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Energy Procedia 82 (2015) 75 – 80

Energy Procedia

ATI 2015 - 70th Conference of the ATI Engineering Association

Optimization of a fast light-off exhaust system for motorcycle applications

Claudio Poggiani[a]*, Alessandro Cimarello[a], Carlo Nazareno Grimaldi[a]

[a]*Department of Engineering, University of Perugia, Via G. Duranti 67, 06125 Perugia, Italy*

Abstract

Emissions standards for two- and three-wheeled powered vehicles are getting more and more stringent, and measurement procedures require to perform driving cycles with engine cold start. Therefore, a fast activation of the exhaust catalytic converter is of primary importance. In this work a numerical and experimental study of the exhaust system layout of a 125cc scooter has been carried out with the main objective of reducing the catalytic converter light-off time, without affecting engine performance and component cost. First, a 1D engine model has been developed to evaluate the impact of the component modification on engine performance. Then, a CFD-3D analysis has been performed to assess and evaluate the velocity and temperature fields of the gases inside of the muffler. After the numerical study, several prototypes have been designed and built for experimental tests. The engine has been installed on the dynamometric bench and instrumented. The exhaust system prototypes have been tested focusing on the engine brake performance and on the exhaust temperatures during warm-up transients. The latter has been monitored in several points inside the muffler, in order to obtain information about the catalytic converter operating conditions. The best prototype configurations have been installed on the vehicle and further road tests. The vehicle experimental results in terms of exhaust gas temperatures at the catalyst inlet and outlet highlight the improvements with the best exhaust prototype compared to the original configuration.

Peer-review under responsibility of the Scientific Committee of ATI 2015

Keywords: Catalyst Light-off, Motorcycle Emission, Dynamometric Bench,Vehicle test.

1. Introduction

The conversion efficiency of a catalytic converter is highly dependent on its operating temperature, with almost no effect when cold. So, the warm-up transient of the catalyst after engine cold start is desired to be as short as possible. In the EU, gaseous pollutants emissions of two wheel motorcycle are

* Corresponding author. Tel.: +39-075-585-3749.
*E-mail address:*claudio.poggiani@studenti.unipg.it.

Peer-review under responsibility of the Scientific Committee of ATI 2015
doi:10.1016/j.egypro.2015.11.885

measured according to the World Motorcycle Test Cycle (WMTC) procedure described in the UN-ECE Global Technical Regulation No.2 [1], which prescribes a specific driving cycle after starting the engine at a temperature of 25°C ± 5°C. These conditions are usually characterized by extra-emissions due to the catalyst being inactive at low temperature, and by the strategies commonly used to accelerate its light-off like extremely retarded sparks, increased throttling, and fuel enrichments [2,3]. To describe the temperature at which the catalytic converter efficiency increases above 50% the term Light-Off Temperature (LOT) is commonly used. Values of 250°C to 300°C are generally found for fresh noble metal oxidation catalyst [4]. Focusing on the catalyst and muffler design, several strategies have also been investigated [5], from exhaust coating to the introduction of extra heaters [6,7], to the use of phase change materials for heat storage [8].

In this work an experimental and numerical methodology has been applied to the development of a fast light-off muffler for motorcycle application, operating on the internal layout without introducing extra devices. The vehicle used is a *Honda Motor Co*. SH 125, and the exhaust systems have been designed, developed and tested jointly by the University of Perugia and Solfer Componenti S.r.l.. The improvement of the catalyst warm-up rate has been the main objective of the work, trying to limit any negative effect on the engine performance and reliability of the exhaust system.

The methodology used involves both numerical and experimental approaches. 1D engine models have been built to evaluate muffler influence on the engine performance. 3D CFD simulations of the muffler have been used to analyze velocity and temperature fields before building any prototypes. Measurements on a dynamometric test bench have been carried out for model validation and prototype assessment. Finally, selected exhaust systems have been tested on the road, on a vehicle equipped with an on-board data acquisition system.

2. Muffler Prototypes

In this work five prototypes have been designed and tested with the goal of reducing the catalyst warm-up transient (Fig.1). The Original Equipment Manufacturer (OEM) exhaust system has been used as a reference for results analysis. For the sake of brevity not all the results will be presented in this paper.

