PARTICULATE MATTERS FROM DIESEL ENGINE EXHAUST EMISSION

by

Velimir S. PETROVIĆ

Original scientific paper
UDC: 621.43.041.6:614.71/.72
BIBLID: 0354-9836, *12* (2008), 2, 183-198
DOI: 10.2298/TSCI0802183P

Air pollution caused by diesel engine emissions, especially particulate matters and nitric oxides emissions, is one of the biggest problems of current transportation. In the near future the emission of diesel particulate matters will become one of the most important factors that will affect the trend of engine development. Ambient airborne particles have adverse environmental and health effects and therefore their concentration in the air is regulated. Recent medical studies showed that different particle properties are important (for example: number/concentration, active surface, chemical composition/morphology) and may take role in the responsibility for their human health impact. Thus, diesel engines are one of the most important sources of particles in the atmosphere, especially in urban areas. Studying health effects and diesel engine particulate properties, it has been concluded that they are a complex mixture of solids and liquids. Biological activity of particulate matter may be related to particle sizes and their number. The paper presents the activities of UN-ECE working group PMP on defining the best procedure and methodology for the measurement of passenger cars diesel engines particle mass and number concentrations. The results of inter-laboratory emissions testing are presented for different engine technologies with special attention on repeatability and reproducibility of measured data.

Key words: *engine emissions, diesel engines, particulate matters, particle number, characterization, particulate filter*

Introduction

We are witnesses of increased particle concentration in the atmosphere, which have effects on decreasing quality of local climate. The short--term exposure to emission of nano and ultra fine particles can lead to eye irritations. The long-term exposure to diesel fine particles emission will lead to an increase in lung cancers and heart diseases.

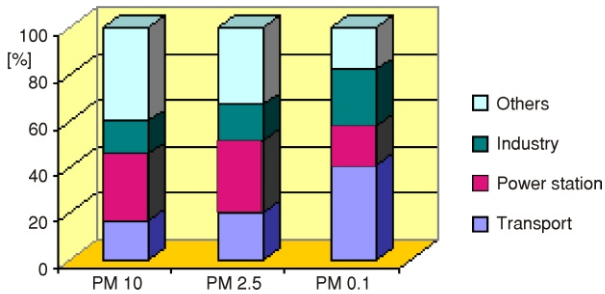

Figure 1. Contribution of particle matters emission from different sources [1]

(color image see on our web site)

Figure 1 shows that the contribution of particles emission from modern engines is less than 20% for particles smaller than 2.5 μm, but the share of transport in the emission of fine particles (smaller than 0.1 μm) is almost 40%. This percentage is slightly higher in urban areas with intensive traffic where high frequency of vehicles, but certain drop can be expected with the development of exhaust gas after treatment for heavy duty and passenger car engines. Nevertheless, this percentage is not trivial, because engine exhaust gases have more toxic components then others sources. Also, it is known that ultra fine particles have a more hazardous effect on human tissue than big particles. However, it is very hard to predict movement of ultra fine and nano particles because they almost don't have mass, so they can be found 3.5 to 5 km away from motorways [2].

Particle size distribution

Formal terms for different size of particle matters (PM) are: PM 10 – coarse particles with diameter less than 10 μm, PM 2.5 – fine particles with diameter less than 2.5 μm, PM 0.1 – ultra fine particles with diameter less than 100 nm, and PM 0.05 – nano particles with diameter less than 50 nm. The emission of PM 10 is mostly involved by ECE regulation R-49 and R-96 for exhaust gases emissions [3].

Figure 2 shows typical particle number ($dN/d\log D_p$) and mass ($dm/d\log D_p$) distribution in the function of particle diameter [4]. Three typical phases of particle formation can be noticed. In the first phase are particles from nucleation phase. The second phase involves fine particles from accumulation phase, and the third are coarse particles (which are eliminated in the modern diesel engines with high pressure injection, so their number is considerably low as well as mass). Total mass of emitted particles comes mainly from accumulation phase with fine particles PM 2.5 smaller then 2.5 μm, but their number can be small (depending on applied technology and exhaust gas after treatment system). As concerns number concentration, nano particles are dominant. The composition of ultra fine particles is mostly solid carbon and the composition of nano particles is mainly liquid compounds and volatile hydrocarbons. Particles from the first phase, so called nano particles, are the biggest problem. They are mostly unstable and almost without mass, but enormous by number.

