URBAN AIR QUALITY: IMPACT OF POLLUTANTS FROM TRANSPORT

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Abstract - Population growth and industrialization have led to increased fossil fuel consumption and environmental pollution. The influence of the energy conversion processes on urban quality air has received an increasing interest in the recent years at various levels, due to the growing awareness of the effects of climate change on human living. Exhaust emissions standards from internal combustion engines are moving automotive industries towards low emission and high efficiency engines. This paper aims to assess some possible techniques and outcomes to prevent emission pollutants.

Keywords - Pollution; Energy conversion; Urban Quality; Engines; Emission reduction

I. INTRODUCTION

Road transport is known to be one of major source of atmospheric pollution [1,2] The on-road release of pollutants, indeed, has experienced a decisive change during the last decades due to the evolving vehicle technologies and the change in the circulating fleet composition [3]. According to the Environmental Protection Agency (EPA), the majority of the carbon and oil savings from current vehicles is due to new petrol technologies [4, 5]. Recently, there have been many measures targeting air pollution in the last 10 years, including among others changes in fuels and vehicle regulation, and there have been significant improvements in European air quality. However, non-compliance with the Ambient Air Quality Directive persists in several areas, in terms of specific ambient air quality limit values being breached either occasionally or more frequently in many cities.

In particular, for two key pollutants, particulate matter (PM) and nitrogen oxides (NOX), road transport have been targeted for emission reductions. Therefore it is of utmost importance to better understand the real contribution of road transport, in order to assess the possible outcomes from measures under consideration.

In this worldwide scenario, the optimization of performance and the reduction of pollutant emissions of internal combustion engines, in both spark ignition (SI) or compression ignition (CI) engine, have become important priorities as a consequence of the spreading concern about the availability of the fossil fuel reserves and the more and more stringent regulations on vehicle emissions at homologation. The SI engines show a strong contribution to the problem of the air pollution, since this type of engine is widely employed as propulsion system for vehicles within the transport sector [6]. Between these, gasoline direct injection (GDI) has proven particularly relevant, as demonstrated by the increase of its share by more than a factor of 5 (from 8% in 2010 to 46% in 2015). The projections for the automotive market in Europe, Japan and North America foresee an average growth of the GDI engine penetration that will triple between 2010 and 2020 [7].

Regarding the market of alternative technologies remains marginal, as the plug-in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV) fleet accounted for 0.42% of the total in 2013. On the other hand, Hybrid electric vehicles (HEV) represented 1.4% of that year [8].

While some zero-emission technologies are under investigation and development, internal combustion engines will continue being the most diffused powertrains for vehicles in the next future.

The worldwide growing of the total number of vehicles, needed to meet the increased demand of transportation, has led to a consequently increase in the global fuel consumption and carbon dioxide (CO2) emissions. Fig. 1 shows as example the world car production trend over 30 years: it is evident that more than 56 millions of cars have been produced till the 2014 [9]. The sharp decrease in 2009 coincides with the recession.

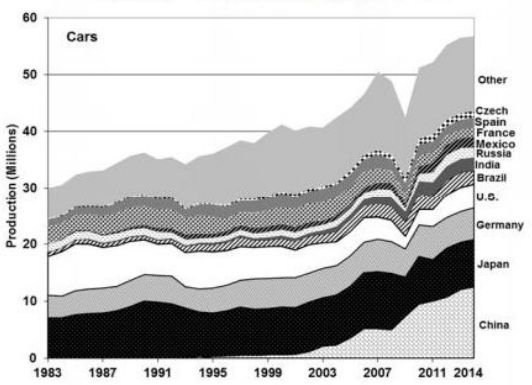


Fig. 1 – World production of cars as function of years and countries [9]

In the next years, the people of emerging countries (such as India, China, South Corea, etc.) will contribute to the worsening of the global fuel consumption through the increased sales of cars. In

Fig. 2 are reported the average numbers of vehicles per 1000 people in various regions of the world. The data show that the presence of vehicle is high for rich countries like USA, Canada, Western Europe while vehicle owernship is low in developing countries (as Africa and Indonesia).
It is evident to underline that the developing countries are characterized by a continuous growing population; thus the number of cars will increase even more than expected prevision. This involves additional problems for the reduction of the global fuel consumption and emissions.