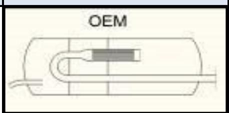
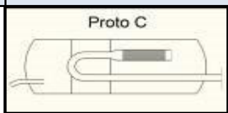
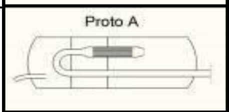
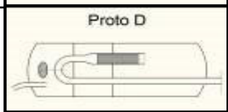
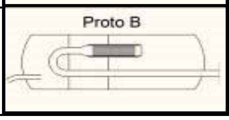
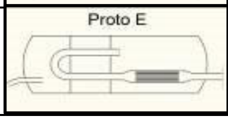
TYPE	SKETCH	DESCRIPTION	TYPE	SKETCH	DESCRIPTION
<u>*OEM*</u>		Catalyst element between 1° and 2° chamber	<u>*Proto C*</u>		Catalyst element in 1° chamber after the bend
<u>*Proto A*</u>		Converging stretched cone inserted downstream of the catalyst	<u>*Proto D*</u>		Bend with elliptical cross section
<u>*Proto B*</u>		Catalyst wall with insulating air gap	<u>*Proto E*</u>		Catalyst element in 1° chamber before bend

Fig. 1. Summary description of the exhaust systems under investigation.

3. Methods

3.1. Numerical Analyses using 1D Engine Cycle Simulation and CFD-3D models

The first step of the methodology has been the implementation in AVL Boost® of a 1D engine cycle model for the single-cylinder, 4-stroke, port-fuel-injected Honda SH 125 engine (cf. Tab.1). The engine model has been validated with experimental data of the stock configuration, and then utilized to evaluate the effects of muffler geometry changes on engine performance. The 1D engine cycle simulations have focused on the analysis of engine torque and power effects deriving from muffler changes, while keeping the rest of the model as in the stock version (cf. Fig. 2 (a)).

Table 1.Honda SH 125 Engine Specifications.

Engine Type	Single Cylinder, 4 stroke, SOHC
Capacity	125 cm3
Bore x Stroke	52,4 x 57,8 mm
Compression Ratio	11 : 1
Max. Power	10,1 kW @ 9.000 rpm (95/1/EC)
Max. Torque	11,5 Nm @ 7.000 rpm (95/1/EC)
Fuel Supply	Electronic Injection, Honda PGM-FI

Steady state CFD-3D studies, using the commercial software STAR-CCM+, have been performed in order to evaluate the velocity and thermal fields inside the muffler. The time-averaged 1D results have been used as input data for the boundary conditions of the exhaust gas in the 3D model. The model encompasses all the materials, i.e., fluid domains (exhaust gases and external air), solid domains (metallic walls) and porous media (catalyst, modeled as a non-reactive porous region). Therefore, the model is able to predict the steady-state conjugate heat transfer across the whole muffler up to the external air. With the goal of reducing the warm-up time of the catalyst, particular attention has been paid to the exact representation of the heat exchange between exhaust gases and muffler metallic walls preserving real and detailed geometries, as this was clearly not possible in the 1D analyses. Furthermore flow velocity distributions across pipes sections and pressure losses have accurately been evaluated.

3.2. Dynamometric Test Bench

The prototypes, once approved and built, have been tested on the dynamometric test bench. The engine has been operated at a fixed load (2.5 kW) and fixed speed (4900 rpm) starting from ambient temperature, until the fully-warm conditions were reached. This engine point, which corresponds to a vehicle speed of 60 km/h with CVT transmission blocked in the higher ratio, has been chosen because close to a barycentric operating point in the WMTC-Part 2 cycle for the vehicle. The exhaust temperatures at the catalyst inlet and outlet, named T1 and T2, have been measured by K-type thermocouples installed inside the silencer. The location is shown exemplary for the OEM muffler in Fig. 2 b (left). The temperature traces of the OEM exhaust and the difference $\Delta T=T2-T1$, reported in Fig.2 b (right), have also been used as a reference for other tested prototypes. As expected, in the first seconds after the cold start the temperature at the catalyst inlet rises more rapidly than the outlet one, due to the thermal inertia of the catalyst brick. The time at which T2 matches T1 for the first time has been defined as $t(\Delta T= 0)$, and it is an index of the catalytic converter activation. In the OEM configuration the catalyst reaches the LOT, set at 280°C, 71 s after the engine start, while $t(\Delta T= 0)$ is 204 s. These values represent the basis for the improvement evaluations achieved with the various prototypes.

3.3. Vehicle Tests

The final step of the methodology consisted in vehicle on road testing, using the best prototype which achieved the shortest light-off time in stationary conditions, while maintaining easy engineering and low manufacturing costs. For this purpose, the scooter has been equipped with an on board data acquisition system. This system, realized with National Instruments hardware and with an acquisition program developed in LabView environment, was designed to acquire different physical quantities, like ambient temperature and pressure, throttle angle, engine speed, vehicle position and vehicle speed via GPS. The chosen speed profile represented highly congested urban driving conditions.

