COMPARISON OF PERFORMANCE OF TWO-STROKE ENGINE WITH CATALYTIC CONVERTER

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Abstract. Applying of catalytic converter in exhaust system of two-stroke engine decreases significantly emission of toxic components but also reduces working parameters. Temperature of exhaust gases in exhaust pipes takes effect on behaviour of converter monolith and reduction of CO and hydrocarbon. In paper exhaust system with converter located in the middle of tuned motorcycle exhaust system is examined and compared with normal system. The paper includes description of physical processes occurring in exhaust pipe, mathematical model of unsteady gas flow, which take into account increase of gas friction in the monolith. Results of simulation process and research work on test stand are shown in figures. Simulation enables optimisation of whole exhaust system at conservation of high temperature in the monolith. In paper result of simulation (torque, fuel consumption, residual gas etc.) were given in comparison to original engine. Comparison of power and fuel consumption indicates on decreasing of work parameters of two-stroke engine with catalyst at higher rotational speed.

1. Introduction

Application of catalytic converter in two-stroke engine is 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 exhaust gas temperature. 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 extent 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 applying of catalytic converter in exhaust system.

The system described (Fig.1) causes longer heating of washcoat during start-up, but retains the same dynamic feature as original 'tuned' system. The problem which was necessary to solve was performed in the task: how to obtain higher power and lower fuel consumption at simultaneous big reduction of exhaust emission.
In the work only influence of catalyst location on engine performance such as: power, fuel consumption, residual gas, delivery ratio was analysed without results of reduction of CO and hydrocarbons. Dynamic nature of gas flow in two-stroke engine system takes effect on cylinder filling efficiency and amount of unburned fuel flowing into exhaust system during scavenge process. System shown in Fig. 1 enables reflection of pressure wave from the perpendicular wall and moving of catalytic converter to gas of higher temperature. In Tab. 1 main parameters of exhaust systems is specified.

Table 1. Parameters of exhaust system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe length L1</td>
<td>400 mm</td>
</tr>
<tr>
<td>Diffuser length L2</td>
<td>300 mm</td>
</tr>
<tr>
<td>Cylindrical part of diffuser L3</td>
<td>210 mm</td>
</tr>
<tr>
<td>Pipe diameter D1</td>
<td>28 mm</td>
</tr>
<tr>
<td>Diffuser diameter D2</td>
<td>80 mm</td>
</tr>
<tr>
<td>Diameter of catalytic converter D3</td>
<td>35 mm</td>
</tr>
<tr>
<td>Length of catalytic converter Lcat</td>
<td>80 mm</td>
</tr>
<tr>
<td>Type of catalytic converter</td>
<td>Metallic</td>
</tr>
<tr>
<td>Volume of muffler</td>
<td>2 dm³</td>
</tr>
</tbody>
</table>

During experimental and simulation tests this parameters have not been changed. In system shown in Fig. 1 location of catalyst in diffuser were moved in a limits from 525 to 850 mm from exhaust port.

2. Mathematical model

2.1. UNSTEADY GAS MOTION IN ENGINE DUCTS

Simulation of engine performance requires to take into account of unsteady gas flow through engine systems. In one-dimensional model gas motion in engine ducts is described by means of three partial differential equations:

1. Equation of the mass continuity

\[ \frac{\partial p}{\partial t} + \rho \frac{\partial u}{\partial x} + F_x \frac{p}{\partial x} = 0 \]  

(1)

2. Momentum equation

\[ \frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} + \rho u^2 \frac{d \ln F_x}{dx} + \rho \tau \frac{u}{D_h} \frac{u}{2} = 0 \]  

(2)

3. Equation of the conservation of energy

\[ \frac{\partial \left( \rho \frac{u^2}{2} + p \right)}{\partial t} + \frac{\partial \left( u \left( \rho \frac{u^2}{2} + \frac{\kappa}{\kappa - 1} p \right) \right)}{\partial x} + u \left( \rho \frac{u^2}{2} + \frac{\kappa}{\kappa - 1} p \right) \frac{d \ln F_x}{dx} - \rho q = 0 \]  

(3)

\( \tau \) - friction coefficient of the gas on wall \( (\tau = 0.003 \pm 0.007) \),