Particle size available to gravimetric measurement is between 0.1 and 0.3 μm in diameter. This diameter is characteristic for the period when agglomerated particles absorb volatile hydrocarbon, sulphur, and dust. The phase of nucleation is between 5-50 nm with typical 1-20% particle mass and more then 90% in particle number concentration. Coarse mode is known by 5-20% in sum of total particle mass, which make them fulfil rest of the particles from accumulation phase, formed in cylinder or inside exhaust system and afterwards they are left free in the atmosphere.

The nucleation phase is not significantly studied because it is very hard to model it, but there are some advanced theses that met wider problem. The mechanism of formation is highly unstable, as well as the chemical composition, because reactions in the exhaust are not finished yet. Conclusions derived from size distribution consideration say that particles number concentration is very important for further

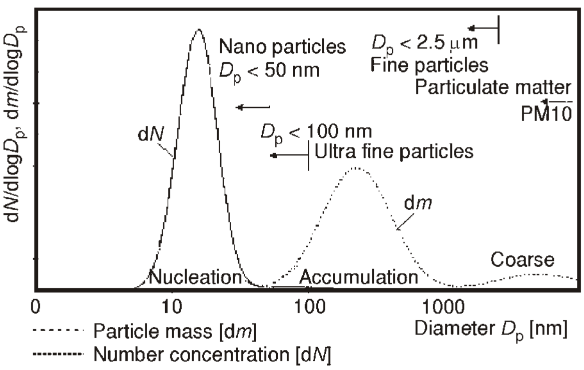

Figure 2. Particle size distribution

evaluation of diesel engine particle emissions. Therefore, measurement of size distribution is very frequent in various research institutions, as well in developing research laboratories [4-6].

Physical properties of nano and ultra fine particles

Formal definition of particulate matter is that it is any material collected on filter during gravimetrical measurement. New definition is: particulate matters are all particles that left exhaust collector and mixed in air forming poly disperse aerosol. During the dilution of exhaust gas in atmosphere, particles larger in diameter than 2.5 μm are also mixed with air. However, the human body has been able to stop them in nose and upper respiratory system. Huge particles, like road dust from dirt, doesn't effect negatively on inner human organs. But smaller particles, defined as ultra fine particles, could be accumulated in lungs. Aftermath they will have morphological and geometrical changes by adsorption and desorption in most unpredictable ways that may last for minutes, hours, days, and months after they have left exhaust system [7].

About 80 to 90% of total particles mass are very small particles between 0.005 and 1 μm, with average diameter 200 nm. Ultra fine particles are from 5 to 100 nm, with average diameter 20 nm. Their share in total particles mass is from 1 to 20% in particle mass, and from 50 to 90% in total particle number. However, fine and ultra fine particles have great specific surface, which make them excellent for accumulation of organic and inorganic compounds (elements or substance).

In the last five years a lot of attention was focused on finding correlations between particle number concentration and mass (which is on the limit of detection) [3-6]. Direct correlation is not yet found because of complex particle nature and because the sampling procedure can influence the measurement results. Meanwhile, the complexity of the phenomena requires new measurement methods, which are mostly used in aerosol science and which can be included in future regulations. There are a lot of interesting parameters that define particle properties, but the most important are:

- active surface,
- size, equivalent diameter,
- solid particle number,
- total particle number, and
- in addition, size distribution.

Actually, in technical sense, active surface is proportional to specific surface of particle (ratio between surface and particle mass). It is important because it defines interaction when a particle freely floats in atmosphere and interacts with gas or with other particles. It is well known that particles have irregular shape (not spherical but like agglomerates "grape" and chain shape). By increasing active surface there is less free space in molecules for adsorption and in the end chemical reaction in the lungs depends on active surface of a particle.

