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Steady-state Characterization of Particle Number Emissions from a Heavy-Duty Euro VI Engine Fueled with Compressed Natural Gas

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Abstract

The objective of the present work is to provide an exhaustive characterization of size distributions and number density of the particles emitted from a modern EURO-VI heavy-duty 4-cylinder engine, fueled with compressed natural gas. To achieve this goal, a wide range of operating conditions (for a total of 60 operating points) were investigated during the experimental campaign. Namely, the engine speed was varied from 800 to 3500 rpm and the engine load ranged from 20 to 100% of the full-load condition. Steady-state and stoichiometric conditions were ensured during the tests. The data were collected by using two particle sample devices, located at two distinct sampling points. In particular, samples were simultaneously collected directly from the exhaust pipe, upstream of the Three-Way Catalyst (TWC) and from an exhaust gas dilution system (CVS). In the first case, a fast-response particle size spectrometer (DMS500) was employed, while a condensation particle counter (APC489) was used in the second case. The experimental approach used in the present work allowed the identification of the correlations linking the main engine working parameters with the emitted particle levels of the tested natural gas engine. Furthermore, the use of two sampling devices located in two different positions along the exhaust stream, allowed to highlight the effects that the TWC and the dilution tunnel can produce on particulate emissions. The reported results provide more insight on the particle emission process related to natural gas engines.

Keywords: Compressed Natural Gas Engines, Particle Size Distributions, Particle Number, Soot

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1. Introduction

Engines fueled with Compressed Natural Gas (CNG) are characterized by very low Particulate Mass (PM) emissions, due to the almost homogeneous combustion of the air–gas mixture, the absence of large hydrocarbon chains and aromatics in the fuel [1–4] and the less presence of dissolved impurities, such us Sulphur compounds, than petroleum fuels [5,6]. In reason of that, for a long time, CNG engines have been ignored by the research studies concerning particulate emissions. More generally, a considerable amount of efforts has been focused to measure and characterize particulate emissions from Diesel engines over the past forty years, while Spark-Ignition (SI) engines have attracted attention only in a more recent past. And even more recent is the raised interest for particle emissions related to SI CNG engines [7,8].

This increased attention is closely related to those evidences pointing out that nanoparticle emissions may be very significant in SI engines [9,10], even though the latter are considered to be less harmful for the environment and the human health than Diesel engines with respect to PM emissions. And CNG engines are not an exception. A bunch of studies showed that, although PM formation is small, the number concentrations of particles emitted by CNG engines are not necessarily negligible when compared to those of Diesel engines, especially at high engine load conditions [11–14]. Jayaratne et al. [13] and Hallquist et al. [14] raised a concern about the possibility that Particle Number (PN) emissions from CNG buses might be even one order of magnitude larger than those from Diesel buses with no after-treatment, in spite of a substantially smaller mass concentration. In addition, other findings highlighted that the size of the particles emitted from natural gas engine falls within the ultrafine size range [1,15–17] both in transient and in steady driving conditions, with peaks that can be smaller than 12 nm [18–20].

Despite only comprising a small fraction of the total PM mass, nanoparticles, which have a high number concentration and an enhanced surface-to-volume ratio, result more toxic than larger particles, because they can penetrate deeper into the lungs, causing serious negative health effects [21,22]. For this reason, the new Euro VI emission standards prescribe a limit of $6 \cdot 10^{11}$ particles per kWh, for both Diesel and CNG heavy-duty vehicles.

Graskow et al. [10] showed that the brake-specific particle number in a CNG engine exhibited a roughly exponential increase as the intake manifold pressure was increased. Instead, the particles smaller than 20 nm showed a relative decrease in number, resulting in an increased number-weighted Geometric Mean Diameter (GMD). Ristowski et al. [23] confirmed that the number of particles in the smaller size range was found to decrease as the engine load was increased. An increase by almost an order of magnitude in the total number concentration due to an increase in load, was also confirmed. However, discrepancies start to appear when these results are compared with those reported in more recent works. For instance, Tonegawa et al. [24] showed that the recorded number of particles below 10 nm emitted by a trial production heavy-duty CNG engine was larger at higher loads.

