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Soot particles experimental characterization during cold start of a micro car engine

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Abstract

Substantial amount of pollutants is emitted during the vehicle start-up, since the engine has not reached its optimal operating temperature.

In urban traffic environment, the engine emissions during its warming up until it reaches a hot stabilized mode are an important source of major air pollutants.

Existing literature indicates that:

- in recent years the vehicle emissions have been reduced significantly, while those related to engine cold starts still remain high;
- emission levels during engine start-up are deeply influenced by the vehicle characteristics.

Most of studies are related to diesel engines equipped with high efficiency DPFs, gasoline port fuel injected and gasoline direct injected engines equipped with three-way-catalysts.

This paper aims at characterizing pollutants and solid particles emissions from a low displacement two cylinder diesel engine, whose main application is in city cars and urban vehicles. During tests, measurements started at the time of the engine cold start-up; transient conditions of load and speed were imposed to the engine. A characterization of solid particle was performed, in terms of particle number and size distribution for three engine thermal conditions: cold, warm and hot starts.

Keywords: Diesel engine, cold start, warm start, particulate matter

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1. Introduction

In urban traffic environment, vehicle cold/ warm start and transient conditions occur very frequently. Substantial amount of pollutants is emitted during these engine operations, since the engine has not reached its optimal hot

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stabilized mode. Particulate emissions along with NOx are an important source of major air pollutants and they have become the focus in diesel engine control technology.

In recent years, the total vehicle emissions have been reduced significantly, while those related to engine cold starts still remain very high and represent key issues in order to satisfy the continuous tightening of worldwide regulations limiting emissions of harmful compounds in the exhaust gas [1, 2, 3]. Since the final result of driving tests is significantly affected by the percentage of emissions during cold phase, research activity is devoted to develop strategies able to eliminate or reduce the harmful compounds in the exhaust gas during these periods.

Literature presents the results of investigations aimed at developing potential strategies able to shorten the cold phase of the engine and at reducing pollutant emissions during engine start-up. [4] presents the results of an experimental analysis carried out in order to understand the behavior and the stability of the combustion process when multiple injection strategies are applied in the idle phase after the cold start of the engine. In [5, 6], an intake heating strategy is presented and its effect on reducing the gaseous and particulate emissions is analyzed.

Research activity has been devoted to investigate the exhaust emission during engine transient operation and during cold and warm start. [7] presents the results of emissions measurements in a turbocharged diesel engine in the first period after its start. [8] compares the emissions from a diesel engine in the initial period following the start-up phase in cold and warm start mode, once cooling water and lube oil have reached a state of equilibrium. [9] and [10] compare solid particle number and size distribution during engine start-up of various light duty engines and highlight the need of control strategies able to reduce particle emissions during engine start-up. [11] investigates the exhaust emission characteristics of a six-cylinder direct injection diesel engine during cold and warm start. [12] presents an investigation of the operating conditions effect on nano-particle emissions from a turbocharged diesel engine. [13] evaluates the impact of cold ambient conditions on cold start and idle emissions of a diesel engine.

Literature highlights that :

- the emission levels during cold engine start-up are higher than those after stable thermal conditions are reached, since fuel atomization, mixture formation and combustion process are penalized and, moreover, facilities used for exhaust treatment and cleaning do not work properly, yet;
- the emissions are deeply influenced by the vehicle characteristics; most of literature is related to diesel engines equipped with high efficiency DPFs, gasoline port fuel injected and gasoline direct injected engines equipped with three-way-catalysts;
- investigations about PM emissions during engine cold start and transients by using advanced instrumentation are limited.

This paper aims at characterizing pollutants and solid particles emissions from a low displacement two-cylinder diesel engine, whose main application is in city cars and urban vehicles. Steady state conditions have been investigated in a previous research activity, in which performance and emissions were analysed in the engine complete operative field [14]. The results here presented are related to dynamic tests: measurements started at the engine idle, then transient conditions of load and speed were imposed. Cold start-up, warm-up and hot period were investigated. The exhaust emissions were analyzed and a characterization of solid particle was performed, in terms of particle number and size distribution by means of Cambustion differential mobility spectrometer.

Nomenclature

D_p	particle diameter
N/cc	concentration of particles per cubic centimeter

2. Experimental system and tests

2.1. Test engine and facilities

Tests were conducted on Lombardini LDW442CRS, a two-cylinder diesel engine equipped with a common rail fuel injection system. Engine specifications are given in Table 1.

The engine was coupled with an asynchronous motor SIEMENS 1PH7. Figure 1 shows the engine test bench.

