Methodology for measuring exhaust aerosol size distributions using an engine test under transient operating conditions

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ABSTRACT

A study on the sources of variability in the measurement of particle size distribution using a two-stage dilution system and an engine exhaust particle sizer was conducted to obtain a comprehensive and repeatable methodology that can be used to measure the particle size distribution of aerosols emitted by a light-duty diesel engine under transient operating conditions. The paper includes three experimental phases: an experimental validation of the measurement method; an evaluation of the influence of sampling factors, such as dilution system pre-conditioning and dilution air particle influence; and a study of the effects of the dilution conditions, such as the dilution ratio and the dilution air temperature. An examination of the type and degree of influence of each studied factor is presented, recommendations for reducing variability are given and critical parameter values are identified to develop a highly reliable measurement methodology that could be applied to further studies on the effect of engine operating parameters on exhaust particle size distributions.

1.   *INTRODUCTION*

The main source of air pollution in urban areas is particulate matter (PM) from vehicles, factories, incinerators, etc. More specifically, combustion particles found in diesel emissions have been of great concern in the past few years, because of their adverse effects on health and their prominence near roads, especially in urban areas [1-7]. This is why the European Union is set to implement a new PM mass emission measurement method in the EURO 5/6 legislation developed by the UN/EC Particulate Measurement Programme (PMP) which adjusts PM mass emission limits to account for differences in results using the old and new methods. The Euro 5/6 legislation also introduces a particle number (PN) emission limit in addition to the mass-based limits. According to the PMP recommendations, particle number systems must sample from a constant volume sampler (CVS). The number measurement system has to comprise a sample pre-conditioning unit (or volatile particle remover) upstream of a particle number concentration counter. A particle size pre-classifier (e.g., cyclone, impactor, etc.) prior to the inlet of the sample pre-conditioning unit is recommended.

Comparisons of numerous particle number counters with aerosols from particle generators have been conducted and reported by various authors [8-10]. In general terms, authors have been in agreement although differences in concentrations or response times have been found depending on the precise model of the particle number counter. The evaluation of the sample pre-conditioning unit is slightly more complex due to the uncertainties of the dilution calibration. Many researchers have evaluated various dilution systems such as ejectors [11, 12], rotating disks [13], and perforated tube diluters [14] to quantify the dilution ratio and the particle losses. Complete measurement system

comparisons (diluter + particle number concentration) have also been conducted [15, 16] with sampling conditions and losses being mainly responsible for the differences observed between nominal and measurement results.

It should be emphasized that none of these studies have used a measurement protocol which characterizes particle size distributions. In this study, a Dekati® Fine Particle Sampler FPS-4000 diluter system was coupled to a TSI® Engine Exhaust Particle Sizer (EEPS) in order to measure the variations in particle size distributions against the changes in dilution conditions under transient test conditions in a light-duty diesel engine.

Thus, the purpose of this paper is twofold. Firstly, it aims to present a comprehensive study of how different sampling and measurement factors affect the particle size measurements of exhaust aerosols emitted by a light-duty diesel engine under transient conditions and secondly, it aims to analyze the type and degree of influence of each studied factor in order to identify the critical values of the studied parameters and reduce variability in the measurement procedure. As a result, a highly reliable comprehensive measurement methodology is proposed which could be applied, in the experimental conditions and configuration of this analysis, to further studies on the effect of engine operating parameters on particle size.

2.   *ENGINE AND GENERAL INSTRUMENTATION*

The engine used in this study was a 2.2-liter, 4-cylinder, high-speed direct injection (HSDI) engine for passenger car applications which complied with EURO 5 legislation. The engine was equipped with high-pressure fuel injection using a common-rail injection system, intercooler and exhaust gas recirculation system (EGR). Further detailed specifications of the engine are given in Table 1. The engine was installed in a fully equipped test cell with all the ancillary devices required for proper engine operation and control. This test cell was designed using the criteria detailed by Martyr and Plint

[17].

Table 1

Ultra low sulfur diesel (ULSD) fuel was used in all the experiments. Fuel properties are provided in Table 2.

Table 2

In order to perform transient cycles, the test cell was equipped with an asynchronous dynamometer manufactured by HORIBA ATS® that enabled us to control online engine torque and speed, and program different types of cycles as a time sequence for gears and vehicle speed taking into account the vehicle features and current driver skills. The engine was fully equipped with type K thermocouples and mean pressure sensors suitably located in the intake, exhaust and cooling system zones.