\( D_h \) - hydraulic duct diameter,

\( x \) - current duct length.
2.2. FRICTION AND PRESSURE DROP IN CATALYST

As a consequence of gas flow through catalytic converter is pressure drop and increasing of washcoat temperature. Pressure drop in the catalyst can be measured during stationary flow on test stand. Carberry and Douglas [2] measured pressure variation across catalytic substrate face on flow rig with different air mass flow rate. At steady flow they found pressure drop from 1 to 10 mm H₂O in dependence of radial distance. In real engine change of pressure in exhaust duct follows very fast and pressure drop in catalyst is caused by laminar and turbulent flow. Change of thermodynamic parameters and reduction of exhaust gas species before and after catalytic converter are shown in Fig.2. As a result of catalyst work an increase of washcoat temperature and decrease of gas temperature takes place.

![Fig. 2. Gas flow through catalytic converter](image)

Catalyst density has a great effect on the mass flow rate through the monolith and on pressure decrease. The pressure drop within the model taken into account is expressed by the developing flow area and the length of which can be calculated. Computational length of the catalyst can be expressed by using the following equation given by Luoma and Smith [1]:

\[ L_e = 0.0288 \cdot \text{Re} \cdot D_h \]  \hspace{1cm} (4)

where Reynolds number is obtained from the following formula:

\[ \text{Re} = \frac{D_h \cdot u}{\nu} \]  \hspace{1cm} (5)

where:

- \( u \) - average particle velocity of gas in the monolith channel,
- \( \nu \) - kinematic viscosity.

The total pressure drop caused in the developing flow area is calculated as a result of turbulent and laminar flow. The turbulent pressure drop is caused by the friction in the channels of monolith and can be determined from the following equation:

\[ \Delta p_{\text{tur}} = \frac{2}{D_h} \cdot f \cdot L_e \cdot \rho \cdot u^2 \]  \hspace{1cm} (6)

in which the friction factor is calculated from the equation:

\[ f = 0.0791 \cdot \text{Re}^{-1/4} \]  \hspace{1cm} (7)

On the contrary laminar pressure drop is determined as a result of influence of monolith length and gas properties and was performed by Luoma and Smith [1] in the following formula:

\[ \Delta p_{\text{lam}} = -\frac{32 \cdot \nu \cdot \rho \cdot u}{D_h^2} \cdot (L - L_e) \]  \hspace{1cm} (8)

The total pressure drop caused in a one channel of the catalytic monolith is then calculated:

\[ \Delta p_{\text{tot}} = C_1 \cdot \Delta p_{\text{tur}} + C_2 \cdot \Delta p_{\text{lam}} \]  \hspace{1cm} (9)

where:

- \( \rho \) - gas density,
- \( L \) - total length of catalyst.

Correction factors \( C_1 \) and \( C_2 \) were determined on the experimental results. For the
metallic catalysts, which are most often used in two-stroke engines, having the cell density <600 cpsi, only the turbulent pressure drop needs to be corrected. Value \( C_1 \) can be calculated from the equation:

\[
C_1 = 1 - 0.2787 \cdot e^{-0.2787 (Re - Re_0)/q_i}
\] (10)

Values coming into equation were determined during experimental tests [1] and amounts respectively: \( Re_0 = 3177.3 \), \( q_i = 1382.1 \). Correction factor for laminar pressure drop is \( C_2 = 1 \). Friction factor of gas flow through the catalyst can be determined on the base medium diameter of the pipe \( D \), length of monolith \( L \) and pressure \( p \) before catalyst as follows:

\[
\tau = \frac{\Delta p}{p} \cdot \frac{D}{4 \cdot L}
\] (11)

2.3. FLOW IN PARALLEL PIPES

Prediction of thermodynamics parameters in every pipe requires the solution of gas flow through the pipes junction. The mass, energy, pressure losses and wave reflection have to be analysed in mathematical model for different flow directions. In the analysed system three pipes of different diameter are connected together in parallel branched pipes. Fig. 3 shows transient incident and reflective pressure waves in every pipe in the junction, when the non-steady gas flow is taken into account. These impulses significantly affect the quantity of gas mass flowing into the connected pipes since they decide of the gas velocity in every pipe resulting from the formula given by Blair [5][7]:

\[
u = \frac{2}{k - 1} \cdot a_o \cdot (X_R - X_L)
\] (12)

where:

- \( P_R \) — impulse of wave in positive direction,
- \( P_L \) — impulse of wave in negative direction,
- \( a_o \) — local speed of sound in reference conditions,
- \( i \) — pipe number.