	Vehicles per 1,000 people	
Country/Region	2004	2014
Africa	23.1	35.1
Asia, Far East	46.6	90.4
Asia, Middle East	90.7	134.8
Brazil	119.7	206.0
Canada	580.8	655.9
Central & South America	115.1	186.5
China	21.4	104.9
Europe, East	222.5	346.8
Europe, West	569.5	590.9
India	10.7	30.8
Indonesia	28.8	82.3
Pacific	530.6	584.2
United States	829.9	816.4

Fig. 2 Number of vehicles per 1000 inhabitants in selected Countries/Regions (Years 2003 and 2014)[9]

As regard the pollutant emissions, recent studies [10] demonstrate that the transportation sector (including the movement of people and goods by cars, trucks, trains, ships, airplanes and other vehicles) is one of the major causes for the emission of the greenhouse gas as shown in Figure 3. Most of greenhouse gas emissions from transport sector are CO2 productions, resulting from the combustion of petroleum-based products, as gasoline in internal combustion engines. The most important sources of transportation-related greenhouse gas emissions include passenger cars and light-duty trucks, such as sport utility cars, pickup trucks and minivans. In particular, for SI internal combustion engines, carbon dioxide emission is strongly linked to the fuel economy and to engine efficiency. With the aim to reduce global CO2 emission, the European Commission has developed an ambitious mandatory CO2 emission reduction program, with a fleet-average CO2 emission target of 95 g of CO2/km to be reached from 2021[11].

As known, internal combustion engines are largely adopted for passenger cars and they are responsible not only for CO2 emissions but also for the production of other pollutants species[12]. In terms of the impact on air quality, vehicle technologies are often assessed by means of their emission of regulated pollutants, for example, for carbon monoxide (CO), non-methane hydrocarbons (NMHC), NOx, particulate matter (PM10) and currently also the particle number (PN, momentarily only for diesel and direct injection engine cars). The reductions according to the Euro emission standards are shown in Fig. 4, expressed in g/Km, for diesel cars and Fig. 5 for gasoline cars. These emission factors (EF) are obtained over the New European Driving Cycle (NEDC) and are not always obtained in real traffic conditions.

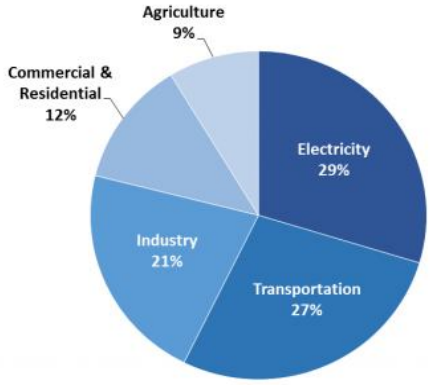


Fig. 3: Sources of greenhouse gas emissions for sector in 2015.[10].

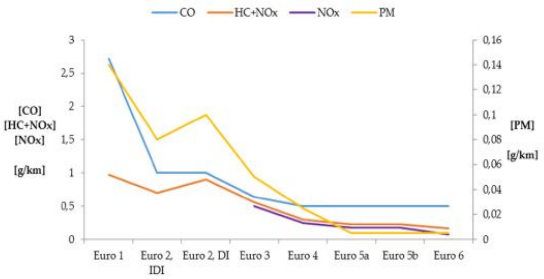


Fig. 4. The Euro emission standards for the regulated diesel car pollutants (based on [13]).

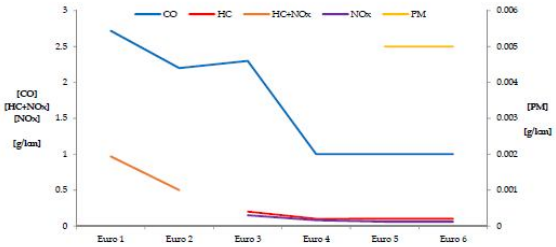


Fig. 5. The Euro emission standards for the regulated for spark ignition engine pollutants (based on [13]).