Fuel consumption was determined by two systems. The first consisted of a fuel gravimetric system with an AVL® 733S Dynamic Fuel Meter. Fuel consumption values were obtained by calculating the vessel's weight loss over time to an accuracy of 0.12% at 75g in accordance with DIN-1319. Since the response time of this system was possibly too long for this study, the fuel consumption signal provided by the ECU was calibrated in a steady state. After calibration, the ECU was used as a second fuel consumption measuring system. The Sensyflow P Sensycon hot-plate anemometer system was used to measure the flow rate of the intake air mass. The measurement range of the anemometer was 0-720 kg·h^{-1}, i.e. accurate to within 2% of the measured value.

A data acquisition system was used to register the data from the engine control system, at a frequency over 100 Hz.

3.   EXPERIMENTAL SET-UP

The dilution system used in this study was a Dekati® Fine Particle Sampler FPS-4000. This system diluted the sample in two stages. A porous tube (PTD) was used as the primary diluter, and a subsequent ejector diluter (ED) was used as the secondary diluter.

In the porous tube diluter, the sample was drawn through a 3.5 mm perforated tube, while the dilution air was introduced from outside through the perforated tube wall via laser-drilled orifices and mixed with the sample. The nominal internal diameter of the orifices was 150 μm, while microscopic studies showed diameters ranging between 130 and 160 μm. The dilution zone consisted of 50 rings of 10 orifices that were evenly spaced around the circumference. According to the manufacturer, the dilution air temperature range is from 0 to 350 ℃. The dilution zone (length 89 mm) was surrounded by a jacket that could be heated or cooled. The dilution air flow was controlled using calibrated critical orifices in which the flow was directly proportional to the pressurized air pressure. The second stage consisted of an ejector diluter, in which a controlled amount of secondary dilution air was conducted to a cavity outside the ejector nozzle. The nozzle was designed to produce high velocity flow and low pressure. Consequently, the pressure drop in the ejector nozzle removed the primary dilution flow to generate self-suction. The dilution air at this stage was controlled by critical orifices, as in the first stage. The ejector dilution ratio was determined using the model developed by Barouch et al., [11].

Nevertheless, due to the limitations in the dilution ratio calculation, the carbon dioxide concentrations (CO_2) were measured in the raw, diluted exhaust and ambient air with non-dispersive infrared (NDIR) analyzers (Horiba Ltd® Mexa-7100). Thus, the dilution ratio was verified by the equation (1):

$$DR = \frac{CO_{2\,(Raw)} - CO_{2\,(Ambient)}}{CO_{2\,(Diluted)} - CO_{2\,(Ambient)}} \quad \text{Eq. (1)}$$

A TSI® Engine Exhaust Particle Sizer (EEPS) was used to measure the size distributions. This system uses a corona charger to put a predictable charge level on the particles. The charged particles were introduced near the center of the column. An electric field inside the column repelled the particles outwards, where they were measured using an array of precision electrometers connected to electrodes on the outside wall of the column, described in full detail in the EEPS manual [18]. This system was programmed to scan particles over a size range of 5.6 – 560 nm across 16 channels per decade.

In order to validate the particle size distribution measurements for the EEPS, a TSI® Scanning Particle Sizer (SMPS 3936L72) was connected in parallel under steady state engine conditions. The operating principle of the SMPS is based on the extraction of an original polydisperse aerosol in different monodisperse fractions by separating the particles according to their size based on their electrical mobility inside an electrical field (LDMA 3081). The extracted monodisperse particle fractions were counted in a condensation particle counter which provided the number of particles per air volume unit for each particle size (CPC). In terms of transient operating conditions, a TSI® CPC 3010 was also connected in parallel with the EEPS and the total particle concentration was compared. SMPS and CPC instruments were individually calibrated by the manufacturer prior to testing. A diagram of the experimental set-up is shown in Figure 1. A detailed explanation on the validation of the EEPS is given in section 4.1.

Figure 1

The systems for the diluted sample extraction of particle size measurements were connected downstream of the dilution system. The sample point where the sample probe of the measurement systems was connected is considered to be an influencing factor on particle size measurement since the degree of mixing between dilution air and the exhaust sample at the sampling point determines particle dynamics and, as a result, particle size measurement [19, 20].

