Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Air Mass Flow Analysis for SI Engine: EGR and Scavenging

Antonio Palma **, **Angelo Palladino** *, **Giovanni Fiengo** *,
Ferdinando De Cristofaro **, **Fabio Garofalo** ** and
Luigi Glielmo *

* *Dipartimento di Ingegneria, Università degli Studi del Sannio, Piazza Roma 21, 82100 Benevento, Italy.*
E-mail: angelo.palladino@unisannio.it, gifiengo@unisannio.it, glielmo@unisannio.it
** *Systems and Controls, Gasoline EMS, PWT dpt., Elasis S.C.p.A. Via ex Aeroporto snc, 80038, Pomigliano d'Arco, Napoli, ITALY.*
E-mail: antonio.palma@fptpowertrain.elasis.it, ferdinando.decristofaro@fptpowertrain.elasis.it, fabio.garofalo@fptpowertrain.elasis.it

Abstract: In order to lower the Nitrogen Oxides (NOx) concentration in internal combustion engine emissions and to improve performance, Exhaust Gas Recirculation (EGR) and Scavenging mechanism are introduced. EGR recirculates a fraction of the exhaust gas back into the cylinders, thus diluting the intake air. This lowers the maximum combustion temperature and, since the formation of NOx is heavily dependent on temperature, it results in a reduction of NOx concentration. Similarly, the Scavenging phenomenon is the air mass flowing from intake manifold directly to exhaust manifold, due to an overlap of intake and exhaust valves, without participating at the combustion.
In this paper, the authors present a mean value engine model, aimed at the challenging purpose of the analysis of EGR and Scavenging. The model is based on an innovative approach for engine dynamics conceived mainly on the analogy with electric systems.

Keywords: SI engine model; Automobile powertrains; EGR; Scavenging.

1. INTRODUCTION

In recent years, the high competition and international regulations on emissions has forced the automobile companies to turn out vehicles able to achieve great performance and emit very low pollutants. To this aim, new solutions are investigated regarding both mechanical components and software strategies. As an example, a promising technology, nowadays under analysis for spark ignition internal combustion engine, is the possibility to flow the air mass from the intake manifold to the exhaust and back, passing through the cylinders without participating to the combustion phase. This is realized acting on the intake and exhaust valves, enabling an overlap during the valves opening.

In particular, the flow of the exhaust gas back into the cylinders is named internal EGR, a well known mechanism adopted mainly for diesel engine where an extra manifold is used to regulate the amount of exhaust gas flowing into the intake manifold. The EGR is a method to lower the temperature in the combustion chamber and, as a consequence, to reduce the amount of NOx produced. The drawback is that an higher EGR rate could yield to an unstable combustion.

Conversely, the phenomenon of the fresh air mass flowing from the intake directly to the exhaust manifold, without participating to the combustion phase, is named Scavenging. It allows to clean the cylinders of gas residuals, permitting a better combustion and the possibility to achieve higher performance.

Unfortunately, due to the high complexity of the phenomenon, it is very complicated and expensive to have reliable measurements of the amount of gas flowing between the manifolds. It is caused both by the impossibility to separate the part of air participating to the combustion with the air flowing across the valves and by the necessity to dispose non invasive and high accurate sensors to not corrupt the measurements. As an example, it is not known exactly the fraction of internal EGR which is used for emissions control during normal functioning of engine. Experimentally, it has been estimated that the 25% of the inlet air consists of recycled gas [L. Nielsen, 2000].

Generally, in order to overcome this kind of problem, mathematical models are used both to analyze the behavior of the system and, eventually, to design advanced control strategies [Scattolini et al., 2006, Alfieri et al., 2006]. In literature, different engine models are presented. Among others, finite models of the combustion chamber allow to calculate all in-cylinder variables with a local resolution. The drawback is the long computing time [Torkzadeh et al., 2001]. Vice versa, MVEMs (Mean Value Engine Models) simulate the dominant physical effects neglecting

978-1-1234-7890-2/08/$20.00 © 2008 IFAC
10.3182/20080706-5-KR-1001.2607

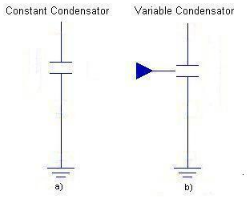

Fig. 1. Volume equivalent circuit: a) constant capacity; b) variable capacity.

the fast dynamics, resulting in a lower computing time [Hendricks and Vesterholm, 1992, Hendricks, 2001].