The strong influence of the automotive industry on the decision making process of the European Commission can explain the European success story for diesel technology over the last decades. Thus, technical measures in favour for diesel engine caused a “dieselization phenomenon” since the end 1990s, as diesel fuel prices have been systematically kept low compared to petrol fuel. Stringent limits for pollutants such as NOx were in force for diesels, allowing them to emit up to three times more than spark ignition gasoline vehicles [14]. NOx and PM emissions have historically been the problems for diesels. Concerning NOx, significant difficulties persist to date, as highly sophisticated and expensive technologies are required to reduce this pollutant to acceptable levels at the end of the exhaust pipe. As regard PM, the introduction of

highly efficient diesel particulate filters (DPF) brought down exhaust PM levels to fractions of the engine-out levels. DPF efficiencies up to 99% for both PM and PN are nowadays achieved, resulting in compliance with type-approval limits.

II. PARTICULATE MATTER EMISSIONS

Between harmful species, PM has a deep negative influence on visibility and on the radiation budget of earth. Ultrafine particles (UPS) with dimensions less than 100 nanometres are potentially dangerous due to the possible deposition in the lungs [15, 16], where they penetrate tissues and are absorbed directly into the bloodstream. PM release in the atmosphere is composed by organic chemicals as soot, an unwanted by-product of combustion of carbon-based fuels arising from nucleation of heavy molecules (precursors), primary organic aerosol (POA), as well as secondary organic aerosol (SOA) and nitrate aerosol via secondary modifications of some gaseous species.

2.1. The limit of GDI engines on particulate matter emissions

A today worrying source of PM is the gasoline direct injection (GDI) engine. As said, the diffusion of this kind of propulsion system increased from 8% in 2010 to 46% in 2015, thanks to its greater flexibility and the better control of mixture formation processes in the combustion chamber, that enhances mixture quality and improves combustion. An increase is expected in the future also because of the recent negative feeling of customers with respect to Diesel engines after the recent violations of emission standards by some cars manufactures [17]. The EURO 6 emission regulations on pollutants at the exhaust of light duty vehicles establish a limit on PM emissions for direct injection spark ignition DISI engines, as reported in Table 3.1 [18]. Until September 2017, the EURO 6b has provided the maximum of 6E12 particulate number/km for the NEDC testing cycle. The final EURO 6c limit, valid starting from September 2017, further lowers this limit to 6E11. The achievement of the limit on PM represents a great challenge for GDI engines manufacturers, which necessarily puts into light the need to strictly control the in-cylinder processes leading to formation of soot. Detailed information about the turbulent reacting flow and the kinetics leading to nucleation of solid particles, and their successive oxidation, can only be achieved by a synergic use of experimental testing and numerical techniques.

Engine Type	Stage	Date	PM[mg/Km]	PM[#/Km]
DIESEL	**Euro 5a**	Sep-09	5	N/A
	Euro 5b	Sep-11	5	6.00E+11
	Euro 6	Sep-14	5	6.00E+11
GASOLINE	**Euro 5**	Sep-09	5	N/A
	Euro 6b	Until Sep-17	5	6.00E+12
	Euro 6c	From Sep-17	5	6.00E+11

Table 1: EU limits on PM emission from light duty vehicles [18].

The control of the mixture formation process in the combustion chamber, hence of fuel injection in direct injection engines, is recognized as certainly detrimental for a stable, clean and complete combustion [19, 20]. The characterization of the dynamics of fuel sprays in their interaction with the surroundings has to be pursued by also considering the possible interaction with solid surfaces, especially if mixture formation strongly relies on vectoring of the vapor and droplet cloud by the piston head, as in the so called “wall-guided” GDI combustion chamber configuration [21, 22]. The analysis of parameters affecting the structure and the spatio-temporal evolution of the spray is to be considered. Correctly dealing with fuel droplets atomization and evaporation is indeed the key factor for predicting the behavior of reacting heterogeneous mixtures, hence to gain reliable information about both power generation and main pollutants formation in internal combustion engines. Soot emissions remains today a great limitation of GDI engines.

It is now generally recognized that the deposition of gasoline wallfilms on the combustion chamber walls determines local mixture enrichments and possible pool-flames, a significant source of HC and PM in GDI engines [23-26]. Particularly, the wall surface temperature and the temperature drop due to the subtraction of the latent heat of vaporization from that surface, needed for gasoline evaporation, are identified as key factors affecting the whole engine behavior [27,28]. Analyzing the number of impacting droplets, their trajectory and the evaporated gasoline mass after impact is a challenging task, whose analysis needs an use of advanced experimental and numerical techniques [29, 30].

