MODELING AND RESEARCH ANALYSIS OF CATALYTIC CONVERTER IN A SMALL SI TWO-STROKE ENGINE

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Abstract.
In modern two-stroke SI engine applying one or two segments of catalytic converter in exhaust system is needed to fulfill requirements of emission of toxic components in burnt gases. In the paper catalytic conversion of toxic components in exhaust gas as dependence of mixture preparation is presented obtained from experiment and simulation. Paper gives mathematical model of gas flow in a exhaust system with taking into account resistant of gas flow through catalytic converter. On the base of mathematical model calculations of physical parameter of gas was done with overall engine output parameters. This enables optimisation of whole exhaust system at conservation of high temperature in the monolith. In the paper result of simulation were given in comparison to original engine. Also experimental results made on stand with 250 cc two-stroke two-cylinder engine with the same geometrical parameters of exhaust system as in calculations are included and compared with computational results. The paper includes several figures obtained from experiments and computer program based on zero- and one-dimensional model as well from experimental work.

Introduction
Catalysis has provided one of the most realistic methods of decreasing the levels of exhaust gas species. However its efficiency of oxidation depends on amount of CO, HC and air and also temperature of exhaust gas. Catalytic converters especially with the fuel enriched exhaust gas of small capacity carburetted two-stroke engine undergo rapid damage of perforation and clog by unburned oil. They can cause also threat of misfire. With its subsequent fuel enriching of exhaust gas causes a thermal shock to the substrate. In general the efficiency of the catalyst is dependent upon two parameters, namely the physical formulation and the nature of the flowing gas containing different chemical species. Recently widely applied fuel injection reduces to a large extend this phenomena. Engine performance changes as a result of negative effect of gas wave motion in exhaust system with monolith of converter, which should be fixed in exhaust pipe, where higher temperature takes place to initiate chemical reactions especially during engine start. Value of decreasing of engine torque and increasing of fuel consumption are the main parameters determining possibility of applying of catalytic converter in exhaust system. Most often catalytic converters in exhaust systems of two-stroke engines are placed before silencer. In presented system catalytic converter was mounted after silence box because of big dimensions of converter applied in the car Tico from Daewoo. Big size of the converter and lower temperature of gas flowing out from silencer takes effect on longer time of heating and oxidation of exhaust compounds. Applying of Tico converter significantly took effect on reducing exhaust emission
in an industrial two-cylinder two-stroke engine of capacity 250 cm³. Exhaust system with catalytic converter is shown in Fig.1.

Fig. 1. Exhaust silencer and catalytic converter

Placing catalytic converter near exhaust port assures higher temperature of wash-coat in catalyst containing precious metal as a result of short distance from exhaust port, but can also influence stronger on pressure variation before exhaust port. The problem which is always necessary to solve is performed in the task: how to obtain higher power and lower fuel consumption at simultaneous big efficiency of oxidation of toxic components in exhaust gas resulting from higher gas temperature.

**Therodynamic reactions in converter**

Thermodynamic reactions in one-dimensional system can be presented in a form of equations of mass balance of certain exhaust components and energy balance in gaseous phase and solid phase (on surface of catalyst walls). There is taken into account four exhaust components:

1. CO, 2. C₃H₆, 3. H₂, 4. O₂

1. **Mass balance of component \( i \) during chemical reaction in the catalyst in gaseous phase:**

\[
\varepsilon \rho_g \frac{\partial C_{g,i}}{\partial t} + \rho_g u \frac{\partial C_{g,i}}{\partial x} = \rho_g k_{m,i} S (C_{g,i} - C_{w,i})
\]

where: \( i = 1, 2, 3, 4 \)

2. **Energy balance in gaseous phase:**

\[
\varepsilon \rho_g c_{pg} \frac{\partial T_g}{\partial t} + \rho_g c_{pg} u \frac{\partial T_g}{\partial x} = h S (T_w - T_g)
\]
where: $i = 1, 2, 3, 4$