A software in Labview10 environment was used to manage stationary and transient tests. During transient tests, in order to guarantee the perfect repetition of a specific set of conditions, the input values were managed by a previously compiled data file.

Table 1. LDW442CRS engine specifications.

cylinders	2
displaced volume	440 cc
stroke	60.6 mm
compression ratio	20:1
maximum power	6.5 kW @3600 rpm
maximum torque	21 Nm @2000 rpm
injection system	common rail

NI boards were used to acquire analogical and digital data [15].

The engine was fully instrumented for pressure and temperature measurements (details may found in [16]).

Exhaust emissions (CO, CO_2, HC, O_2, NO_x) were measured by Bosh BEA352.

The particulate emissions were measured by DMS500. Is uses a classifier column to compute the particle size distribution in the range 5nm-1µm, with a size resolution of 16 channels per decade.

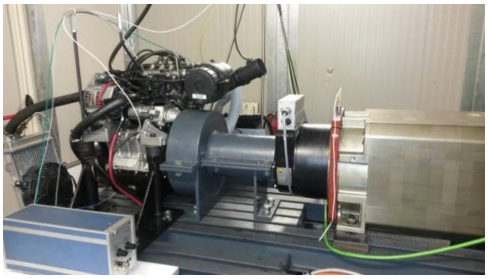

Fig. 1. Engine test bench.

Exhaust gas passes first through a cyclone separator in order to remove particles above the measurement range (1µm). Two stages of dilution are applied before the sample gas passes through a corona charger and into the classifier column. The charged particles flow within a particle-free sheath flow and are deflected towards grounded electrometer rings by their repulsion from a central high voltage rod. Their landing position is a function of their charge and their aerodynamic drag.

The particles yield their charge to the electrometer amplifiers and the resulting currents are translated by the user-interface into particle number and size data.

2.2. Experimental tests

Transient tests were performed and their repeatability was guaranteed by means a programmable dyno: a file was built in which analog signals are used to impose the percentage of fuel and load, respectively to the ECU and the asynchronous motor control system.

9s of transient period was imposed: 5s of steady idling, 1s of rpm and load transient condition (fuel percentage increased from idling to 100%; load condition increased from 2Nm to 18Nm); 3s on steady state condition at the operative point reached by the engine.

Warm-up period was investigated to quantify the effect of temperature on particulate matter during the engine start. Three values were investigated: cold period after engine start (temperature of cooling water and lube oil equal to ambient temperature (25°C); warm start at coolant temperature of 43°C and stable condition after reaching the equilibrium state (coolant temperature at 86°C).

Cambustion differential mobility spectrometer was set in order to have an acquisition frequency of 10 Hz; primary dilution was set to 5:1 and second one was imposed to 400:1.

3. Results and discussion

Figure 2 shows the engine torque and speed variation with time during starting process. Torque value was kept constant at idle for 5s, at minimum position of accelerator. Then, it was quickly increased in 1s to 18 Nm while the accelerator value reached its maximum. Hence forward, engine stable operating conditions were maintained. During the process, engine speed increased from 1100 rpm to 1500 rpm. The ramp was built by reproducing the operating condition acquired during the starting process of a mico-car CVT powertrain.

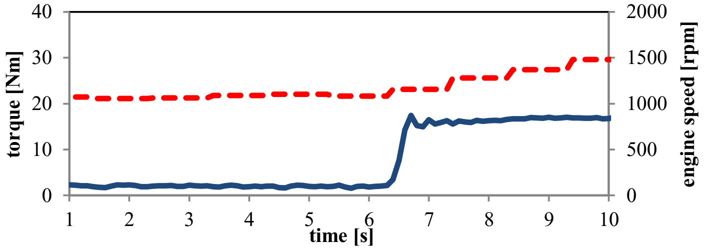

Fig. 2. Engine torque and speed trend during tests.

Figure 3 presents the evolution of coolant and exhaust gas temperature during tests.

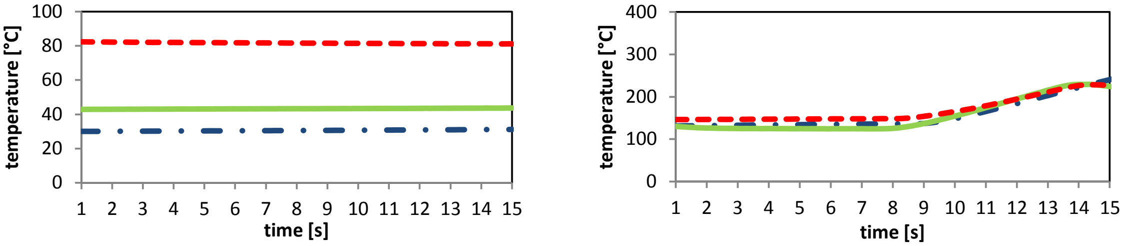

Fig. 3. (a) coolant and (b) exhaust gas temperature: — · · cold start, —— warm start, – – – hot start.