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4.   METHODOLOGY

An extensive experimental study was conducted to evaluate the dispersion factors that are considered to have an influence on particle size measurements. The effect of a factor may depend on the characteristics of the exhaust aerosol to be studied, i.e. on the nature, number and size of particles.

Three steady state engine modes were driven in order to generate aerosols with different properties and study whether an unequal effect of the dispersion factors was produced as a result of the difference in the characteristics of the emitted aerosols. The operating conditions used were ($A_{(H)}$) where the particle size distribution was dominated by nucleation. The second operating condition was ($B_{(H)}$) which presented bimodal distribution for the particle size. The third condition was ($C_{(H)}$), and in this case, particle size distribution was dominated by accumulation. The engine operating modes are specified in the Table 3.

Table 3

Two different test cycles were also used. A step change test (SCT) was defined consisting of an engine power change by switching 10% and 100% of the load on the engine at a constant speed of 2500 min^{-1}. The stabilization time of the up step was 10 seconds, while the stabilization time of the down step was 20 seconds (see Figure 2 (a)). A variation of the European Load Response test cycle (ELR) was used to observe the influence of the dilution parameters at different engine speed conditions. The test consisted of a sequence of three load steps at each of the three engine speeds 2000, 2500, 3000 min^{-1} and a load of between 10% and 100%. The sequence of the dynamometer operation on the test engine is shown in Figure 2 (b).

Figure 2

To obtain accurate values for accumulation particle number concentration and geometric mean

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diameters, the size distributions can be described as the combination of two individual distributions by assuming the log-normal size distribution function according to the equation (2) [22]:

$$\frac{dN_i}{d\log dp_i} = \frac{1-x}{\sqrt{2\pi}\log \sigma_{g2}} e^{\left(-\frac{\log^2\left(\frac{dp_1}{dp_{g2}}\right)}{2\log^2 \sigma_{g2}}\right)} + \frac{x}{\sqrt{2\pi}\log \sigma_{g2}} e^{\left(-\frac{\log^2\left(\frac{dp_2}{dp_{g2}}\right)}{2\log^2 \sigma_{g2}}\right)} \qquad \text{Eq. (2)}$$

Where x is the ratio of the total number of concentrations of two distributions and d_{p1}, d_{p2}, σ_{g1} and σ_{g2} are the geometric mean diameters and the geometric standard deviations of each peak, N_i is the particle number concentration of particle size d_{pi}. The fit was achieved by minimizing the mean square error function by means of the Nelder-Mead simplex method.

Diverse studies proposed the limits of the nucleation mode between 50 and 30nm [6, 23]. In this study, the decomposition of particle number size distribution was: nucleation mode particles from 5.6 to 30nm; and accumulation mode particles from 30 to 560nm. To calculate total particle number concentration and geometric mean diameter (GMD) the equations (3) and (4) were used for each mode:

$$dN = \sum_{dplower}^{dpupper} dN_i \; \text{Eq. (3)}$$

$$GMD = e^{\sum_{dplower}^{dpupper} dN_i \ln dp_i / dN} \text{Eq. (4)}$$

Particle number size distributions measured with the EEPS and SMPS under diluted conditions were correctly scaled so that they could be expressed for the raw exhaust gas. In the discussion that follows, the results are described separately for the method validation, sampling and preconditioning and dilution parameters used in the experimental study

4.1 Measurement method validation

4.1.1   Steady state test

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In Figure 3 the particle number size distributions measured in the different steady state conditions with the EEPS were compared to the distributions measured with the SMPS. In order to obtain reliable values, the measurement methodology developed by Desantes et al.[19] was used in this study. The SMPS specifications for the performance of these experiments were: scan-up time: 90 seconds, scan-down time: 30 seconds, and sample flow: 0.8 liters per minute.

Figure 3

As the EEPS gives faster time resolution, the data for the EEPS shown is the average of 4500 size distributions and corresponds to the same time interval as 3 SMPS histograms. The particle size distribution agreed fairly well over most of the size distribution. The coefficients of variations in the particle concentration are shown in Table 4. The maximum difference between the two measurement systems for nucleation mode number concentration was 9.7% in operating mode $A_{(L)}$. It can be seen that the smaller particle sizes measured by the SMPS have a lower concentration possibly due to diffusion losses. The higher sample flow of the EEPS (10 liters per minute) avoided diffusion losses. In the case of the accumulation particle, slight differences in the measured number concentrations were obtained, and the number concentration variations were near to 7% for all operating conditions. The size range covered by the EEPS was wider than the size range covered by the SMPS, so differences in the total particle number concentration were expected, but both systems covered the entire range of interest for vehicle exhaust particles.