In this context, the paper presents an SI engine model aimed at simulating the gas flow across the intake manifold, the cylinders and the exhaust manifold and back. The proposed model is obtained exploiting an innovative approach based on the analogy of the engine components with electrical circuits [Palma et al., 2008]. The robustness of the model is tested comparing some measurable variables with experimental data, while the analysis on EGR and Scavenging is based only on simulation results due to lack of measurements.

In the following, the utilized modeling approach is briefly described. Then the proposed engine model is detailed and some simulation results are commented. Conclusions and future activities end the paper.

2. EQUIVALENT CIRCUITS FOR ENGINE COMPONENTS

In this paper, the engine model used to analyze EGR and Scavenging is derived by [Palma et al., 2008]. The authors, starting from a simple analogy with electrical systems, have obtained an engine description similar to an electrical circuit, with all the useful consequences in term of existence and numerical availability of the solution. The advantages are in the specific comparison that is founded between the engine components and variables (as throttle valve, cylinder, inertial flows) with electrical counterparts (current, voltage, resistance). In the following, the utilized modeling approach is briefly described. For details and equations see [Palma et al., 2008].

The engine is seen as an array of cylinders, having common connections with an intake and an exhaust manifold. The connections are regulated by valves opening. It is then possible to distinguish separate subsystems interconnected each others, such as the intake manifold equipped with throttle valve, the exhaust manifold and cylinders. From the phenomenological point of view, the elements composing the engine can be classified in the following categories: volumes, orifices, inertial effects and combustion.

The intake and exhaust manifolds and cylinders are grouped respectively as constant and variable volumes. The electric counterpart is the quantity of charge stored in a capacitor, as shown in Figure [1] 1 reporting the corresponding circuit.

The orifices are responsible of the pressure drops along the gas path. They are modeled as variable resistances causing equivalent voltage drops, as illustrated in Figure 2.

[1] The circuits have been drawn using Modelica.

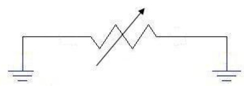

Fig. 2. Orifice equivalent circuit.

The size of the orifice. and consequently the resistance, is variable and regulated by valve opening, as throttle valve, air bypass, intake and exhaust valves [Heywood, 1988].

The inertial phenomena can be considered as minor efforts but not complectly negligible. They describe the reduction or the increase of the pressure upstream the valve of a quantity proportional to the derivative of the mass flow through the same valve. Here, they are modeled as an linear inductance, as shown in Figure 3.

The combustion process constitutes the most meaningful and complex phenomenon occurring into the engine. In order to model the in-cylinder cycle pressure, an equivalent electric circuit has been adopted, as shown in Figure 4. The circuit is formed by a variable condensator, representing the cylinder volume, equipped by an impulsive voltage generator. This causes an impulsive increase of the voltage at the condensator extremities and, consequently, generates a current flow thought the capacitor. This phenomenon corresponds to the well known combustion process, i.e. an impulsive increase of the in-cylinder pressure caused by the combustion resulting in a torque generation and in mass flow through the exhaust valves.

3. FRESH AIR MASS DYNAMICS

Based on the analogies summarized in the previous section, the entire engine can be represented by the circuit shown in Figure 5.

Starting from the left of the figure, the model describes the dynamic of the air crossing the intake manifold, i.e. driven by the ambient pressure (a current generator), the air mass passes the filter (a resistance) and the throttle body (a variable resistance) and arrives into the cylinders through the intake valves (a new variable resistance). Here, the internal EGR is introduced as a backward current flow, coming from the combustion chambers into the intake manifold. The cylinders are then described by a parallel of "n" combustion equivalent circuits, with "n" the number of cylinders composing the engine.