RESULTS

To better understand which are the technical aspects and the physical phenomena involved in the pollutant emissions processes are shown, as example, the results obtained from a synergical experimental and numerical research developed for a GDI engine, in the laboratories of National Research Centre (CNR) of Napoli. Details about the experimental set-up and the numerical model are deeply developed and

described in a previous work [20, 31]. The use of Computational Fluid Dynamics (CFD) helps highlighting the chain of events that goes from the spray injection and interaction with the surrounding air flow, up to the combustion phase and pollutants formation characterization [32]. Numerical simulations are realized under the same operating conditions as for the experimental cases, by varying the piston head temperature. The goal of the numerical analysis is to both accurately validate the numerical model, in the view of its future inclusion in a complete 3D CFD engine simulation tool, and to derive more detailed information about the studied phenomenon. In particular, the numerical model can give information about the wallfilm accumulation and evaporation that cannot be obtained experimentally. The quantification of the wallfilm gasoline mass, as related to the piston temperature and to the local cooling of its surface by the impacting spray, is also a fundamental aspect for the future investigation about the occurrence of pool-flames and the evaluation of HC and soot amount forming close to the piston head, due to the presence of rich fuel zones under real engine operation. By means of specific numerical approach of the AVL FIRE software,, called “Thin Wall” temperature boundary conditions for the calculations are updated in time on the basis of the calculation of the heat transfer exchange between the spray and the hot piston surface and between this last and the interior by conduction.

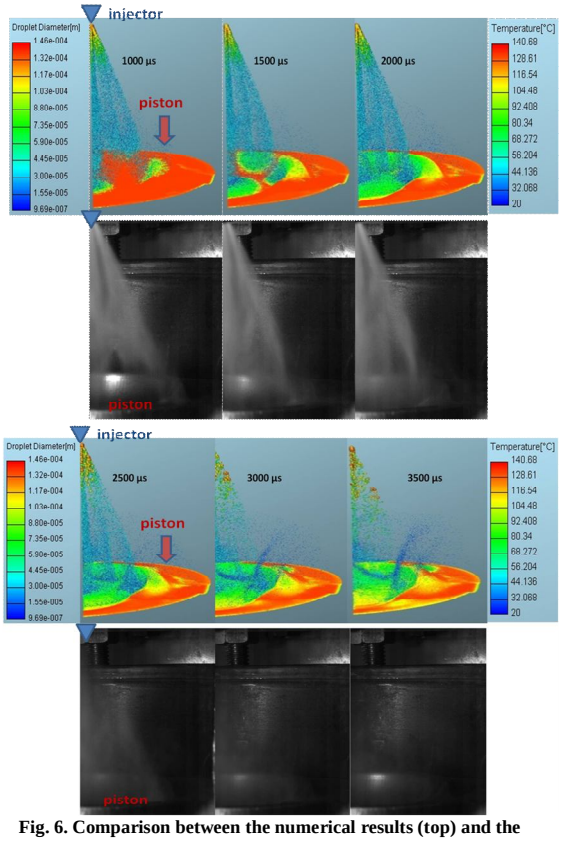


Fig. 6. Comparison between the numerical results (top) and the experimentally collected images (bottom) during impact for different instants after start of injection (SOI) at 100 bar of injection pressure, duration of injection (DOI)=2220 µs and wall piston temperature of 134°C

In Fig. 6 is shown the comparison between experimental and numerical image obtained. The numerical images clearly show the droplet evolution after impact and the path the reflected droplets have due to the shape of the specific piston tip, with accumulation in some zones, where wallfilm is most likely to form.

The numerical results support the experimental investigation on the cooling effect of the piston during the spray-wall interaction and show additional details regarding the diameter of spray droplets and their path. Also the temperature value evolution of the piston is monitored in the time. Images obtained by means of the 3D CFD investigation for the wallfilm formation and for the equivalence ratio distribution close to the piston surface underline the key role of the wall temperature in the mixture formation process and in the wall film deposition that is directly connected to the HC and PM formation in GDI engines. The appropriated numerical methodology of Thin Wall approach allows taking into account the transient heating of the spray and the not homogenous piston cooling process. Fig. 7 shows the wallfilm thickness distribution on the piston surface on the top the Figure for various instants of time after fuel impact. The importance of keeping into account the surface cooling effect by the spray derives from the fact that this leads to an increase of the wallfilm thickness with respect to the case the temperature remains constant, shown in the bottom (“no thin wall” approach case).