4. Energy balance on wall’s surface:

$\begin{align*}
(1-\varepsilon)\rho_w \frac{\partial c_{pw} T_w}{\partial t} - (1-\varepsilon)\lambda_w \frac{\partial^2 T_w}{\partial x^2} = hS(T_g - T_w) + a(x) \sum_{i=1}^{n} (-\Delta H_i) R_i (C_{w,i}, T_w)
\end{align*}$

where:
- $g$ – index of gaseous state,
- $\varepsilon$ – ratio of monolith volume to catalyst volume,
- $w$ – index related to the walls of monolith cells,
- $i$ – index appointed to individual toxic chemical compound of exhaust gas, $i = 1$ (CO); $i = 2$ (C$_3$H$_6$); $i = 3$ (H$_2$); $i = 4$ (O$_2$)
- $a(x)$ – concentration of precious metal on the walls surface defined as a surface occupied by precious metal on unity of volume [cm$^2$ (Pt)/cm$^3$],
- $c_{pg}$ – specific heat of gas [J/(kg K)],
- $c_{pw}$ – specific heat of metal [J/(kg K)],
- $u$ – gas velocity,
- $C_{g,i}$ – concentration of component $i$ in gaseous state,
- $C_{w,i}$ – concentration of component $i$ on surface of catalyst wall,
- $h$ – coefficient of heat exchange [J/(cm$^2$ *s* K)] defined on the base of Nusselt number and coefficient of heat conductivity of gas $\lambda_g$ [J/(cm*s*K)] and hydraulic radius $R_h$:

$\begin{align*}
h = \text{Nu} \cdot \frac{\lambda_g}{(2 \cdot R_h)}
\end{align*}$

however coefficient of heat conductivity is a function of temperature:

$\begin{align*}
\lambda_g = 2.269 \cdot 10^{-6} \cdot T_g^{0.832}
\end{align*}$

$k_{m,i}$ – coefficient of mass exchange for component $i$ is defined as follows:

$\begin{align*}
k_{m,i} = Sh \cdot D_i / (2 \cdot R_h)
\end{align*}$

$\begin{align*}
D_i & \text{ – diffusion of component } i \text{ in a reaction mixture [cm}^2\text{/s]}
Sh & \text{ – Sherwood number,}
T_g & \text{ – gas temperature,}
T_w & \text{ – temperature of monolith walls,}
(-\Delta H_i) & \text{ – heat release during combustion of component } i \text{ [J/mol]}
\end{align*}$

During work of reactor there is decrease of concentration of precious metal along the catalyst and follows so called aging of catalyst. However model takes into account only constant concentration of precious metals. In calculations it is assumed often:

1. omitting of gradient of temperature in solid phase in radial direction,
2. omitting of axial diffusion of mass and heat in gaseous phase,
3. occurrence of chemical reactions only on the surface of catalyst walls.

Whole thermo-chemical model of catalytic converter has been presented in the work [1] and some examples of calculations were shown. Influence of location of catalytic converter in exhaust system on power and fuel consumption in two-stroke engines were describe in the paper
Conversion of chemical compound in a converter takes place not equal in its whole space after starting of the engine. Initially conversion of CO is much more in a middle of converter and after certain time is more evident also in inlet part as shows Fig.2.

Some experimental work done by Dabadie et al [4] showed better oxidation of hydrocarbons and carbon monoxide by applying of longer catalytic converter and different washcoat materials (Fig.3).

HC conversion over the catalyst is limited by the short gas contact times and can be improved by using of larger converter with greater geometric surface area. In motorcycles, catalysts have time contact with gas around one tenth that of passenger cars. Catalyst efficiency is generally higher for CO emission than for HC emissions in the case of longer converter but this phenomenon depends on washcoat materials (case A-PtRh, case B-PtPd)

The same authors [4] investigated behaviour of the catalytic converter during light off period for different size and different washcoat materials. In Fig.4 there is presented exhaust emperature after the catalyst showing the light of differences between the tested catalysts. With the direct injection engine, exhaust gas contains very low CO level. The HC conversion does not generate CO on the catalyst, as it is the case for carburetted engine [4].
European mopeds generally have continuously variable transmission (CVT) and during ageing of the catalyst give a steady temperature and emission profile without step changes due to gear shift (Fig. 5). The catalyst inlet temperature reaches around 400°C after 200 s and excess air ratio $\lambda$ changes from lower value to higher value (leaner mixture).

**Fig. 4.** Heating process of catalyst at different coat and length of the monolith [4]

**Fig. 5.** Speed, lambda and temperature for light-off test [3]

Catalysts with optimal size and quicker ageing process point higher outlet exhaust gas temperature than inlet temperature. By using of bigger size of the monolith sometimes outlet temperature can be lower than inlet temperature.