The superposition pressure \( P_s \) in every pipe near junction is determined from the equation:

\[
P_s = P_{Ri} + P_{Li} - 1
\] (13)

There are many mathematical models of solving the gas flow in branched pipes [5][6][7]. In the work the model of QUB given by Blair [5] was used at assumption of the same pressure value in pipe’s junction.

Fig. 3. Pressure at inlet of catalytic converter in diffuser

The gas flow in pipes is treated as a flow of low pressure amplitudes. There are three equations to solve, which allows to determine the right pressure values outgoing from the junction:

\[
P_{Ri} = \left[ 2F_2P_{L2} + 2F_3P_{L3} + (F_1 - F_2 - F_3)P_{L1} \right] \frac{1}{\sum F}
\] (14)
\[ P_{R2} = \left[ 2F_1P_{L1} + 2F_2P_{L2} + (F_2 - F_3)P_{L2} \right] \frac{1}{\sum F} \]  
(15)

\[ P_{R3} = \left[ 2F_1P_{L1} + 2F_2P_{L2} + (F_3 - F_2)P_{L2} \right] \frac{1}{\sum F} \]  
(16)

The above given equations can be determined total pressure in junction and gas velocity in each pipe.

3. Simulation of engine work

On the base of given mathematical model of unsteady gas flow in engine system, especially through exhaust system with catalytic converter the computer program was done to predict the transient thermodynamics parameters, delivery ratio, residual gas and output parameters. Computer program can analysed many systems of different parameters at short time. For this reason the experimental test were carried for verification of the mathematical model and for obtaining of basic characteristics of power and pressure variation both for engine with catalyst and standard engine. Calculations of gas parameters for different systems and engine parameters were determined by change of location of catalytic converter for the same overall dimensions of exhaust pipe and muffler. There was not possible to calculate the optimum of engine performance for different exhaust systems. However the local optimum of power and specific fuel consumption were determined by alteration of monolith location for constant exhaust pipes length and diameter of exhaust pipes. The simulations of engine work were conducted for whole engine work cycle in iteration way until the required convergence was obtained. Calculations concerned only to one cylinder engine which is specified in Table 2.

<table>
<thead>
<tr>
<th>Engine specification</th>
<th>DEZAMET 154</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore</td>
<td>52 mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>58 mm</td>
</tr>
<tr>
<td>Connected rod length</td>
<td>110 mm</td>
</tr>
<tr>
<td>Geometric compression ratio</td>
<td>8.5</td>
</tr>
<tr>
<td>Geometric compression ratio of the crankcase</td>
<td>1.35</td>
</tr>
<tr>
<td>Beginning of exhaust port open</td>
<td>77 deg BBDC</td>
</tr>
<tr>
<td>Beginning of inlet port open</td>
<td>60 deg BTDC</td>
</tr>
<tr>
<td>Exhaust port width</td>
<td>33 mm</td>
</tr>
<tr>
<td>Main diameter of carburettor</td>
<td>20 mm</td>
</tr>
</tbody>
</table>

The engine used in experimental test was adopted from industry two-stroke engine DEZAMET 154 and applied with two exhaust systems. For simplest adaptation timing phases were not changed and therefore the engine has not reached optimum performance which could be obtained from 125 cc capacity.
4. Verification of mathematical model

Experimental test was done on laboratory stand with carbureted engine specified above with two exhaust systems which were applied with metallic catalyst specially prepared by polish company LINDO-GOBEX. The results from experimental test were compared with results obtained from simulation tests. The engine was tested at air excess $\lambda=0.95$. With application of catalyst the engine showed 60% decrease of hydrocarbons and only 20% of CO. For verification of computer program comparison of power for the system was carried out as shown in Fig.4.