Table 4

4.1.2   Transient test

The second step towards validating the measurement method consisted of identifying the patterns during transient operation. A comparison of total number concentration from the EEPS (with a one second average) with the concentration output of the CPC was made. The engine test cycle used

was the step change test (SCT). The spikes in the data corresponded to emission changes that occurred with the changes in load in this test cycle (Figure 4). The one second data updates on the CPC and the one second average on the EEPS data did not necessarily overlap completely, because the response of the CPC was considerably slower than the EEPS.

Figure 4

Figure 4 shows good correlation in the total number concentration of the EEPS and the CPC. In addition to the total number concentration, an evaluation with different monodisperse aerosols was made. To obtain these types of aerosols, fixed voltage in the LDMA 3081 was used in order to separate the particles. The extracted monodisperse particle fractions were then counted in the CPC which provided the number of particles per air volume for each particle size and were compared with the measured number concentration for the same particle size with the EEPS. Figures 4 (b), (c) and (d), show the particle number concentration for monodisperse aerosols with 30, 80 and 100 nm of mobility electrical diameters respectively.

4.2 Sampling and preconditioning

4.2.1   Dilution system activation

As mentioned previously, the EEPS was connected to a dilution system which was used to dilute the sample flow that entered the instrument. When the dilution system was activated, clean air was mixed with the exhaust sample flow and dynamic processes related to aerosol formation such as nucleation, adsorption and condensation took place. Under these conditions it should be determined whether a stabilization time is necessary to achieve a balance and acquire a stable aerosol.

In order to analyze the influence of the dilution air temperature on the stabilization of the aerosol, constant measurement (with a one second average) of the particle size distributions in operating mode $A_{(L)}$ was performed after the activation of the dilution system and once engine stabilization had

been reached. Figures 5 (a) and (b) show the evolution of particle number concentration for two different particle sizes. There was a decrease in particle number concentration for particles of 50 nm with an increase in the dilution air temperature. In the opposite case an increase in particle number concentration was observed for particles of 30 nm. The maximum differences in particle number concentration before the stabilization time of the dilution system (1800 seconds) was 20.40% for 50 nm particles when the dilution air was heated, and +16.07% for 30nm particles when the dilution air was cooled.

Figure 5

This behavior indicates that a higher gas-to-particle conversion of volatiles existed at the start of the mixing process between the cooled/heated dilution air and the exhaust sample. Results indicate that a stabilization time should be taken into account to obtain steady particle size distribution measurements. In this study, a stabilization time of 40 min to activate the dilution system was chosen, as the nucleation and accumulation mode were stable for this amount of time.

4.2.2 Dilution air particle influence

The dilution air used to condition the sample flow may carry particles that produce errors in particle size distribution measurements. In order to study the measurement offset associated with the particles transported by the dilution air, the particle size distribution of the dilution air was measured. In this study, a filtration unit was used to obtain dry and free particle air. The filtration unit consisted of a coarse particle filter, a high efficiency sub-micrometer particle filter and a charcoal filter for hydrocarbons, which helps to reduce particles in the dilution air to almost zero (sub-micrometer filtering efficiency over 99.999% for particles with a diameter of 0.01 μm).

Figure 6

Figure 6 shows the particle size distribution for the dilution air and for mode $B_{(M)}$ with and without subtraction of the dilution air size distribution.

Although the offset introduced by the dilution air was negligible, it must be considered and subtracted from the particle size distribution to obtain more accurate results. The influence of dilution air is less important when a large number of particles are emitted.

4.3 The influence of dilution parameters

As the engine exhaust was diluted, some of the gaseous hydrocarbons underwent a gas-to-particle conversion to form the soluble organic fraction (SOF) of diesel particles by adsorption onto existing particles and/or by nucleation to form new particles. The gas-to-particle processes depend on factors such as the relative concentration of volatiles and carbonaceous soot, temperature, dilution ratio, dilution residence time and humidity.

Dilution ratio and dilution air temperature effects were analyzed as the main influential factors of the dilution system.