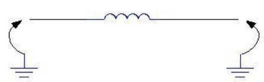

Fig. 3. Inertial effects equivalent circuit.

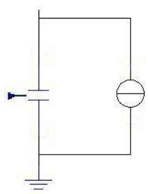

Fig. 4. Combustion equivalent circuit.

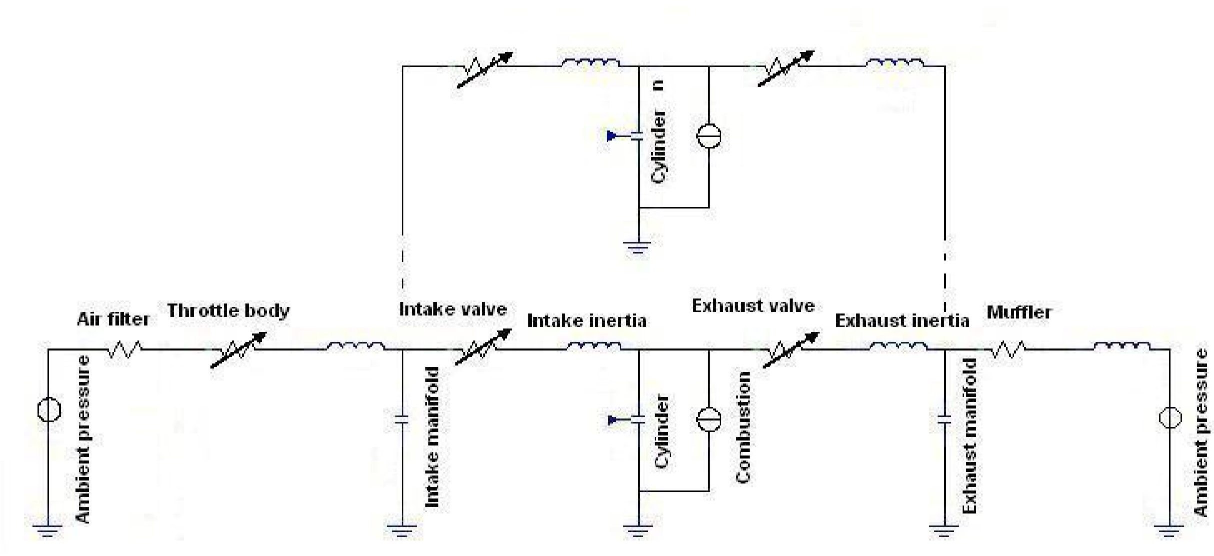

Fig. 5. Internal combustion engine equivalent circuit.

Finally, the gas mixture is discharged into the exhaust manifold through the exhaust valves (a variable resistance) and ends into the ambient crossing the muffler (a resistance). To this amount of gas, the fresh air flowing directly from the intake manifold is added, modeling the scavenging phenomenon. For sake of completeness, it is possible to introduce the inductors that naturally represent the inertial effects of the current and are able to describe the analogous effects of the fluid columns.

The main contribution of the paper is the analysis of the fresh air dynamics, i.e. EGR and Scavenging. It is remarked that do not exist accurate and reliable measurements of the interested variables, as the fraction of air crossing the intake and exhaust valves or the recycled exhaust gas. Therefore, a detailed model able to capture the above mentioned phenomena is essential for their analysis and, eventually, to design a control strategy. This work gives his contribution in this direction.

In particular, the exhaust gas recirculation is adopted to reduce the quantity of NOx produced during the combustion, acting on the temperature reached in the cylinders. In details, the presence of EGR determines an increase of temperature and pressure inside the combustion chambers during the intake phase. This is regulated opening the throttle valve and allowing the correct flow of fresh air. At the end of intake phase and at the beginning of the compression, the temperature is higher for the presence of internal EGR in the air mixture. But this quantity of inert gas slows down the combustion [Reid et al., 1987, Wark, 1995, Heywood, 1988]. As a result, the temperature in the combustion chamber is lower and this reduces the amount of NOx formation.