A comparison of engine power confirmed good agreement of measurements and calculations. The correlation between calculation and measurement results at the level of 0.9, which should be considered satisfactory. With such conformity, it can be stated that the proposed mathematical model is suitable for solving the process of engine performance of the systems discussed.

5. Comparison of results

Comparison of results of thermodynamic parameters and engine performance for original engine and that applied with catalytic converter is the base for assessment analysed system. Results of tests shown in figures were given only for full (WOT\(^1\)) and half throttle engine operation. Applying of exhaust system with catalytic converter variation of power both at full throttle and part throttle operation changes considerably. Maximum of power moves to middle range speed as shown in Fig.5 and Fig.6 at full and half throttle operation, respectively. In comparison to standard engine at high speed power value significantly increases. Results were obtained for catalyst located at length 600 mm from exhaust port.

\[\text{Fig. 5. Comparison of power of standard engine and engine with catalytic converter at full throttle}\]

\(^1\) Wide Throttle Operation
Fuel consumption at standard engine as well as in engine with catalyst changes of low value. However is significantly smaller at lower and higher rotational speed in standard engine as shown in Fig. 7 at full throttle and in Fig. 8 at half throttle operation.

During experimental and simulation tests location of catalytic converter was changed in diffuser (Fig. 1). Length from exhaust port to the catalyst located in output pipe were
changed from 525 to 850 mm. Catalyst location has considerable influence on engine power and fuel consumption. In Fig.9 variation of power and bsfc at 6000 rpm at full throttle operation are performed.

Maximum of power takes place for system with catalyst location about 650 mm from exhaust port. On the other hand specific fuel consumption is quite high and amounts about 480 g/kWh. Decrease and increase of length of the catalyst to exhaust port causes significantly reduction of power. However specific fuel consumption decreases to small values.

The same performance was obtained at 3000 rpm and full throttle operation as shown in Fig.10. Engine with different systems was tested also at part throttle operations. Limitation of the paper does not allowed to present results obtained from this test. It is difficult to determine optimum of location catalytic converter for the sake of maximum power and fuel consumption. Each engine and exhaust system requires its own tests to improve power and fuel consumption performances with taking into account decreasing of toxic species. At middle rotational speed after scavenge process in cylinder remains less exhaust gases and more air is delivered by transfer ports as is shown in Fig.11.

Additionally CFD simulation process was done to obtain thermodynamic parameters of exhaust gas in exhaust system. PHOENICS code of finite element method was used [8]. Gas flow through the catalyst was conducted at assumption of higher porosity of cells in output pipe. In Fig.12 variation of gas temperature is performed from opening of exhaust port in full engine cycle at assumption of Initial temperature in cylinder equal 1200 K and pressure 3.5 bar. Gas temperature before converter located in diffuser is also high to initiate chemical reactions taking place on surface of washcoat.
6. Conclusions

Theoretical solution together with experimental work of the analysed exhaust system with different location of catalytic converter in a diffuser of two-stroke engine were presented and modified in this work. Both the tests and computer simulation carried out for the exhaust system applied with have shown higher power and lower specific fuel consumption at lower engine speeds. At higher rotational speeds engine efficiency is more affected by pressure wave reflection from the muffler barrier. In work of Mallamo [10] a considerable decrease of engine power were pointed out at full throttle operation on scooter engine.

It is quite significant to compare the two-stroke engine performance applied with catalyst to the traditional exhaust system. As a result of the experimental tests and computation the following conclusions can be drawn.

1. Applying of catalytic converter at ‘tuned’ exhaust system influences on engine performance and thermodynamic parameters of exhaust gas.
2. Catalytic converter in proposed system (Fig.1) increases engine power and specific fuel consumption at low and middle range speed. This phenomena was proved also by Mallamo [10].
3. Catalytic converter in analysed system moves maximum engine power to middle range speed and increase bsfc at lower and higher speeds.
4. Exhaust system with catalytic converter decreases power at higher rotational speed.
5. Reflected pressure waves from the catalyst take effect on filling efficiency and residual gas in the cylinder.

All results were obtained for one cylinder two-stroke loop scavenge industry engine modified by applying of ‘tuned’ exhaust systems with catalytic converter.

7. References