4.3.1   Dilution ratio

The dilution ratio is a factor that affects particle size measurements in the gas-to-particle conversion phenomenon from supersaturate vapor condensation (homogeneous nucleation) or by the adsorption and nucleation of volatiles onto the soot surface (heterogeneous nucleation). Studies were carried out to determine the volatility of diesel particles using a thermal denuder to remove volatile particles from the diesel aerosol [19, 24]. In these experiments it was found that the nucleation mode consisted mainly of volatile material and that although the main component of the accumulation mode

was carbonaceous matter, volatile material adsorbed and/or condensed coexisted in this mode and contributed to total particle concentration.

Homogenous nucleation occurs when sufficient free energy exists in the vapor to form a new spherical cluster and the nucleation can be modeled by the RKC (Reiss-Katz-Cohen) theory [25]. This theory states that the nucleation rate of supersaturated vapor is:

$$J \ (nuclei \cdot cm^3 \cdot s) = \frac{a}{\rho} \sqrt{\left(\frac{2 \cdot N_A^3 \cdot \sigma \cdot M}{\pi}\right)} \cdot \left(\frac{S \cdot P_e}{R \cdot T}\right)^2 \cdot exp\left[\frac{-16\pi \cdot N_A}{3(\ln S)^2} \cdot \left(\frac{M}{\rho}\right)^2 \cdot \left(\frac{\sigma}{R \cdot T}\right)^3\right] \quad Eq. (5)$$

Where J is the rate of nucleation, N_A is Avogadro's number, R is the gas constant, T is the gas temperature, M is the molecular weight of the vapor, ρ is the density of the liquid, σ is the surface tension, P_e is the equilibrium vapor pressure, a is the condensation coefficient and S is the supersaturation, S= P/P$_e$, where P is the local pressure.

The adsorption of hydrocarbon molecules onto the surface of soot particles by chemical or physical forces (van der Waals) can be modeled by the Langmuir and BET (Brunauer-Emmet-Teller) isotherm [26, 27]. The Langmuir equation relating to the fraction of surface occupied by the adsorbate is as follows:

$$\theta = 1/(1 + (C \cdot q)/(\chi_{HC} \cdot exp((-E)/(R \cdot T)))) \quad Eq. (6)$$

Where C is a constant that includes the atmospheric pressure and the Arrhenius preexponential factors for adsorption and for desorption, DR is the dilution ratio, E is the difference between the apparent activation energies for adsorption and desorption, T is the local temperature and χ_{HC} is the gaseous hydrocarbon mole fraction prior to dilution.

Several experiments were performed for the SCT and ELR test cycles to study the effect of the dilution ratio on the measured particle size distributions. The test was done to increase the dilution ratio from 20 to 160. The results are shown in Figures 7 and 8. Under the conditions studied there was no

competition between the temperature and the dilution ratio as the dilution air temperature was kept constant and equal to 30 ºC for the PDT and 30ºC for the ED for all the experiments.

Figure 7

Increasing the dilution ratio values decreased homogeneous nucleation as a result of the reduction of the partial pressure of gaseous hydrocarbons according to the RKC.

For both test cycles at the minimum dilution ratio of 20, a higher number of particles were measured in the accumulation mode while for higher dilution ratios the accumulation mode was reduced and became independent of the dilution ratio for values above 100, as Figure 9 shows. A similar reduction of the accumulation mode with the dilution ratio was observed by [28]. On the other hand, other researchers have found that the accumulation mode is not sensitive to the dilution ratio, while volatile particles of the nuclei mode show high sensitivity to this parameter [29, 30]. Thus, the observed variation in the particle concentration of the accumulation mode may be attributed to the presence of volatiles adsorbed and condensed on the carbonaceous particles of the accumulation mode. For the lowest dilution ratio, the partial pressure of the volatile matter was high enough to lead to the adsorption of volatile hydrocarbons. As the dilution ratio increased the adsorption of volatiles was dramatically reduced, a trend that is explained by the BET theory. For a further increase in the dilution ratio, the size distribution showed the independence of the dilution ratio in both test cycles.

Figure 8

The independence of the size distribution for dilution ratios above 100 suggests that the resulting distributions at dilution ratios above these values are mainly composed of carbonaceous matter and that adsorption takes place to a very low extent, resulting in a low amount of adsorbed volatile material.