In absolute terms, specific surface has less importance than the size of active surface, which is considered responsible for adsorption of organic and non-organic material on particle nucleus. Approximately, specific surface can vary from 50 to 150 m^3/g for each particle itself. The fact is that if the particles are smaller their specific surface will be larger. This means that for same total particle mass, larger number of small particles has greater active surface than the big ones, so they can easier absorb organic and non-organic substance. The conclusion is that the active surface is inversely proportional to particle size, *i. e.* to equivalent particle diameter.

However, it is hard to define appropriate diameter of spherical particle which will represent irregular shape of real particle and which will have the same behaviour in physical (under the influence of drag and inertia forces) or electrical field (under the influence of electro-magnetic forces. Therefore, equivalent diameter is fake diameter for idealized sphere particle that will have same properties as real one. There are four characteristic diameters, which are use to represent particle properties during different measurement procedure [6]:

(1) Geometric or Stokes diameter is the diameter of sphere particle with same mass and density as real one: $\rho_s = \rho_p$; it is not representative because the particle of this diameter does not have the same behaviour as real particle in physical or electrical field; therefore, it is not used in modern aerosol instruments.

(2) Aerodynamic diameter d_a, is imaginary diameter of spherical particle (with unit density) which have same velocity as real particle $v_a = v_p$ (under the traction force F_a); certain instruments use aerodynamic diameter as operating parameter, based on principle of particle inertia.

(3) Mobility diameter d_m is imaginary sphere particle diameter as real particle with same velocity ratio and traction force induced upon particle in gravimetrical field. This diameter is defined in instruments which use particle mobility properties (declination in physical field) for measuring particle size.

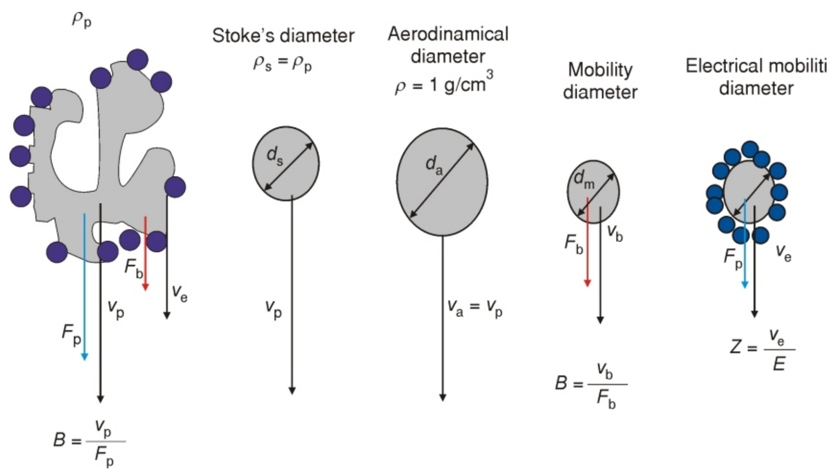

Figure 3. Different equivalent particle diameters

(4) Diameter of electrical mobility is imaginary sphere particle diameter that has same mobility (declination in electric field under the traction of electro-magnetic force) as real particle. This parameter is used in an instrument which defines particle size on their behaviour in electrical field upon declination of particle affecting by changing the current.

Solid particle number is the most stable number of particles with small coefficient of variation. Total number concentration is given by sum of solid number and unstable volatile emission of heavy hydrocarbons from nano phase particle formation. It could be expected that this parameter might be operational too, when final limits of concentration are being established in homologation procedure. Therefore, instruments based as counters and/or (additional) evaluation of size distribution will take part in regulation procedure.

Since total active surface of particles is proportional to number of particles, next important particle property is particle number concentration. This parameter is the most frequently used and it can be meet in future legislation for number concentration in approval type procedures.

Total particle number is sum of solids and liquid (volatile) particles, respectively particles from the phases of nucleation and accumulation. If volatile components are separated, then only the number of solids particles will be obtained, practically only particles from phase of accumulation. Concentration of particles from nucleation phase is very unstable and it is influenced by sampling conditions and other parameters (weather condition, working regime, applied engine technology, *etc.*). Therefore, it is much precise to perform measurement of solid particles as much stabile number.