Cold test started at coolant temperature of 25°C; during warm test, it was about 42°C and once the hot stabilized condition was reached, coolant temperature was 86°C.

Exhaust temperature during idle condition was in the range of 120-140°C and once the transient conditions were finished, it was in the range of 200-230°C.

Figure 4 presents the variation with time of the rail pressure and injected fuel mass during tests. The injection strategy of the engine was always a double injection process: during pre-injection phase, a fixed amount of 1mm^3/stroke was injected in all operating conditions; the amount of fuel delivered during the main phase was varied depending on ECU setting.

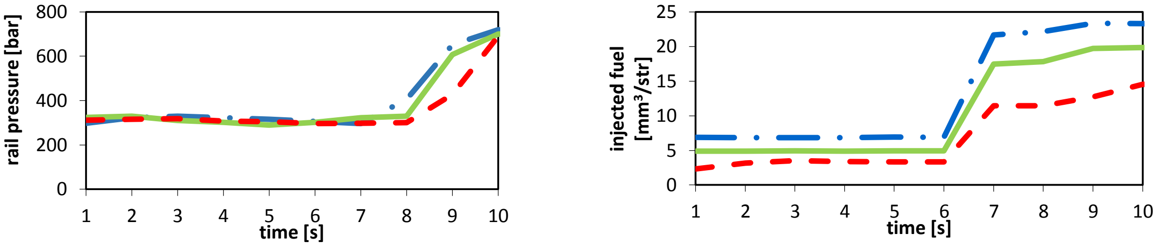

Fig. 4. Left hand side: rail pressure, right hand side: injected fuel; — · · cold start, ——warm start, – – – hot start.

Rail pressure quickly increased during the transient phase of the engine and reached the value of 700 bar when torque value of 18Nm was imposed to the engine. Injected fuel quantity was closely related to the thermal status of the engine: throughout all tests, the idling and maximum value of injected fuel quantity decreased as the coolant temperature rose. During cold test, injected fuel was increased starting from 8mm^3/stroke to 24mm^3/stroke. This value was the maximum in the entire experimental tests and was imposed by ECU in order to facilitate the engine start-up. During warm test, delivered fuel mass changed from 5mm^3/stroke at idle to 20 mm^3/stroke at the end of the ramp. During hot test, fuel quantity changed from 3mm^3/stroke to 14mm^3/stroke, that corresponds to the typical value of this engine once thermal stabilized condition is reached.

Following figures are devoted to characterize the solid particle emission from the engine during the engine warm-up. Figure 5 shows the comparison among the variation with time of the total particle concentration during cold, warm and stable starts. These trends were obtained by integrating the concentration size spectral density over the size range of 5nm-1µm. The traces highlight the effect of the thermal condition of the emission that follows the injected fuel trend and therefore the air/to/fuel ratio changes. The increase of fuel/air ratio during cold start is the dominant factor for the increase of emitted particles. The lower temperature of the exhaust gas is another important factor affecting the increase of particle emission.

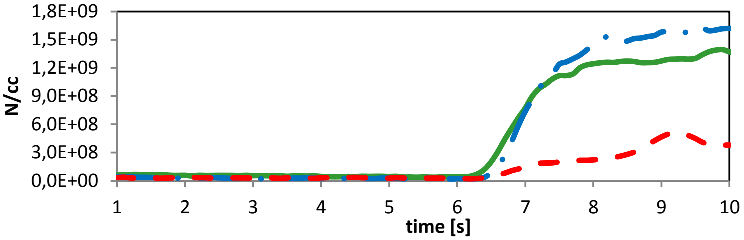

Fig. 5. Total particle concentration: — · · cold start, —— warm start, - - - hot start.

In order to analyze the size distribution of particles, the measured range of diameters (5nm-1µm) was subdivided into three regions: ultrafine (<100nm), 100-300nm and 300nm-1µm particles. Following figures 6, 7 and 8 present their evolution with time.

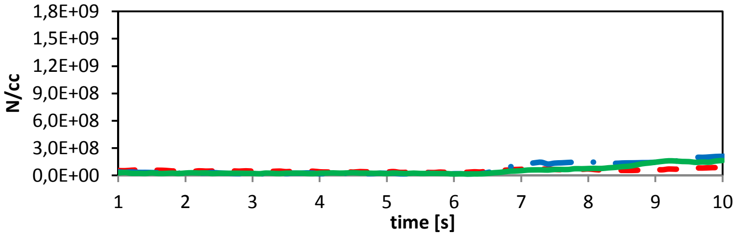

Fig. 6. Total concentration of particles <100nm: — · · cold start, —— warm start, - - - hot start.