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Figure 9

4.3.2   Dilution Temperature

To discriminate the effects of the dilution air temperature several experiments were conducted by changing the dilution air dilution temperature in the porous tube diluter (PTD) from 30 ℃ to 320 ℃ and keeping the dilution air temperature in the ejector diluter (ED) constant at 30 ℃. The total dilution ratio used for these experiments was 1:160. The measurement of total particle concentration for the SCT and ELR test cycles are shown in Figures 10 and 11.

Figure 10

A reduction in the nucleation and accumulation modes was observed with the increase of the dilution air temperature in the PDT diluter. These results show that hot dilution of exhaust gas has an influence on particle size distributions. When the primary dilution air temperature was increased it was found that the concentration of nucleation mode particles decreased but the influence of the dilution air temperature became insignificant between the dilution temperatures of 220 ℃ and 320 ℃. However, the concentration of the nucleation mode particles of 15 nm in diameter or less did not vary significantly even when hot dilution was performed, as the decrease of the geometric mean diameter in the nucleation mode shows in Figure 12.

Figure 11

Figure 12

Based on the experimental result, the nucleation mode particles were classified into two groups. Particles within the size range of 5 - 15 nm and a distribution peak of around 10 nm were included in the first group. Particles in this group are relatively stable and may not be affected by the dilution

conditions. These particles are assumed to be core nucleation particles, which may be metallic ash, carbon or heavy hydrocarbons whose boiling point is over 320 ºC. The second group in the nucleation mode is particles within the size range of 10 - 50 nm and a distribution peak of around 25 nm. Particles in this group are very unstable and are significantly affected by the dilution conditions and therefore assumed to be particles which may or may not consist of a solid core depending on the conditions but always contain some volatile fractions. The volatile fractions may be condensed water due to the cold dilution and molecular hydrocarbons with a boiling point of less than 320ºC.

5.   *PROPOSED EXPERIMENTAL METHODOLOGY*

To develop a highly reliable experimental methodology for performing particle size measurements, the sensitivity of total particle concentration and geometric mean diameters to different factors was analyzed. The critical values to define the optimum operation threshold for dispersion factors were selected to reduce variability, avoid the generation of new particles and optimize measurements. The critical values of the dilution parameters were also chosen to provide the thermodynamic stability of the volatile fraction in the exhaust gases and at the same time make the accumulation mode independent from the dilution conditions

Figure 13 shows a theoretical phase diagram of the volatile compounds plotted against temperature. In fresh engine exhaust in the tailpipe, the temperature and concentration of the volatile were high (denoted by point A). During the first isothermal dilution in the PTD, the concentration of the volatile was reduced (path to point B) and subsequently in the cold dilution of the diluted aerosol performed in the ED, both the temperature and the concentration of the volatile decreased thus preventing the formation of nano-droplets.

Figure 13

Table 6 shows the sensitivities of total particle number concentration and the geometric mean diameter to changes in each of the factors along with the optimum operating thresholds for reducing variability and optimizing measurements. For the critical values, the variability in the particle size distribution measurements was reduced to less than 3% for all the factors.

Table 6

Figure 14 shows the sensitivity of particle size measurements at non-optimized conditions and at the optimum operating thresholds for the dispersion factors. The assumed optimum values are valid for this specific set-up yet may be different for other experimental set-ups, dilution systems, engine types and running conditions. This occurs because the dilution system configuration (dimensions, heating, etc.) and exhaust aerosol characteristics (volatile and carbonaceous matter contents) may modify particle dynamics and the values at which stabilization and the reduction of variability are reached. Thus, in order to reduce uncertainty under other conditions, similar tests should be carried out to find the dilution and measurement stabilization conditions which correspond to the specific experimental configuration.

Figure 14

6. CONCLUSION

The necessity has arisen for an experimental methodology to perform particle size measurements owing to the fact that a standard procedure has not yet been established. Although the simulation of real phenomena has not been reached under current laboratory conditions, the use of a methodology to perform comprehensible measurements can be useful and significant for further study concerning particle size distributions under transient operating conditions.

On this basis, a comprehensive experimental analysis of the factors affecting the particle size

distribution of the exhaust aerosol emitted by a light-duty diesel engine was performed. An analysis of measurement sensitivities to each factor was performed and as a result, a highly reliable measurement methodology is proposed that could be applied, under the experimental conditions and configuration of this analysis, to further studies on the effect of engine operating parameters on the particle size distribution of exhaust aerosols. An experimental analysis of the different dispersion factors affecting particle size measurements was carried out. The study included the validation of the EEPS system, the evaluation of parameters that affect the dilution system and sampling factors such as measurement stabilization and the effect of dilution air particles. Critical values were chosen for each parameter to reduce variability and recommendations were given to optimize measurements.