More recently, Kwak et al. [25] investigated the Particle Size Distributions (PSDs) and the PN emitted from buses fueled with conventional Diesel, CNG, Liquefied Petroleum Gas (LPG), and dimethyl ether (DME). For all the buses, the PSDs recorded at idling conditions had larger mode diameters than those recorded at speeds of 50 km/h or 80 km/h. When the vehicle speed was increased, a significant increase in the total PN was detected, regardless of the fuel type, and, in particular, a significant increase in the number concentrations of particles smaller than 50 nm was observed in the CNG and LPG-fueled vehicles. Vijayakumar et al. [26] confirmed that the PSDs significantly vary with engine speed. In such study, the engine speed was varied in the range 1200-2800 rpm and three loads (25%, 50% and 75%) were considered. The GMD varied between 10 and 40 nm, with a maximum diameter observed at medium speed and load conditions. In addition, it decreased as the engine speed was further increased.

The population of natural gas engines in urban applications is rapidly increasing, because natural gas is regarded as one of the most promising alternative fuels [1,6,27], especially if one looks at those under-development technologies for internal combustion engines, comprising both innovative combustion techniques [28,29] and their control strategies [30–33]. Thus, more systematic and dedicate research on these engines is required. Considering the increasing concerns about the limited reserve of crude oil and the atmospheric pollution, the need of reducing the emissions from natural gas engines too will probably become crucial [31,34]. The present work provides an extensive characterization of particle emissions from a modern heavy-duty SI CNG engine, during steady-state operating conditions, in terms of PN and PSDs. A wide range of operating conditions were analyzed throughout the experimental campaign. Namely, 12 different engine speeds (from 800 to 3500 rpm) and 6 engine loads (from 20 to 100%) were considered. Two different sample devices, sampling from two different points, were employed. This allowed establishing correlations between engine parameters and particle emissions, thus providing more insight on particle emission process in modern CNG engines.

2. Experimental method

2.1. Apparatus

The study was conducted on a heavy-duty, Euro VI engine with 4 cylinders and 4 valves per cylinder. It was a production engine with no modifications, chosen for the present study because it represents the latest-generation in heavy-duty CNG engine technology. The main specifications of the engine are reported in Table 1. The engine was turbocharged and equipped with a high-pressure injection system, based on a multipoint sequential phased injection strategy, entirely electronically driven. It was also equipped with a double Three-Way Catalytic (TWC) converter.

Two different instruments were used throughout the experimental campaign: a fast-response Differential Mobility Spectrometer Cambustion DMS500 and a Particle Measurement Programme (PMP) and United Nations Economic Commission for Europe (UN-ECE) Regulation 49 (and 83) compliant Particle Number device APC 489, which includes a Volatile Particle Remover (VPR) and a TSI 3790 Condensation Particle Counter (CPC). The DMS500, which has a built-in dilution system and a heated sample line, was used for sampling directly from the exhaust pipe. It works on the principal of electrical mobility and it was used to measure PN concentrations and PSD functions, from 5 to 1000 nm, at 10Hz. The APC 489 was employed for collecting samples form a full-flow dilution tunnel with Constant Volume Sampling (CVS) system. The samples were conditioned as specified by the PMP [35]. This conditioning involved dilution with air using a variable ratio rotary diluter heated to 150°C. The diluted aerosol then passed through a VPR, which mainly consists in a tube heated to 300°C, with the aim to vaporize volatile material before being cooled by a further dilution with clean air at ratio of 10:1. A TSI 3790 CPC then sampled the cooled dilute sample, with a 50% cut point d_{50} at 23 nm.

2.2. Experimental procedure

In the present work, several experimental measurements were carried out on the above-described heavy-duty CNG engine, with the aim of highlighting any existing correlations between particle emissions and two of the most important engine parameters, such as the engine speed and load. The whole engine operating range was swept, namely, 12 different engine speeds (from 800 to 3500 rpm) and 5 engine loads (from 20 to 100%), were analyzed, resulting in a total of 60 cases examined. A large variety of operating conditions allowed a detailed analysis of the engine behavior in terms of sizes and number density of the emitted particles.

The schematic diagram of the experimental setup is depicted in Figure 1. It shows the complete intake and exhaust systems, as well as the full-flow dilution system, used for conditioning the exhaust gases according to the PMP. In addition, on the same figure, the sampling points chosen along the exhaust line are highlighted by means of green marks. Steady-state exhaust particulate emissions were simultaneously measured directly from the exhaust pipe (upstream of the TWC) by using the DMS500 and from the dilution tunnel by means of the APC489. In the latter case, the measurements followed the procedure established by the PMP, namely, by means of the full-flow dilution tunnel, the exhaust gasses were mixed with clean air, which was at ambient conditions and filtered using a High-Efficiency Particulate Air (HEPA) filter. Temperature and humidity of the primary dilution air were also continuously monitored.