A transformation during particle formation is shown in the upper part of fig. 4 [4, 8]. During combustion mainly solid particles are formed (on the left), but in the exhaust system and during dilution, condensed volatile material is formed and it is partially adsorbed on the carbon particle but a lot of volatile particles stay free (on the right). The separation of nucleation and accumulation phase, by use of thermodesorber (volatile remover), is shown at the bottom part of fig. 4. In classical diesel engine without particles filter (non-DPF) (blue lines at the right), the accumulation phase is dominant, so solid (dotted line), and total (solid line) particles number is very close. At diesel engine with particulates filter (DPF) (red lines at the left) the nucleation phase is dominant, so the solid particles number is very low.

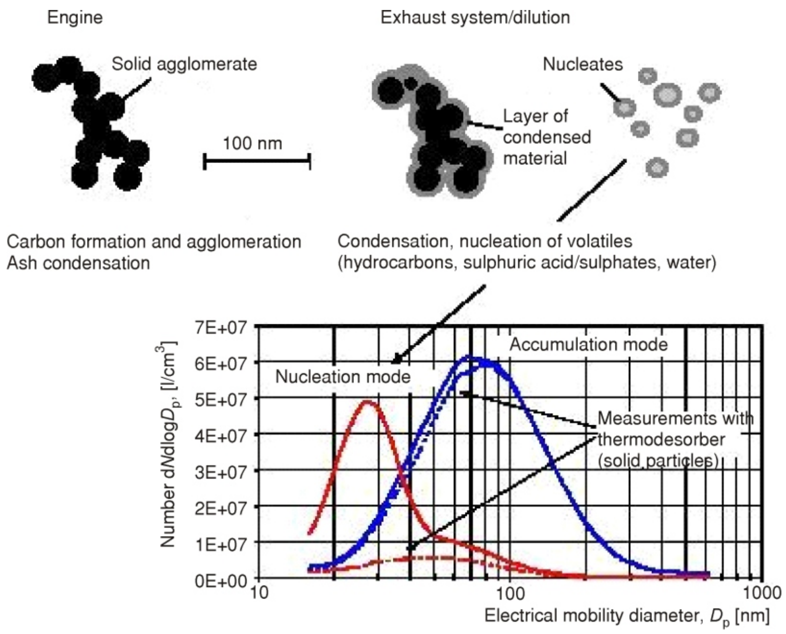

Figure 4. Typical particle size distribution for DPF and non-DPF diesel engine (color image see on our web site)

Particle measurement program (PMP)

Having in mind that at current new diesel engines emission of coarse particles is practically eliminated and that fine and ultra-fine particles emission is dominant (with serious effects on human health), under the great public and political pressure, Working group on pollution and energy (GRPE) of ECE/UN World Forum for harmonization of Vehicle Regulations (WP.29) have undertaken some steps for defining installation for measurement of particle mass and number concentration, which can be use for certification procedure.

During 7 years of discussions and measurements, PMP/GRPE group of experts studied possibilities of different measurement methods for fine particle emission control and at last defined proposal of installation and sampling procedure that can be included in regulation ECE R49, R83, and R96. Actually, they agreed on the following conclusions [4]:

(1) In modern diesel engines coarse particles are almost completely eliminated, so their effect is not longer an issue, but emission of fine and ultra fine particles becomes important.
(2) Mass measurement is not sufficient for two reasons: first, it is not only factor interesting for human health, and second, the emission levels are so low and on limit of detection that the measurement accuracy is a problem.
(3) Beside the particle mass, there are other particle properties which are interesting from heath point, so the new measurement methods and certification procedures must be defined for particles characterization.
(4) New measurement methodology and installation must be simple and accessible enough to be used in regular certification procedure.
(5) Though the measurement of some particles properties is interesting and important, the measurement of wide range of particle properties is too complex for type approval test.
(6) Measurements of ultra fine and nano particles are not so precise because a lot of factors and sampling conditions have the influence on test results.
(7) Measurement of accumulation phase is stable, and a lot of existing installation for particle measurement can be used.
(8) Therefore, the most common measurement parameters are particulate matter mass (PM) and concentration of solids particles (particle number PN).
(9) Taking in account low emission levels, the installation should be suitable for the measurement of particle emissions of direct injection gasoline engines and diesel engines with DPF.