Based on an analysis of the results, the following conclusions were reached:

- The EEPS presents a good fit with particle size distributions measured by the SMPS in steady state operating conditions. The variation between the measurements of both systems is due to the difference in the particle detection ranges. For transient tests, the particle number concentration compared with the CPC also presented a good fit.

- The particles carried by the dilution air can produce an offset in particle size measurements when a low number of particles is measured. Under these conditions the particle size distribution of the dilution air must be subtracted from the measured size distribution.

- A time of 40 minutes is needed for the dilution system to become stable after activation. This stabilization time must be taken into account to obtain unchanging particle size distribution.

- The dilution ratio greatly affects the measurements, due to their influence on the adsorption/condensation of volatiles. Critical values were chosen to reduce variability

and make the accumulation mode independent of the dilution conditions.

- The dilution air temperature affected the nucleation mode, due to the reduction in the homogeneous nucleation which decreased the rate of nucleation of supersaturated volatile compounds. Nevertheless "solid" nucleation (particles with dp< 15nm) were not affected by dilution conditions.

- A hypothetical classification of the nucleation mode is proposed with one group of "solid" core nucleation which is very stable and not sensitive to thermal conditions, and a second group which is very unstable and considerably affected by dilution conditions.

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Table 1.

Stroke (S)	96 mm
Bore (D)	85 mm
S/D	1.129
Number of cylinders (z)	4
Displacement	2.179 liters
Valves per cylinder	4
Maximum power	125 kW @ 4000 min-1
Compression ratio	17:1

Table 2.

Summarized formula	$C_{14.3} H_{26.6}$
Cetane number	50.5
Viscosity at 40ºC ($mm^2/_s$)	26.8
Density at 15ºC ($^{kg}/_l$)	0.84
Lowest heating value ($^{MJ}/_{kg}$)	42.9
Sulfur content ($^{mg}/_{kg}$)	7.4
Oxygen content (% $^{m}/_{m}$)	0

Table 3.

Operating Mode	Speed (min^{-1})	Load (%)	Fuel mass (kg/h)
$A_{(L)}$	1500	20	3.1
$B_{(M)}$	2500	40	6.8
$C_{(H)}$	3000	80	13.5

Table 4.

Operating Mode	Total PN variation (%)	Accumulation PN variation (%)	Nucleation PN variation (%)
$A_{(L)}$	1.21	5.86	9.68
$B_{(M)}$	6.25	7.06	1.72
$C_{(H)}$	4.98	6.42	6.85

Table 5.

Parameter	Particle number concentration sensitivity	Geometric mean diameter sensitivity	Optimum threshold
Dilution system activation	• Hot dilution 10.13% for every 10 min before activation 2.74% after stabilization • Cold dilution 8.69% for every 10 min before activation 2.68% after stabilization	• Hot dilution 6.51% for every 10 min before activation 2.33% after stabilization • Cold dilution 4.28% for every 10 min before activation 0.67% after stabilization	40 min after activation
Dilution air particles	Maximum 0.77% at DR=160	Maximum 0.33% at DR=160	Subtracted from measurements
Dilution ratio	8.60% for 20 unit variation (<DR 100) 0.68% for 20 unit variation (≥DR 100)	7.22% for 20 unit variation (<DR 100) 0.97% for 20 unit variation (≥DR 100)	≥ 100
Dilution air temperature in the PTD	6.49% for 30ºC variation (<DT 220ºC) 0.41% for 30ºC variation (≥DT 220ºC)	5.31% for 20 unit variation (<DR 100) 0.36% for 20 unit variation (≥DR 100)	≥ 220ºC

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9. *Influence of the dilution ratio on nucleation, accumulation, and total particle number concentration and geometric mean diameter over transient test cycles. (a) Step change test variations, (b) European load response variations*

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11. *Influence of dilution air temperature on particle number concentration and geometric mean diameter over the European load response test cycle. (a) Variation of particle number concentration, (b) Variation of geometric mean diameter, (c) Particle size distribution measured with dilution air temperature in the PTD at 30ºC, (d) Particle size distribution measured with dilution air temperature in the PTD at 320ºC.*

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