Such configuration, in which the two sampling devices were located in two different positions along the exhaust stream, allowed important considerations about the effects that the TWC, as well as the dilution tunnel could have on PN. Although involved two different sampling principles, this comparison can be considered reliable, on the basis of a comparative analysis performed in a previous study [36]. In such a study the two instruments were used for sampling from the same location and the results showed that the number of particles larger than 50 nm recorded by the DMS500 was in good agreement with the total number of particles detected with the APC489.

Table 1. Main specifications of tested engine.

Displacement	2998 cc
Stroke	104.0 mm
Bore	95.8 mm
Compression ratio	12.5:1
Maximum power	100 kW at [2730 ÷ 3500] rpm
Maximum Torque	350 Nm at [1500 ÷ 2730] rpm

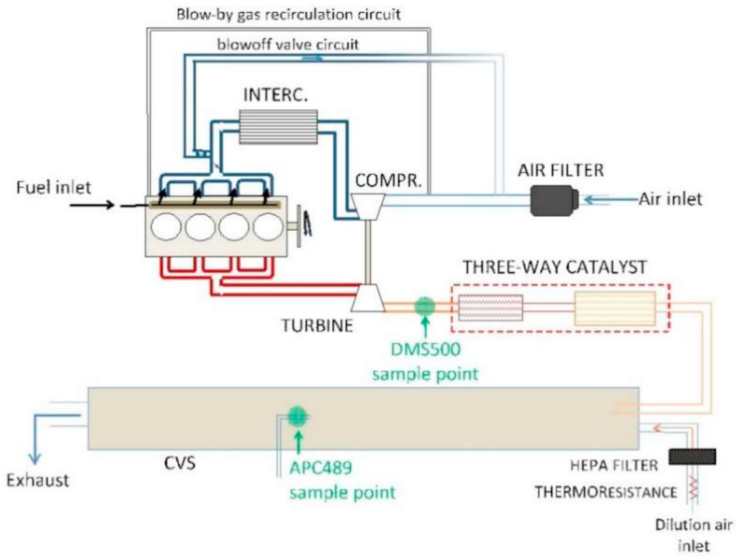

Figure 1. Schematic diagram of the experimental setup in which are highlighted sampling locations and devices.

To ensure proper operation and reliable response of the particulate analyzers, the engine was first warmed up at 1500 rpm and the data were recorded only after the engine conditions were stabilized. The sampling procedure started from the highest engine speed (3500 rpm) and full load. Once the condition was stabilized, data were recorded for about 1.5 minutes. This sampling time represented a reasonable choice for obtaining good statistics and for manage the presence of some spikes in the particle per minute emitted from the engine, even though stationary conditions were ensured during the tests (more details about this aspect are provided in the next sections). Once the measurement was completed, the engine speed was decreased, while the load was kept constant. After another stabilization period, a new sample was collected. All the 12 engine speeds were swept following this procedure. Once the measurement at the lowest speed (800 rpm) was completed, the load was reduced by a 20% and the maximum speed (3500 rpm) was reestablished. The engine speed was then progressively decreased as described before for the new load condition. After having collected data in each of the 60 operating conditions considered, the entire procedure was repeated following the opposite direction, namely starting from the lowest engine speed and load and progressively increasing them.

3. Results and discussion

The results obtained from the entire experimental campaign are summarized in Figure 2. Figure 2 (a) refers to the total PN recorded by means of the DMS500, sampling from the exhaust pipe, upstream of the TWC, whereas the data collected from the CVS by using the APC489 are depicted in Figure 2 (b). The DMS500 data relative to the total PN were also decomposed in nucleation and accumulation mode fractions, as reported in Figure 2 (c). Such decomposition is well known, and it results particularly useful, since it is possible inferring the nature of the particles from their size. Namely, nucleation mode particles (smaller than 50 nm) are formed from condensation of volatile material, whereas accumulation mode particles (larger than 50 nm) are solid predominantly carbon-based products of combustion [36,37].