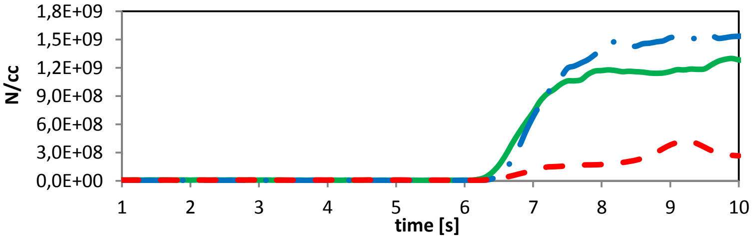

Fig. 7. Total concentration of particles between 100nm and 300nm: — · · cold start, —— warm start, - - - hot start.

The traces highlight that particles sizes between 100nm and 300nm are responsible for most quantity of emitted particles, regardless what the engine thermal condition is.

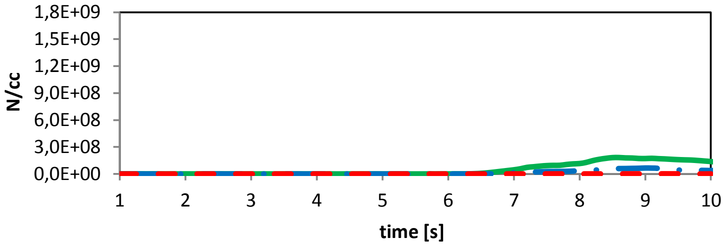

Fig. 8. total concentration of particles between 300nm and 1µm: — · ·cold start, —— warm start, - - - hot start.

Figures 9, 10 and 11 compare the particle size distributions just before the beginning of the acceleration ramp (time equals to 6s). In the plots, values on the abscissa are the aerodynamic diameter; values on the ordinate represent the particle concentration, expressed as a size spectral density in dN/dlogDp.

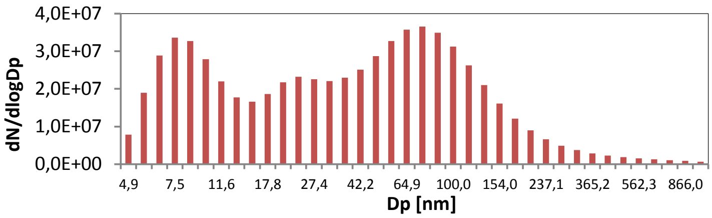

Fig. 9. size spectral density: cold start, t=6 s.

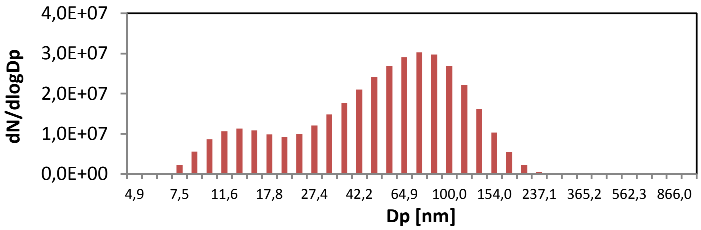

Fig. 10. size spectral density: warm start, t=6 s.

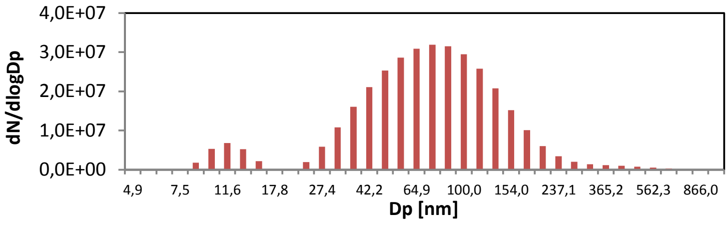

Fig. 11. size spectral density: hot start, t=6 s.

Cold start is characterized by a wide dispersion of sizes: nucleation and accumulation modes are both shown. The two categories are distinguished by the particle diameter: nucleation mode has particle sizes that are typically less than 30nm; accumulation mode has particle sizes larger than 30nm; however, the boundary between the modes is variable [12]. Two peak values are exhibited: 7,5nm for nucleation mode and 75nm for accumulation mode.

As the engine temperature increases, concentration levels of nucleation mode gradually decreases and at hot conditions, most of the particles was found in the accumulation mode. For warm start, the particle size peaks of nucleation and accumulation modes are 13,3nm and 75nm, respectively. For hot start, the particle size peaks for the two categories are 11,6nm and 75nm, respectively.