Figure 5 shows PMP/GRPE proposal of the installation for measurement of particle number concentration [9]. According to this proposal standard CVS dilution tunnel should be used. The exhaust gas sample, taken from the tunnel, goes to the cyclone pre-classifier which remove particles bigger than about 2.5 μm. After dilution with hot air, one part of sample goes to the total particle number counter (CPC_Ref), and another part is driven through heated evaporation tube (heated up to 150 °C) where volatile components are removed. As the sample has to

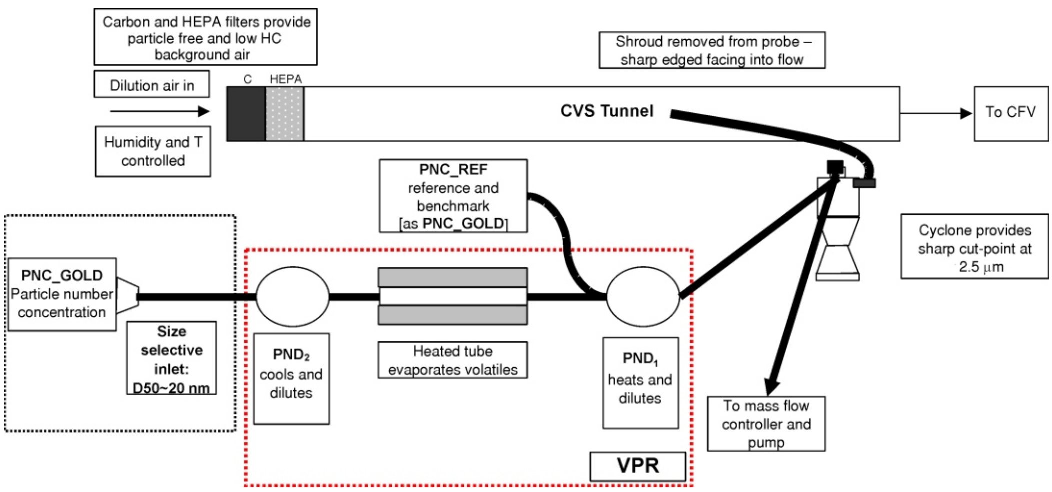

Figure 5. Schematic of proposed installation for the particle number measurement

be cold at the entrance of particle counter, and to prevent condensation, the sample is again diluted and then it is driven to particle number counter (CPC_Gold).

According to this proposal, PMP/GRPE group has first undertaken the investigation on particle emission measurements repeatability and reproducibility results of passenger cars. In these measurements, always the same vehicle, so called "golden" vehicle, is tested in different laboratories where particles concentration is measured with two set of instruments: first one is always the same referent, so-called "golden" instrument, and another one is the relevant instrument of laboratory where measurements are performed. The "golden" vehicle and "golden" instrument have passed 11 laboratories: JRC – EU Joint Research Center (Ispra, Italy) (three times), AVL MTC (Sweden), Ricardo (Shoreham, UK), RWTUEV (Essen, Germany), Laboratory of Applied Thermodynamics (Thessaloniki, Greece), NTSEL (Japan), NIER (Korea), Shell (Cheste, UK), UTAC (Paris, France). The "golden" vehicle had direct injection EURO 4 diesel engine with diesel particulate filter (DPF), but every laboratory had to include in the measurement another vehicle by their own choice (either diesel engine with or without DPF or spark ignition engine with MPI or DI injection). Also every lab had to use another particle number counter by their choice for comparison.

Results of particle concentrations measurments

Figure 6 shows an example of measured regulated emissions on "golden" vehicle with diesel particulate filter in one laboratory according to the regulation ECE R83.04 (using New European Driving Cycle – NEDC: urban, extra urban, and total emissions). Measurements were repeated five times in five days. Particles mass emission was very low (one hundred times lower than regulated: EURO 4 PM limit is 25 mg/km), but repeatability was not satisfactory with variation coefficient (CoV) of 20%. Evidently, the reason is very low emission level [8]. However, the emission of NO_x is still very high, almost at the same EURO 4 limit (0.25 g/km). Evidently, the main goal of manufacturer was to reduce the emission of particulate matters.