The results shown in Figure 2 indicate that both engine speed and load influence the number of particles generated by the CNG engine in a non-negligible way. It must be noted that between the lowest and the highest PN value, recorded via DMS500 from raw, there was a difference of more than six orders of magnitude (Figure 2 (a)). An increase in load, as well as in engine speed, corresponded to an increase in the rate of particle emitted by the engine. However, contrary to what might be expected, the emission peak did not correspond to the maximum engine speed and load, but it was recorded for a load comprise between 70 and 80% and for an engine speed between 65 and 80% of the relative maximum values, confirming what recently observed by Vijayakumar et al. [26]. This finding suggests that there might be a combination of in-cylinder temperature and engine regime that promotes soot formation more than others and which does not necessary match the full-load condition.

Generally, higher temperatures in the combustion chamber favor soot precursor formation in the early stages of the combustion process. When the engine speed is high, there might not be sufficient time for its oxidation. A further increase in engine speed might reduce the time for soot generation as well. Lower speeds and high temperatures represent favorable conditions for a more effective oxidation [1,36]. All these considerations can explain why the highest PN values were characterized by a predominance of accumulation mode particles. Namely, a large number of large particles (50÷100 nm) were emitted in the above-mentioned ranges of engine speeds and loads, as it is also possible to infer from the granulometric distributions reported in Figure 3. A larger variability in the characteristics of the emitted particles at 80% of load is observable.

The PN levels recorded by the APC489 sampling from the CVS system were generally lower, as shown in Figure 2 (b). This result is ascribable to both the dilution of the exhaust gases with fresh air and the catalytic stripping effects of the TWC. Although all these aspects contributed to level off the number density, a noticeable variation, attributable especially to a variation in engine speed, is still observable. It is known that the TWC removes volatile hydrocarbon particle precursors, with a removal efficiency depending on engine speed and load [10]. This explains why a comparison between Figure 2 (a) and (b), points out a stronger reduction in PN at low speeds, suggesting that TWC can play a crucial role in determining the final size distribution of the emitted particles.

The influence that the dilution system and the TWC had on the measured particle emissions is better highlighted in Figure 4, in which it is possible to compare the trends recorded for the accumulation mode fraction of the DMS500 samples with those of the APC489. At low load the particles measured upstream the TWC were mainly comprised in the nucleation mode distribution. The total levels recorded along the exhaust pipe and within the dilution tunnel were comparable each other, indicating a limited abatement action, especially at high engine speeds. Contrariwise, at high load, although the accumulation mode became predominant, the number of particle measured by APC489 was drastically lower, indicating an enhanced abatement effect, primarily due to the TWC.