Contrarily to EGR, Scavenging is the flow of fresh air mass from intake to exhaust manifold, crossing the cylinders but without participating at the combustion. It is performed acting on intake and exhaust valves, imposing an overlap period during which the valves are slightly opened. It can occur at engine TDC (Top Dead Center), during the end of the exhaust phase and the beginning of the intake. Moreover, it is also necessary that, during valves overlap, the instantaneous intake pressure is higher than the exhaust pressure in order to have the correct flow direction. Usually, it is obtained by using a boost system.

The advantages to adopt the Scavenging mechanism are both the capacity to increase the intake efficiency, and consequently the produced engine torque, and the possibility to perform a post combustion in the exhaust manifold. It can be generated mixing the scavenged fresh air mass with the unburned fuel from the previous combustion, purposely regulated in rich condition. The effect of the post combustion are an increase of temperature and pressure in the exhaust manifold that can be exploited to improve the efficiency both for the aftertreatment emissions system and for turbine in turbocharger engine. Conversely, the drawback of scavenging, without performing the post combustion, is the reduction of temperature in the exhaust manifold. It cannot have effect on emissions, if the aftertreatment system has already reached the correct temperature, but can cause a reduction of the turbine efficiency.

In the following, the dynamic model proposed to describe the above phenomena, i.e. EGR and Scavenging, is presented. It calculates the quantity of fresh air mass flowing from intake to exhaust manifold. Hence, the exhaust gas recirculated is obtained by subtracting this fresh air mass to the total mass contained into the manifold.

Let then consider a generic volume (intake manifold, cylinders or exhaust manifold) and indicate with $\dot{m}_{fresh\_in}$ and $\dot{m}_{fresh\_out}$ respectively the incoming and outgoing fresh air mass flow. The variation of the fresh air mass contained into the volume (m_{fresh}) can be easily computed according to

$$\dot{m}_{fresh} = \dot{m}_{fresh\_in} - \dot{m}_{fresh\_out} \tag{1}$$

where $\dot{m}_{fresh\_in}$ and $\dot{m}_{fresh\_out}$ can be considered as a fraction (k_{fresh_in} and k_{fresh_out}) of the total air mass flow respectively at the input ($\dot{m}_{in}$) and the output ($\dot{m}_{out}$) of the volume

$$\dot{m}_{fresh\_in} = k_{fresh\_in} \times \dot{m}_{in} \quad (2a)$$
$$\dot{m}_{fresh\_out} = k_{fresh\_out} \times \dot{m}_{out} \quad (2b)$$

Finally, considering the amount of fresh air mass flowing outside the volume proportional to the amount of fresh air mass contained, the fraction k_{fresh_out} can be computed as follows

$$k_{fresh\_out} = \frac{m_{fresh}}{m_{tot}} \quad (3)$$

with m_{tot} the total mass into the volume, calculated with the ideal gas equation

$$m = \frac{pV}{RT} \quad (4)$$

where p and T are respectively the volume, pressure and temperature, R is the gas constant and V is the volume size.

Therefore, the model is obtained connecting in series three volumes, one for each engine part. In the following subsections, the differential equations governing the dynamics in each part are derived by equations (1), (2) and (3).

3.1 Intake Manifold

The amount of fresh air mass at the inlet of intake manifold is the air flowing through the throttle valve ($\dot{m}_{th}$), while the quantity outgoing the manifold could be only a fraction (k_{fresh_int}) of the total air mass flow entering into the cylinder ($\dot{m}_{cyl}$) due to the possible presence of EGR. So, the intake manifold model can be obtained as follows

$$\dot{m}_{fresh\_int} = \dot{m}_{th} - k_{fresh\_int} \times \dot{m}_{cyl} \quad (5a)$$
$$k_{fresh\_int} = \frac{m_{fresh\_int}}{m_{tot\_int}} \quad (5b)$$

where m_{fresh_int} and m_{tot_int} are, respectively, the fresh air mass and the total air mass present into the manifold.