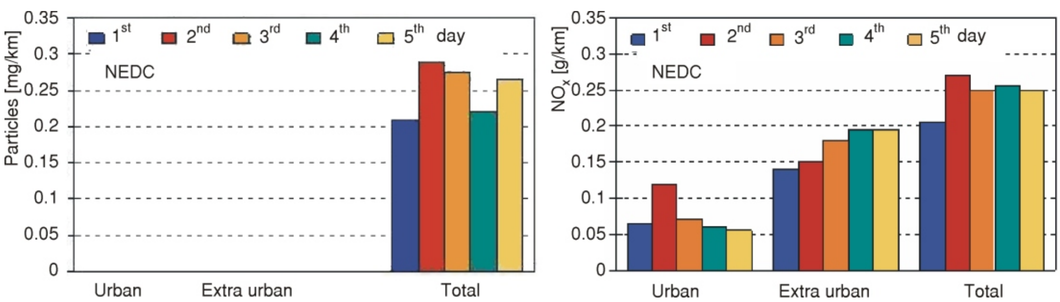

Figure 6. Particulate matters and NO_x emissions of "golden" vehicle obtained in one laboratory (color image see on our web site)

In other laboratories the situation with particulate mass emission is much worse and in some laboratories CoV is even more than 60%. Figure 7 shows that PM repeatability (variation of measured PM in certain laboratories during several tests) varied considerably from laboratory-to-laboratory with CoVs ranging from ~10 to ~65%. Mean emissions levels also varied considerably from ~0.2 to ~0.6 mg/km. The high CoV level may have been influenced by the occurrence of regenerations of DPF during testing. The reproducibility level (variation of aver-

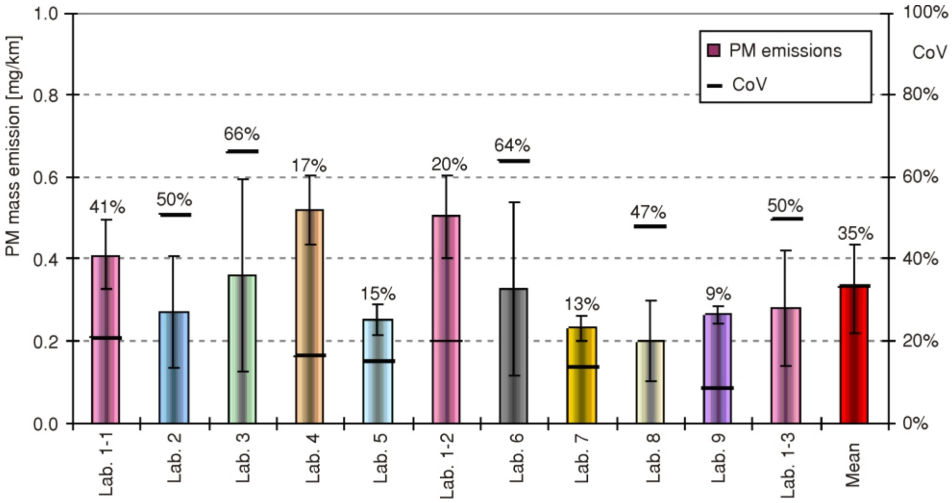

Figure 7. Particulate mass emission of "golden" vehicle in different labs (color image see on our web site)

age PM emission between different laboratories) of the mass emission across all labs was ~35% at a mean emission rate of 0.34 mg/km. Difference in measured average mass particles emission between laboratories was almost 100% [10].

Number concentration of particles measured in NEDC cycle is very interesting. Figure 8 shows relatively low average particle number concentration (~10^{11} particles/km) from diesel engine with DPF during five days testing in one laboratory. However, repeatability was major problem because coefficient of variation was 60%. The results show that the greatest amount of emitted particles was from urban divining cycle [8].