**Investigation results**

Experimental test was done on laboratory stand with carburetted two-cylinder engine of 250 cm$^3$ capacity. On the outlet side of exhaust system the metallic catalyst from Tico was fixed. The results from experimental test were compared with results obtained from simulation tests. The engine with inlet fuel injection was tested on special stand and loaded by electric generator with excess air ratio much more than stoichiometric value ($\lambda > 1$). Measurements of exhaust gas composition were conducted by AVL DiGas device, which shows volumetric concentration of CO, CO$_2$, HC, O$_2$ and excess air coefficient $\lambda$. The results shown here were obtained at 2500 rpm.
of continuous work and time of injection amounted 2.07 ms. Power needed for driving of
generator amounted 2.8 kW. Because of larger size of catalytic converter than this engine
requires inlet temperature of exhaust gas was higher than that measured on outlet side. Initially
inlet temperature grows rapidly reaching after 500 s about 1000°C and then it decreased to
800°C as is shown in Fig. 6.
Outlet temperature of exhaust gas after 100 s increased from 600°C to more than 900°C and later
temperature decreased to 500°C (Fig.7). Bigger size of the catalyst than in standard application
causes longer time of heating and reducing of total temperature of the catalyst.

There is unknown the chemical composition of washcoat of catalytic converter taken from
Tico car, but it was founded a significant reduction of toxic components of exhaust gas after the
catalyst. In spite of larger size, reduction both carbon monoxide and hydrocarbons follows after
short time about 100 s from starting of the engine reaching efficiency of reduction above 80%.
As shown in Fig.8 oxidation of CO rapidly takes place at initial stage of ageing and after 300 s
almost whole composition of CO is reduced to CO₂ (100% conversion).

The same effect is observed for oxidation process of hydrocarbons (Fig.9). Whole contents of
hydrocarbons is burned in catalytic converter. However the engine was fuelled by very lean
mixture, where \( \lambda > 1.5 \). The mixture was very well prepared by inlet fuel injection system.
Reducing of hydrocarbons by catalytic converter from value above 1200 ppm to almost zero ppm during time interval 350s is shown in Fig.10. Small amount of fuel in large mass of air causes smaller values of emission both CO and HC, but engine worked steady during experimental tests. However it did not work continuously by long period and therefore we cannot found so good reduction of toxic components after thousand hours in normal conditions. Variation of excess air coefficient measured on the base of chemical composition of exhaust gas is shown in Fig.11. After ageing process lambda coefficient does not go below value of 1.6. Probably the leaning of mixture takes effect on bigger values of NOx concentration caused by higher temperature of charge during combustion process in the cylinder. However concentration of NOx was not measured and in normal fuelling at stoichiometric mixture exhaust gas does not contain this component.

Because of lean mixture delivered to the cylinder exhaust gases contain also big amount of oxygen. In spite of the fact that some amount of oxygen is used to reduce CO and HC in catalytic converter in exhaust gases is still about 9% of that compound, as shown in Fig.12. Concentration of carbon dioxide shown in the same figure increases after ageing and amounts about 9.5% of total volume. Applying of catalytic converter from small car can reduce significantly emission of CO and HC, but in two-stroke engines system of lubrication takes effect on clogging of cells in the catalyst after some hundreds hours. Leaning of the mixture and applying of catalytic converter in exhaust system in two-stroke engines reduce concentration of carbon monoxide and hydrocarbons to zero values in steady conditions.
Simulation results

On the base of presented mathematical model of conversion of basic toxic exhaust components was made computer program enabling to analyse any catalytic system in a two-stroke engine. Initial values of exhaust components and inlet temperature in simulation process were taken from experimental tests. Taking into account the same geometrical parameters as in industry catalyst the simulation was conducted and only chosen results are shown in the paper.

In Figures 13 and 14 there are shown variation of carbon monoxide and hydrocarbons emission obtained from the tests and calculations, respectively. Emission of both components decreases during time of ageing which is evident for simulation process and experimental tests. Results obtained from calculations do not differ significantly from those from laboratory tests.

Conclusions

Theoretical solution together with experimental work of the analyzed exhaust system with catalytic converter in a two-stroke engine was presented. The aim of the idea of application of
catalytic converter in exhaust systems is to use the possibility of decrease the engine emission in the whole range of engine speed without decreasing of engine performances.

1. Applying of big size catalytic converter decreases significantly emission of carbon monoxide and hydrocarbons in steady work condition.

2. Ageing process lasted very short about 100 s reaching reduction efficiency about 80%.

3. Leaner mixture assures less concentration of CO and HC and enables to apply of industry catalytic converters.

4. Longer time of using of catalytic converter in two-stroke engine without modifying of lubrication system can cause clogging of the cells.

5. Simulation process can help to analyze chemical processes taking place in the catalyst and assessment of designed exhaust system. Results obtained from simulation do not deviate from experimental results.

References

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