Consequently, the amount of EGR (m_{EGR_int}) is computed according to

$$\begin{aligned} m_{EGR\_int} &= m_{tot\_int} - m_{fresh\_int} \\ &= (1 - k_{fresh\_int}) \times m_{tot\_int} \end{aligned} \quad (6)$$

3.2 Cylinders

Since the cylinders are connected in series with the intake manifold, the amount of incoming fresh air mass coincides with the quantity outgoing the manifold ($k_{fresh\_int} \times \dot{m}_{cyl}$). Regarding the fresh air flowing into the exhaust manifold, i.e. the Scavenging mechanism, it is a fraction (k_{fresh_cyl}) of the total mass flow crossing the exhaust valves ($\dot{m}_{exh}$). Moreover, during combustion it is supposed that the fresh air present in the cylinders (m_{fresh_cyl}) is completely burned. It means that fresh air flow toward exhaust manifold can occur only at the beginning of the intake phase if the exhaust valves are still opened. Therefore, the model is the follows

$$\dot{m}_{fresh\_cyl} = k_{fresh\_int} \times \dot{m}_{cyl} - k_{fresh\_cyl} \times \dot{m}_{exh} \quad (7a)$$
$$k_{fresh\_cyl} = \frac{m_{fresh\_cyl}}{m_{tot\_cyl}} \quad (7b)$$

where m_{tot_cyl} is the total mass into the cylinders.

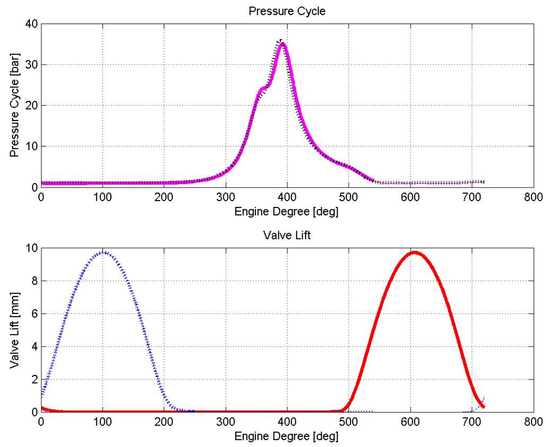

Fig. 6. Simulated (solid-magenta line) and experimental measurement (dotted-black line) of in-cylinder pressure cycle. The second plot shows the measurements of intake and exhaust valves lift. The experiment is conducted at 1500 rpm and WOT.

Similarly, at the end of the intake phase, the EGR (m_{EGR_cyl}) is calculated according to

$$\begin{aligned} m_{EGR\_cyl} &= m_{tot\_cyl} - m_{fresh\_cyl} \\ &= (1 - k_{fresh\_cyl}) \times m_{tot\_cyl} \end{aligned} \quad (8)$$

3.3 Exhaust Manifold

The exhaust manifold, connected in series with the cylinders, is the last component modeled. Here, the input is the fresh air flow from the cylinders ($k_{fresh\_cyl} \times \dot{m}_{exh}$) and the output is a fraction (k_{fresh_exh}) of air mass flow entering the catalyst ($\dot{m}_{twc}$), as follows

$$\dot{m}_{fresh\_exh} = k_{fresh\_cyl} \times \dot{m}_{exh} - k_{fresh\_exh} \times \dot{m}_{twc} \quad (9a)$$
$$k_{fresh\_exh} = \frac{m_{fresh\_exh}}{m_{tot\_exh}} \quad (9b)$$

where m_{tot_exh} is the total mass into the exhaust manifold.

4. SIMULATIONS RESULTS

In order to verify the reliability of the proposed model, some experiments are conducted aimed at comparing some measurable variables with experimental signals. The model has been designed by means of a simple approach based on the analogy of mechanical components with electrical circuits. This methodology has been presented in [Palma et al., 2008], where the validation of the model has been detailed. Here, for sake of brevity, it is reported only the in-cylinder pressure cycle (see Figure 6). The experiment is performed at 1500 rpm, Widely Opening Throttle (WOT) and without EGR and Scavenging, as highlighted in the second plot of Figure 6 showing the absence of overlap between the intake and exhaust valves.