Figures 12, 13 and 14 compare the size spectral density of the particles emitted once the acceleration event was completed (time equals to 7s). The traces highlight that as soon as the engine heated it up, the quantity of emitted particles is smaller. It is possible to observe that nucleation mode is negligible, most of emitted particles belongs to accumulation mode and is characterized by diameters in the range between 80nm and 420nm for cold start, 75nm and 350nm for warm start and 50nm and 250nm for hot start. With engine conditions getting steady, particles are oxidized and the size of emitted particles is decreased.

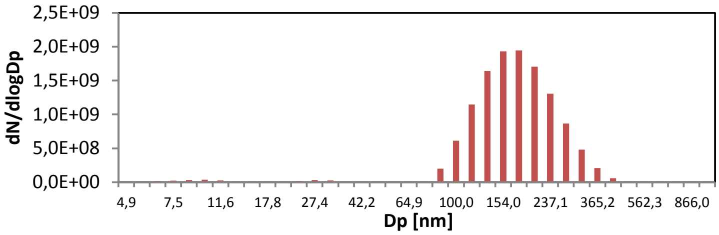

Fig. 12. size spectral density: cold start, t=7 s.

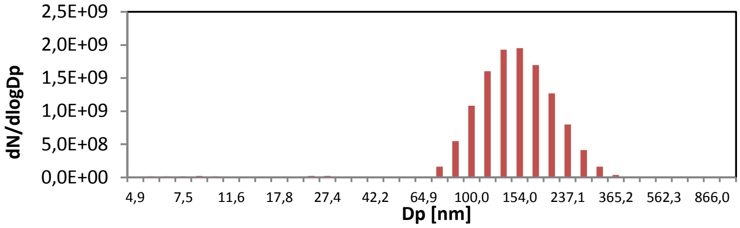

Fig. 13. size spectral density: warm start, t=7 s.

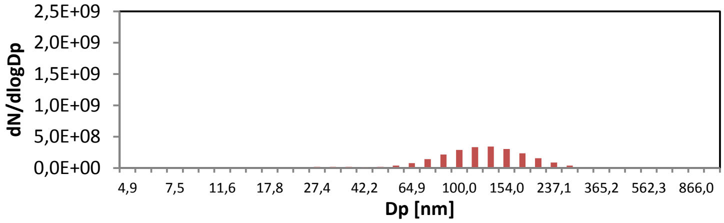

Fig. 14. size spectral density: hot start, t=7 s.

Figure 15 presents the NOx evolution during engine tests. The plot highlights that the emissions rapidly increase and reach a steady state condition closely related to temperature, since it is one of the main parameter affecting NOx formation.

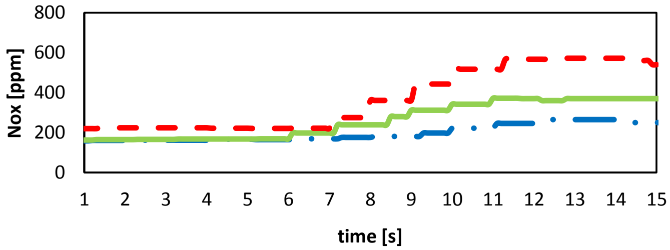

Fig. 15. NOx emission: — · · cold start, —— warm start, - - - hot start.

4. Conclusions

The paper reports the results of an experimental investigation on the particles emission characteristic of a common rail two-cylinder diesel engine under dynamic operating conditions during the engine warm-up period. The main application of this type of engine is in city cars and urban vehicle.

The research activity aims at deeper insight into the emissions related to urban traffic areas, where cold/warm start and transient conditions are responsible for a large amount of harmful compounds.

During the investigation, exhaust emissions were analyzed in terms of particle number and size distribution, since both aspects have great influence on human health. The comparison among the total particle concentrations emitted in cold, warm and hot stabilized conditions showed how average size of the particulate matter is influenced by the thermal condition of the engine. The analysis of the particles diameter distribution highlighted that:

- in all conditions, most of particles belongs to the dimensional range 100nm-300nm;
- during idle condition, nucleation and accumulation modes are exhibited; as soon as the temperature increases, concentration levels of nucleation mode gradually decreases;
- once the stable condition was reached, after the acceleration event was completed, the quantity of emitted particles is reduced and their size is decreased.

The investigation allowed to refine an experimental procedure able to characterize the soot emissions during engine transient conditions; through this procedure, it will be possible to calibrate optimization strategies of exhaust emissions during engine warm-up period.

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