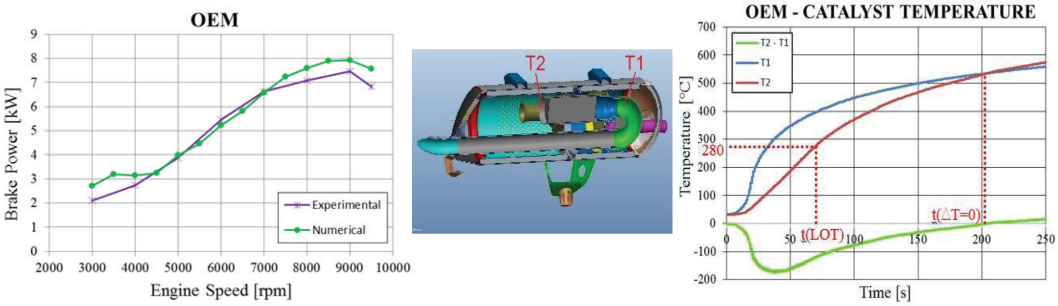


Fig. 2. (a) Brake power, measured and predicted by 1D model (OEM case). (b) Thermocouples locations (left) for OEM; experimental temperatures at catalyst inlet and outlet (right).

4. Results

In this section the main results achieved in the study are shown. Only prototype C and E will be discussed in detail, for brevity. However, global performance will be shown for all the configurations, at the end of the section.

4.1 PROTO C

The PROTO C is characterized by the catalytic converter fully located in the first muffler chamber, where the surrounding gases are hotter. The preliminary numerical analysis has highlighted an improvement of the engine performance at high engine speed and an improvement of the catalyst brick average temperatures: therefore, this version has been built to further test it at the dyno. As reported in Fig.3 (left), the experimental results highlight an increase in the maximum power of about 4% compared to the OEM. In addition, the warm up transient temperatures, reported in Fig.3 (right), highlight an improvement in the heating rate, with t(LOT)=73s and t(ΔT= 0)=71s.

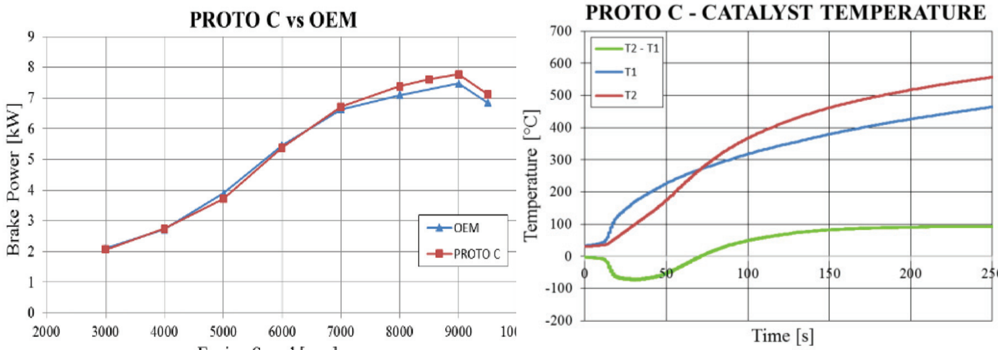


Fig.3. Experimental results for PROTO C compared to the OEM: brake power (left); catalyst temperatures (right).

4.2 PROTO E

The PROTO E is characterized by a positioning of the catalyst just downstream of the silencer inlet, allowing the catalyst to be immediately heated by the exhaust gases. The 1D analysis highlighted slightly lower engine performance compared to the stock version (Fig.4 left), but the CFD simulations highlighted the possibility to obtain further advantages in the catalyst efficiency, deriving from a more uniform distribution of the gas in the catalyst brick (Fig.4). The dynamometric tests confirmed the predicted trend, with a decrease in terms of maximum power limited within acceptable values, around 5%, as shown in Fig.5 (middle). The warm-up transient on the dynamometric bench, reported in Fig.5 (right), highlights the further improvement compared to the OEM, with a t(LOT) of 44s and a t(ΔT= 0) of 79s. So, the PROTO E has been chosen for the final road tests.

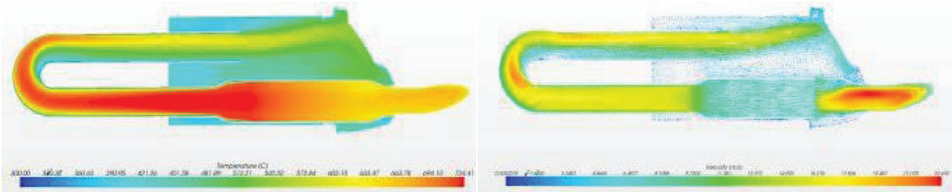


Fig.4. CFD-3D results for PROTO E:temperature contours (left) and velocity vectors (right) for the exhaust gas domain.