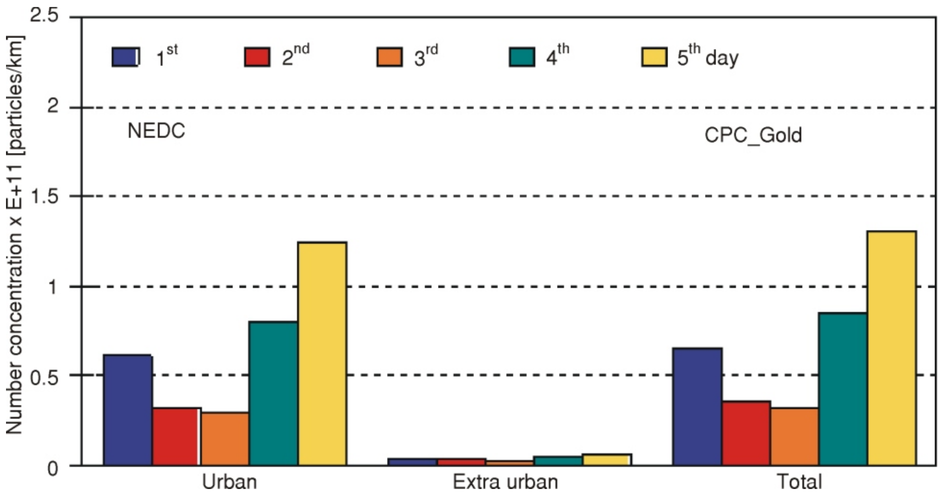

Figure 8. Particles number measured in test cycle (color image see on our web site)

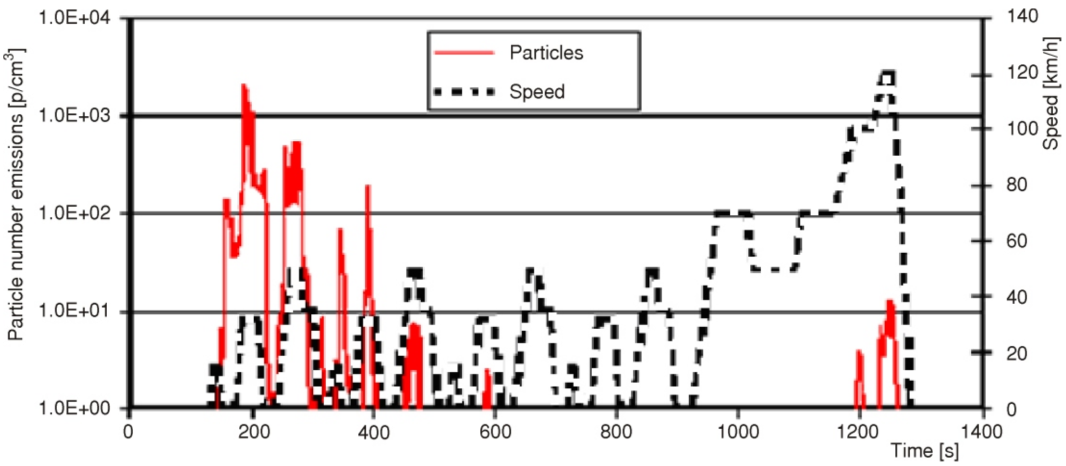

Figure 9. Particle number emissions measured during New European Driving Cycle (NEDC) (color image see on our web site)

This is confirmed by measured particles number concentration during NEDC cycle shown in fig. 9. The average value of emission in five days is presented in the graph. The concentration was high in first two parts of urban driving cycle, but in the other parts of cycle it was on background level. It can be concluded that during the engine warm up, the phase of nucleation was dominant, when the small particles pass diesel particle filter in gaseous or liquid shape, and go into sampling system. In extra urban driving cycle particles emission was also very low and it is only detected during acceleration close to full load.

Similarly to measured PM mass emission in different laboratories, the repeatability of particle number concentration is very bad. Figure 10 shows that mean NEDC emissions of particle numbers of "golden" vehicle varied from laboratory-to-laboratory from ~$5 \cdot 10^{10}$ particles/km to ~$1.3 \cdot 10^{11}$ particles/km. Repeatability level between laboratories ranged from 12 to 72%. Av-