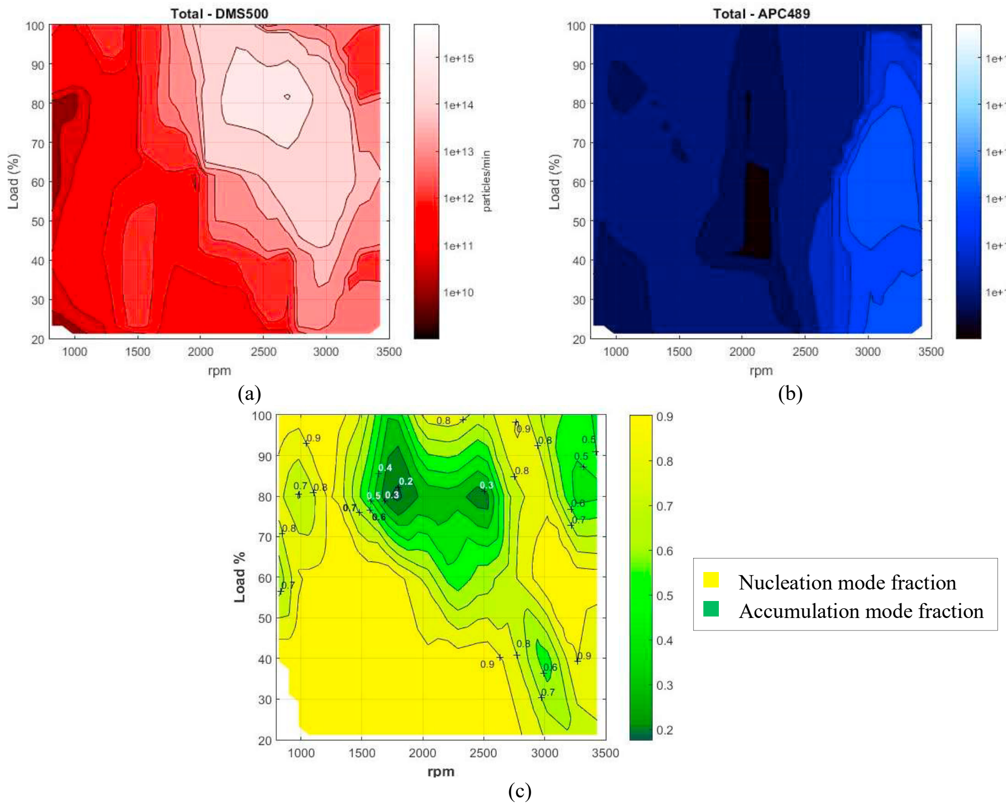

Figure 2 PN [particles/min] variation with engine speed and load, recorded by DMS500 upstream of the TWC (a) and by APC489 from the dilution tunnel (b). Nucleation and accumulation decomposition (fractions of the total emitted particles) of the DMS500 data (c).

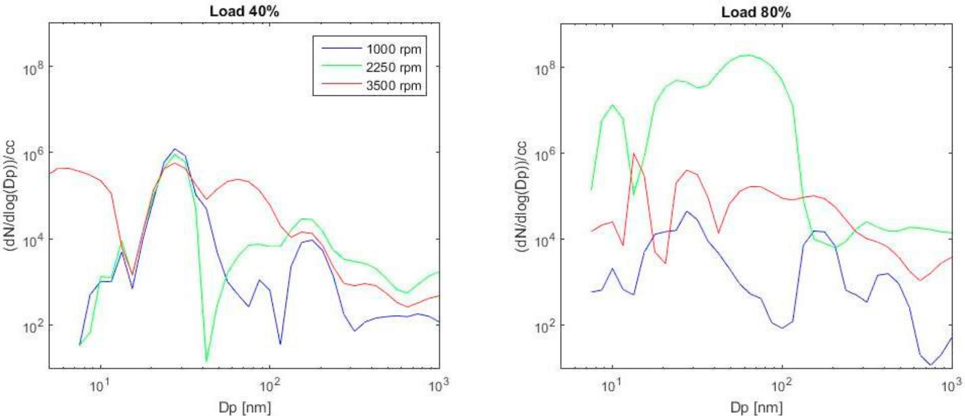

Figure 3 Particle Size Distribution functions recorded by DMS500 upstream the TWC for mid- and high-loads and for three engine speeds, representative of low, medium and high regimes.

An interesting result that emerged from the experiments is that particle emissions were periodically unstable even though steady-state engine operating conditions were ensured during the tests. Figure 5 shows typical time-resolved particle concentration profiles recorded with the DMS500 upstream of the TWC, for two different operating conditions. The stationary emission was occasionally perturbated by sudden increases in the emitted particles. These emission spikes were observed at every engine operating condition, but their magnitude and frequency varied depending on the cases. In addition, it was observed that these spikes were almost completely composed of nucleation mode particles. Such particle spikes have been already observed in the literature in the case of gasoline SI engines. They can be most likely associated with an occasional break-up of intake valve and combustion chamber deposits [10], as well as with lubricant oil contaminations [8,15,36].