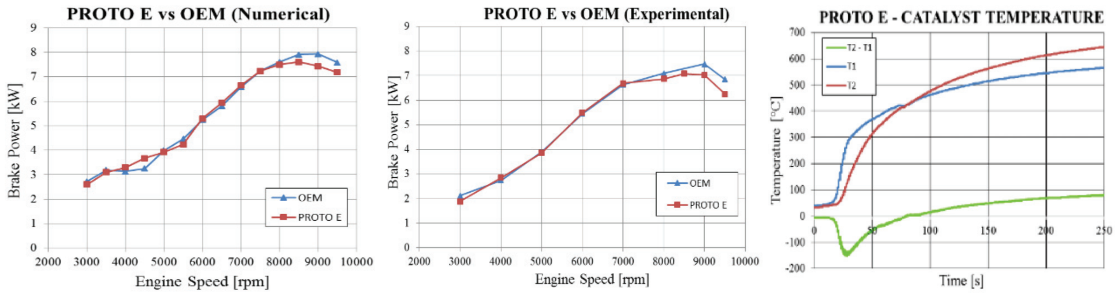


Fig.5. Experimental results for PROTO E compared to the OEM: predicted (left) and measured (middle) brake power, catalyst temperatures (right).

As reported in Fig.6, while performing the road cycle, PROTO E reaches the outlet temperature (T2) of 280°C after 370 s, compared to the 450 s required by the OEM exhaust system, with a gain of 80 s. The vehicle data confirmed the simulation and dyno test results, suggesting that the PROTO E was the most efficient solution for subsequent development and product industrialization.

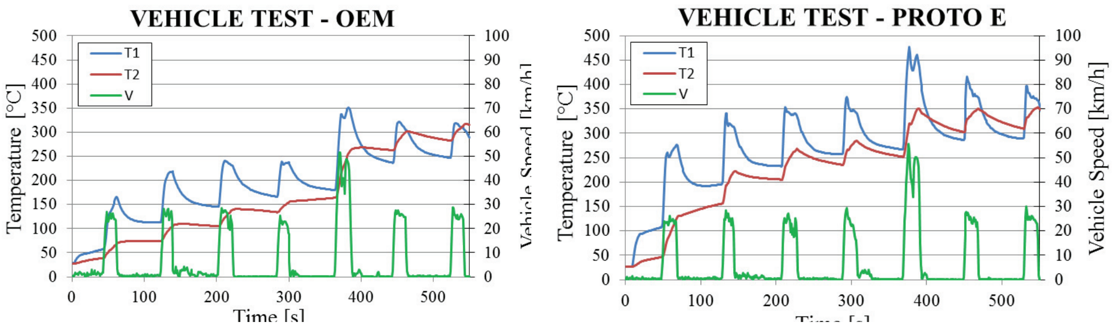


Fig.6:Road tests: vehicle speed and catalyst temperatures: OEM (left); proto E (right).

4.3 Test Bench Results Summary

The values of the t(LOT) and t(ΔT= 0) parameters obtained from all muffler prototype and OEM configuration are reported in Table 2. From these data, the best results are provided by PROTO E, as it allows to reach the minimum t(LOT) of 44 s, which is 27 s shorter than the baseline, and at the same time it gives a very short t(ΔT= 0), equal to 79 s.

Table 2. Prototypes results in terms of catalyst activation times after engine cold start.

	t(LOT) [s]	t(ΔT= 0) [s]
OEM	71	204
PROTO A	86	466
PROTO B	65	96
PROTO C	73	71
PROTO D	83	233
PROTO E	44	79

Conclusions

In this work, an experimental and numerical methodology has been applied to the development of a fast light-off muffler for motorcycle application. With 1D and CFD-3D simulations and experimental tests, the OEM muffler configuration has been characterized and used as reference to compare with the five prototypes designed and built. Among all, the PROTO E design was the best prototype in term of light-off temperature, attaining 27s gain on the dyno and80s on the vehicle, compared to the OEM.

Acknowledgements

This work has been carried out with the support of Solfer Componenti S.r.l.(Italy).

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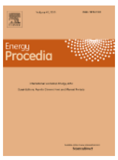

Biography

Claudio Poggiani, was born on 12/12/1985. Graduated in Mechanical Engineering at the University of Perugia in 2011, currently he is in the third year of his PhD program in Industrial Engineering. His research interests are primarily in the automotive field, focusing on engines experimental activities,1D engine cycle simulations, and experiments on optical access engines.