The results, showing a good level of the model of reliability and accuracy, allows to carry on the simulated analysis of air mass dynamics. It is remarked again that the purpose of the work is the study in simulation of phenomenon aimed at a better knowledge of the system. Then, in the following are reported experiments conducted at 1500

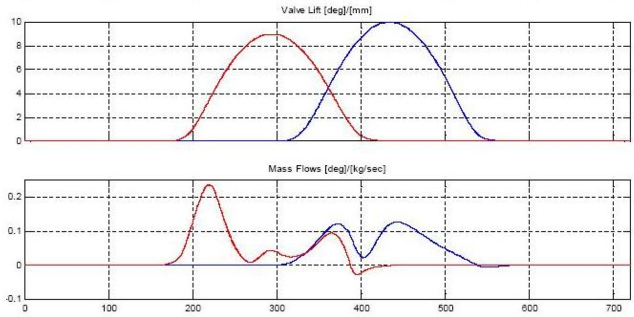

Fig. 7. Valves lift and the corresponding mass flows. Solid-red line for exhaust valve and dotted-blue line for intake. The experiment is conducted at 1500 rpm and WOT.

rpm and WOT, obtained varying the Intake Opening Advance (IOA) angle and the Exhaust Closing Delay (ECD) angle by using two Variable Valve Timing (VVT), as shown in Figure 7 reporting, in the firs plot, the valves overlap and, in the second plot, the corresponding air mass flow respectively crossing the exhaust and intake valves. Finally, the intake manifold pressure is regulated at 2 bar by acting on a boost system. This is necessary in order to perform the scavenging air flow from intake to exhaust manifold, allowed if instantaneous intake pressure is larger than exhaust pressure during valves overlap.

Therefore, Figures 8 and 9 report the maps of the percentage, respectively, of EGR and of Scavenging, function of IOA and ECD. It is interesting to note that, mainly for Scavenging phenomenon, the percentage of fresh air crossing the valves is proportional to the duration of the valves overlap (i.e. the algebraic sum of IOA and ECD) rather then when the overlap occurs.

The performance are finally analyzed in Figures 10 to 12. In particular, Figure 10 shows the possibility to vary the combustion torque generated at 1500 rpm and WOT acting on IOA and ECD while fixing the other control variables, as air-fuel ratio and spark advance. In fact, varying IOA and ECD it is possible to regulate the quantity of active mixture participating to the combustion and, as a consequence, generating torque. It is a further

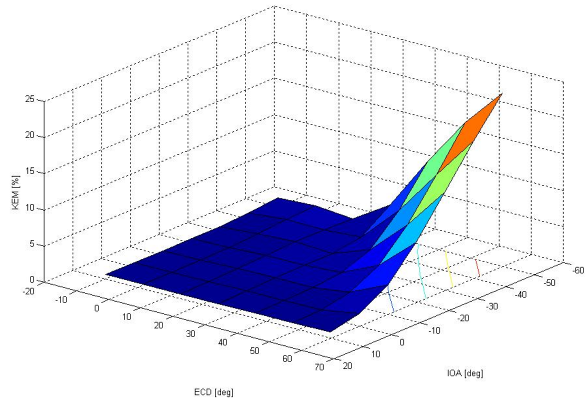

Fig. 9. Scavenging percentage (KEM) in exhaust manifold, function of IOA and ECD. The simulations are conducted at 1500 rpm and WOT.

degree of freedom that can be used to achieve higher performance.

Finally, regarding the emissions reduction, it is also possible to regulate both the intake and exhaust manifold temperature by acting on EGR. In particular, the increase of EGR percentage results both an increase of the intake manifold temperature, for the presence of gas coming by the previous combustion, see Figures 11, and a decrease of the exhaust manifold temperature thanks to the presence of inert gas in the combustion chamber, as shown in Figure 12. This causes the consequent decrease of the temperature inside the cylinders and the reduction of NOx concentration in the emissions.

