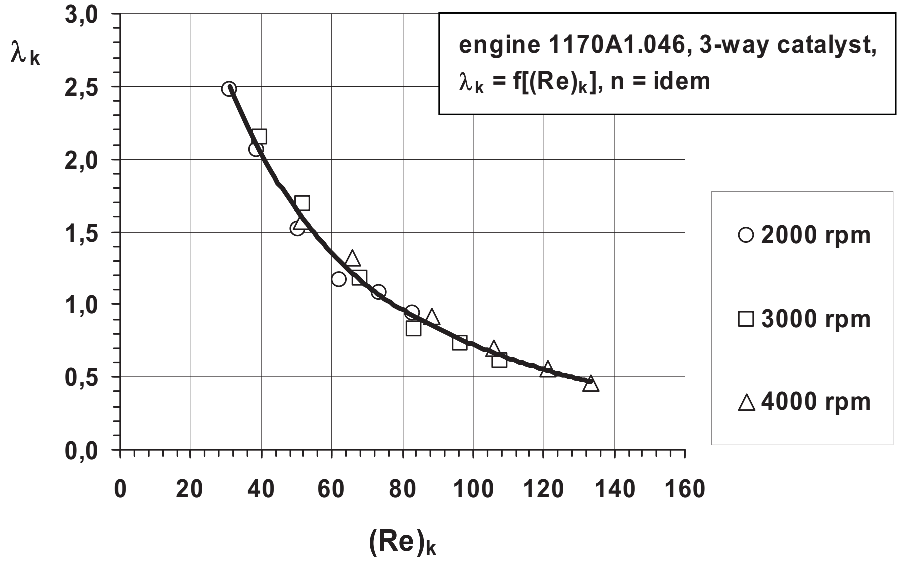

Fig. 7. Friction number λ_k versus Reynolds's number $(Re)_k$ for the catalyst channels

Considerable values of friction number λ_k result from big relative surface roughness (e/d_k) of the converter channel walls. Relative surface roughness (e/d_k) can be calculated, using determined friction number λ_k and Reynolds number $(Re)_k$, e.g. according to Colebrook–White's formula [2]:

$$\frac{1}{\sqrt{\lambda_k}} = 2\lg\left[\frac{(\mathrm{Re})_k\sqrt{\lambda_k}}{2{,}51} + \frac{3{,}71}{\left(\dfrac{e}{d_k}\right)}\right]. \tag{14}$$

For tested catalytic converter, the value of relative surface roughness of the converter channel walls was obtained $(e/d_k) = (0{,}09 - 0{,}20)$.

Bibliography

[1] Maus, W., *Jumping the SULEV Hurdle with "Cascades"*, Auto Technology 2, 2001.

[2] Postrzednik, S., *Termodynamika zjawisk przepływowych*, Wydawnictwo Politechniki Śląskiej, Gliwice, 1991.

[3] Postrzednik, S., Żmudka, Z., *Improvement if IC Engine Work by Modification its Thermodynamic Cycle*, Proceedings of ECOS'2002, 15th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Berlin, 2002.

[4] Żmudka, Z., Postrzednik, S., *Characteristics and Diminishing of Gaseous Emission from Diesel Engine*, International Journal of Applied Thermodynamics, International Centre for Applied Thermodynamics, Vol. 3 (No. 1), pp. 43-48, March, 2000.

[5] Żmudka, Z., Postrzednik, S., Ciesiołkiewicz, A., *Evaluation of work parameters of oxidation catalysts in diesel engine exhaust system*, Journal of KONES – Internal Combustion Engines, Vol. 10, No. 3 – 4, 2003.

[6] Postrzednik, S., Żmudka, Z., *Solid Material Porosity and the Method of its Determination*, (paper 4-10-1018), Proceedings of the 29th International Symposium on Combustion, Hokkaido University, Sapporo, 2002.

[7] Żmudka, Z., Postrzednik, S., Ciesiołkiewicz, A., *Operation Aspects of Automotive Catalytic Converter Application*. Proceedings of ECOS'2004, 17th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Guanajuato, Mexico, 2004.