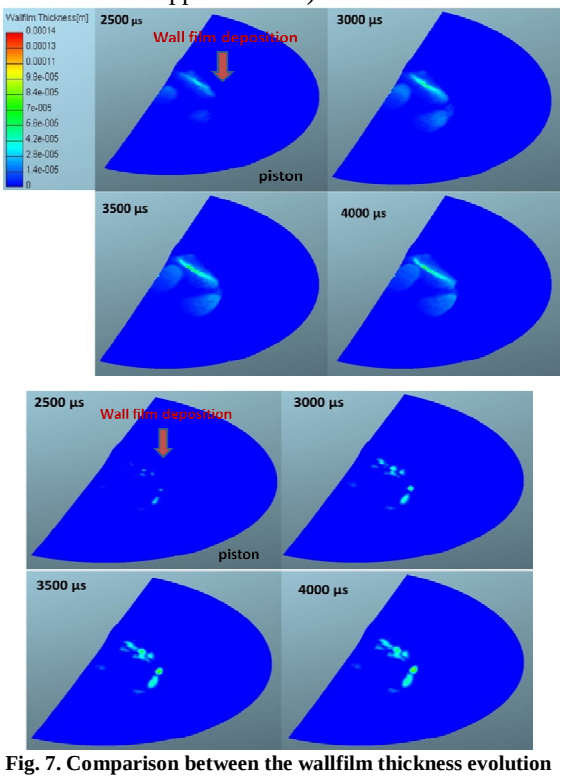


Fig. 7. Comparison between the wallfilm thickness evolution for different times after SOI at 100 bar of injection pressure, DOI=2220 µs and wall piston temperature of 180°C for the case including the numerical so called Thin Wall approach (on the top) and without the Thin Wall approach (on the bottom).

This circumstance is better highlighted in Fig. 8 that shows, for the same cases of Fig. 7, namely for the wall piston temperature of 180°C, the total wallfilm mass deposited during the considered injection event. This is calculated in the case the thin wall approach is not considered and in the case this is activated. The wallfilm mass is higher in this last situation. The prediction of PM emission is in this way more accurate. All the details about the numerical and experimental research developped are in Ref [31].

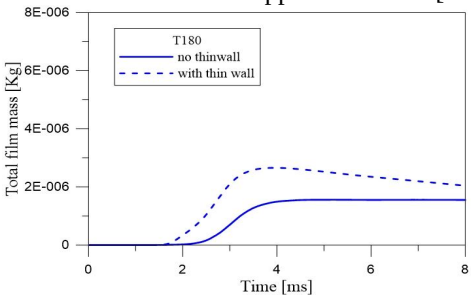


Fig. 8. Wallfilm mass for piston temperature of 180°C obtained with and without the Thin Wall approach.

CONCLUSIONS

Main conclusions are:

- -Policy makers should enforce further stringent regulations in the transportation sector regarding emissions as well as promote the usage of alternative means of passenger transport. Such a change would highlight the benefits, both environmental, economic and social of these alternative means [33] (such as human powered and electric two-wheelers).
- While HEV, PHEV, BEV represent alternative technologies that remain marginal .internal combustion engines will continue being the most diffused powertrains for the transport sector.
- SI engines show a strong contribution to the problem of the air quality pollution, since this type of engine is widely employed as propulsion system for vehicles within the transport sector
- -While in Diesel engine PM emissions are largely reduced thanks to highly efficient diesel particulate filters (DPF), in SI engines the soot emissions represent actually a problem.
- -Numerical and experimental researches can help to better understand which are the technical aspects and the physical phenomena involved in the pollutant formation during the injection phase and in the combustion phase for a SI engine. PM emissions is infact strongly related to the fuel evaporation phenomenon and wall film deposition in the GDI engine.
- A correct validation of the numerical models describing the spray formation after injection phase is therefore fundamental to correctly reproduce the consequent phases of combustion and pollutants formation.

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