5. CONCLUSIONS AND FUTURE ACTIVITIES

A reliable model, based on an simple engine modeling approach, is proposed to analyze the EGR and the Scavenging mechanism. The model has been compared with experimental data while the analysis has been conducted in simulation.

Future activities are addressed toward the modeling of the aftertreatment system, in order to provide a more complete tool for analysis and control design.

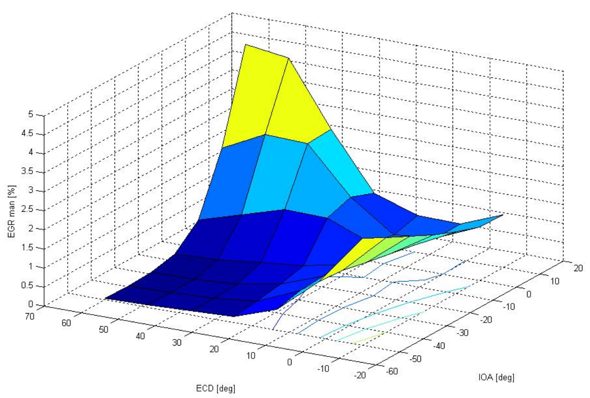

Fig. 8. EGR percentage in intake manifold, function of IOA and ECD. The simulations are conducted at 1500 rpm and WOT.

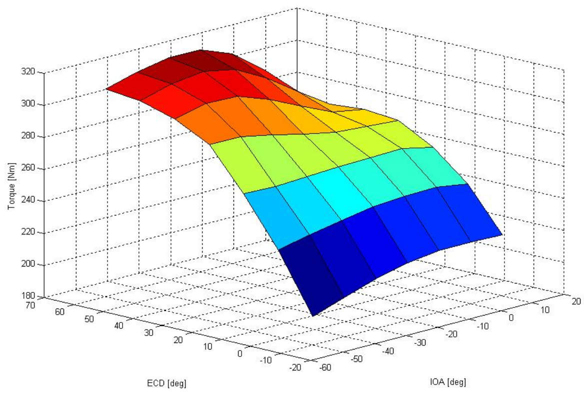

Fig. 10. Engine torque, function of IOA and ECD. The simulations are conducted at 1500 rpm and WOT.

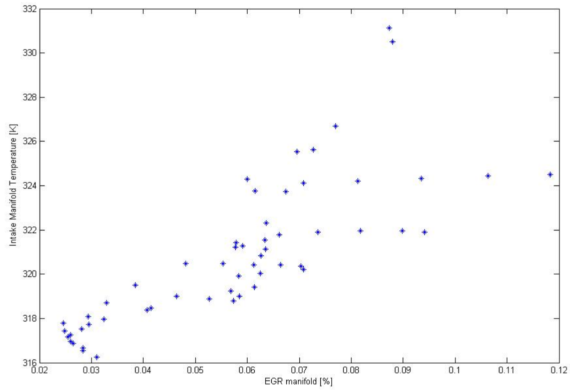

Fig. 11. Intake manifold temperature, function of manifold EGR percentage. The experiments are conducted at 1500 rpm and WOT.

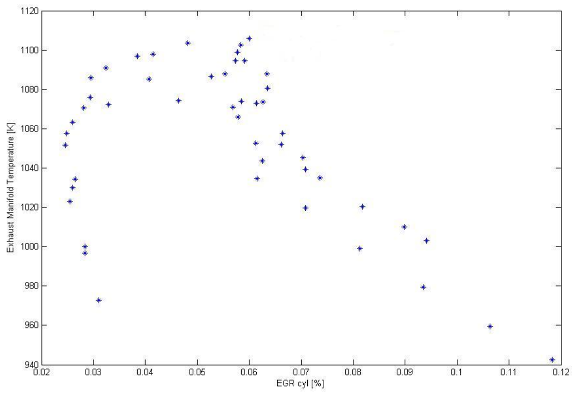

Fig. 12. Exhaust manifold temperature, function of cylinder EGR percentage. The experiments are conducted at 1500 rpm and WOT.