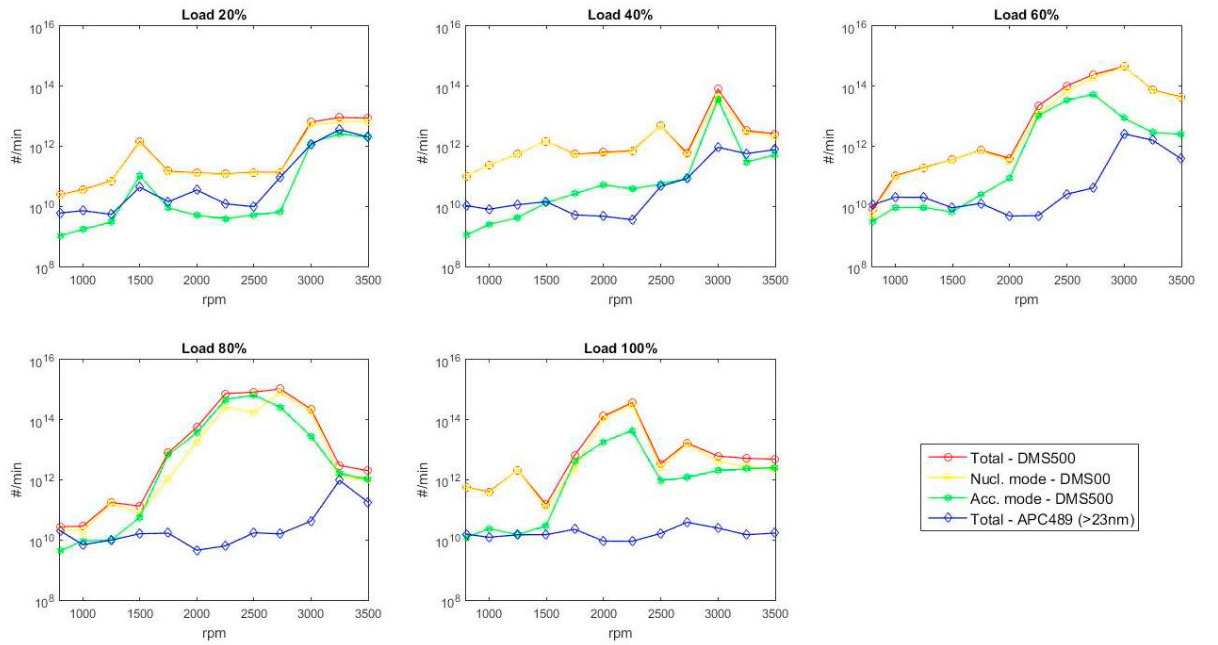

Figure 4 PN [particles/min] variation with engine speed for each of the considered loads. Comparisons between measurements by DMS500 upstream of the TWC (red, yellow and green lines) and by APC489 from the dilution tunnel (blue lines). Decomposition of the total number of particles recorded by DMS500 (red lines) in nucleation (yellow lines) and accumulation (green lines) modes (c).

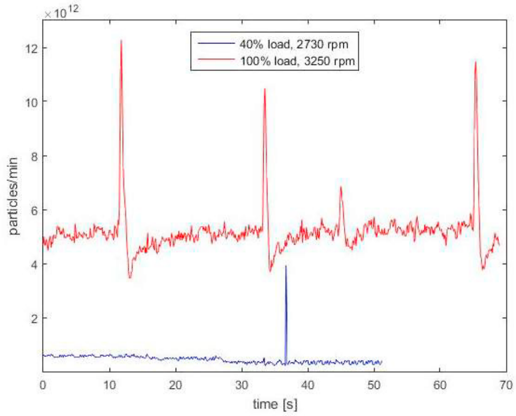

Figure 5 Time-resolved particle concentration profiles recorded via DMS500 upstream of the TWC, for two different operating conditions and representative of the random perturbations of the stationary emission levels.

4. Conclusions

The present work provided an extensive characterization of particle emissions of a modern (EURO-VI-compliant) heavy-duty stoichiometric natural gas engine, during steady-state operating conditions. Particle Size Distributions and Particle Number emissions were collected by using two different sample devices and two distinct sampling points. A wide range of operating conditions were analyzed, namely the engine speeds was varied from 800 to 3500 rpm and the engine load was varied from 20 to 100%, for a total of 60 operating points.

Samples were simultaneously collected directly from the exhaust pipe (upstream of the TWC) by a fast-response particle size spectrometer (DMS500) and from an exhaust gas dilution system (CVS) by a condensation particle counter (APC489). The experiments aimed at ascertaining the existing relations between engine speed and load with particle emissions. Moreover, the use of two sampling devices, located in two different positions along the exhaust stream, allowed to highlight the influence of the TWC and the dilution system on particulate emissions.

The results pointed out that both engine speed and load have a non-negligible influence on the number of particles generated by the CNG engine. High load and speed corresponded to high particle emission levels, but the peak did not correspond to the maximum engine speed and load. It was instead recorded for a load comprise between 70 and 80% and for an engine speed between 65 and 80% of the relative maximum values. In this operating range a large number of particles with size between 50 and 100 nm was emitted.

The PN levels recorded by the APC489 sampling from the CVS system were generally lower due to the effects of the dilution system and the TWC. At low loads, a limited abatement action ascribable to the TWC was observed, especially at high engine speeds. Contrariwise, at high loads, the reduction effect was strongly enhanced, highlighting that TWC can play a crucial role in determining the final size distribution of the emitted particles.

An interesting result was that the stationary emission was occasionally perturbated by the presence of some emission spikes, which were observed at every engine operating condition, but their magnitude and frequency varied depending on the cases. It was observed that these particle spikes were almost completely composed of nucleation mode particles and were associated with the occasional break-up of intake valve and combustion chamber deposits and with lubricant oil contaminations.

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