ACKNOWLEDGEMENTS

The authors would like to thanks Luigi Maresca and Elena Giugliano for their contribution to this work and Elasis-FPT, research company of the FIAT holding, for providing the experimental data.

GLOSSARY

$\dot{m}_{fresh}$	fresh air mass flow in a generic volume [g/s]
$\dot{m}_{fresh\_in}$	incoming fresh air mass flow [g/s]
$\dot{m}_{fresh\_out}$	outgoing fresh air mass flow [g/s]
k_{fresh_in}	fraction of the total fresh air mass flow [-]
k_{fresh_out}	fraction of the total fresh air mass flow [-]
m_{fresh}	fresh air mass in a generic volume [g]
m_{tot}	total air mass in a generic volume [g]
$\dot{m}_{fresh\_int}$	incoming fresh air mass flow in intake manifold [g/s]
k_{fresh_int}	fraction of the total fresh air mass flow in intake manifold [-]
$\dot{m}_{th}$	air mass flowing the throttle valve [g/s]
$\dot{m}_{cyl}$	air mass flowing into the cylinder [g/s]
m_{fresh_int}	fresh air mass in intake manifold [g]
m_{tot_int}	total air mass into the intake manifold [g]
m_{EGR_int}	EGR mass into the intake manifold [g]
k_{fresh_cyl}	fraction of the total fresh air mass into the cylinder [-]
$\dot{m}_{exh}$	air mass flowing the exhaust valve [g/s]
m_{fresh_cyl}	fresh air mass contained into cylinder [g]
$\dot{m}_{fresh\_cyl}$	fresh air mass flowing into cylinder [g/s]
m_{tot_cyl}	total air mass into the cylinder [g]
m_{EGR_int}	EGR mass into the cylinder [g]
$\dot{m}_{fresh\_exh}$	incoming fresh air mass flow in exhaust manifold [g/s]
k_{fresh_exh}	fraction of the total fresh air mass flow in exhaust manifold [-]
$\dot{m}_{twc}$	air mass flow entering the catalyst [g/s]
m_{fresh_exh}	fresh air mass in exhaust manifold [g]
m_{tot_exh}	total air mass into the exhaust manifold [g]

REFERENCES

E. Alfieri, A. Amstutz, C. H. Onder, and L. Guzzella. Model-based feedback control of the air-to-fuel ratio in diesel engines based on an empirical model. *IEEE International Conference on Control Applications*, 2006.

E. Hendricks. Isothermal vs. adiabatic mean value si engine models. *3rd IFAC Workshop Advances in Automotive Control*, 2001.

E. Hendricks and T. Vesterholm. The analisys of mean value si engine models. *SAE Paper 920682*, 1992.

J. B. Heywood. *Internal Combustion Engine Fundamentals*. McGraw-Hill International Editions-Automotive Technology Series, 1988.

U. Kiencke L. Nielsen. *Automotive Control Systems*. Springer, 2000.

A. Palma, A. Palladino, G. Fiengo, F. De Cristofaro, F. Garofalo, and L. Glielmo. A modeling approach for engine dynamics based on electrical analogy. *IFAC World Conference*, 2008.

R.C. Reid, J.M. Prausnitz, and B.E. Poling. *The properties of gases and liquids*. Mc Graw Hill int, 1987.

R. Scattolini, A. Miotti, G. Lorini, P. Bolzern, P. Colaneri, and N.Schiavoni. Modeling, simulation and control of an automotive gasoline engine. *IEEE International Conference on Control Applications*, 2006.

D. D. Torkzadeh, W. Lhgst, and U. Kiencke. Engine modeling and exhaust gas estimation for di-diesel engines. *American Control Conference*, 2001.

K. Wark. *Advanced thermodynamics for engineers*. Mc Graw Hill int, 1995.