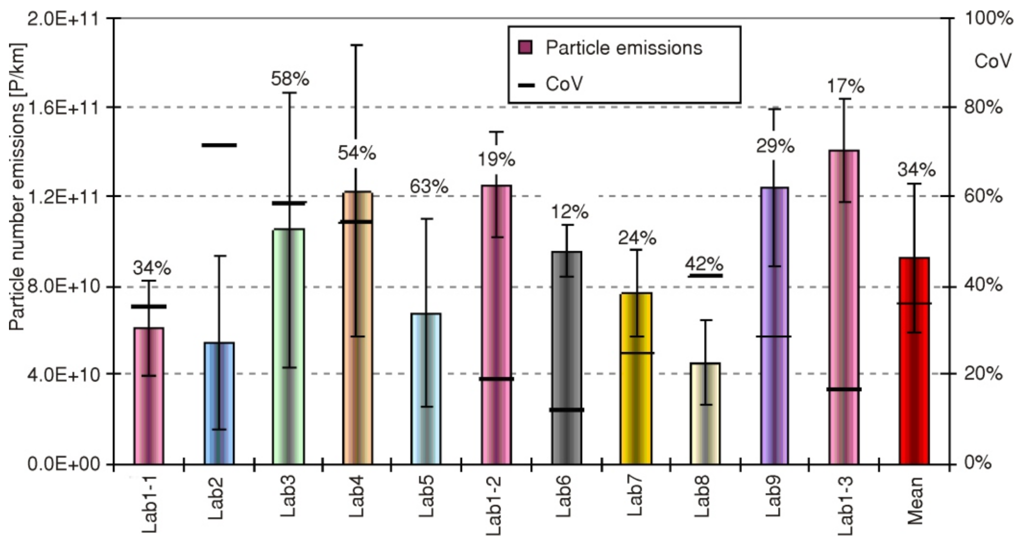

Figure 10. Particle number emissions, repeatabily and reproducibility of "golden" vehicle in NEDC (color image see on our web site)

erage NEDC particle number concentration was about 10^{11} particles/km and reproducibility level was about 34%. Reason for that was very low measured value and unstable process of nucleation phase formation [10].

Figure 11 shows an example of similar results in the same laboratory for secondary arbitrary chosen vehicle. This vehicle had 2.2 liter EURO 4 conventional diesel engine without particulate filter (non-PDF). Emission was measured on same installation as it was with "golden" vehicle. Normally, the emission of particulate mass was much higher than it was for the "golden" vehicle. This emission was only 30% below limit (25 mg/km), but with very small coefficient of variation of 10%. NO_x emission was smaller than for the "golden" vehicle and it mainly comes from extra urban driving cycle [8].

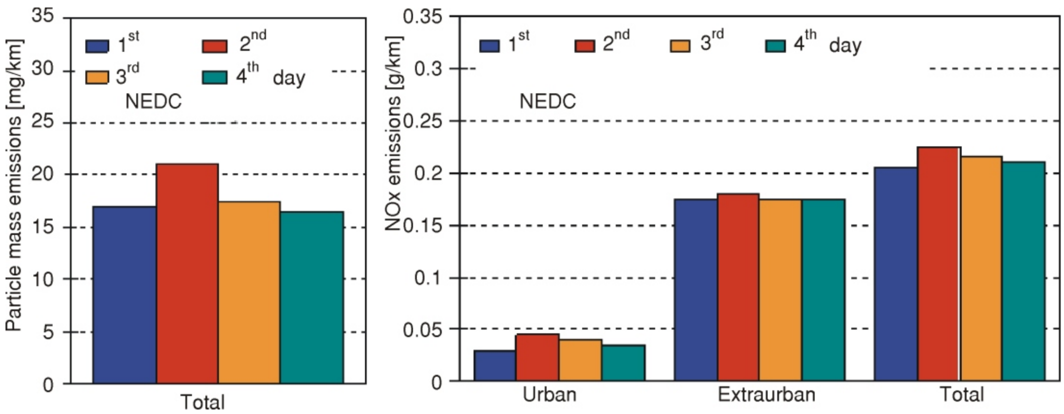

Figure 11. Particulate and NO_x emissions of conventional non-PDF diesel vehicle obtained in one laboratory (color image see on our web site)

Emission of particle number concentration in NEDC is shown in fig. 12 for this vehicle. Particle number concentration is two orders of magnitude higher than it was for "golden" vehicle and it was about $6 \cdot 10^{13}$ particles/km. Repeatability was satisfactory with coefficient of variation of 3%. Emission of particles was present in both cycles: urban and extra urban.

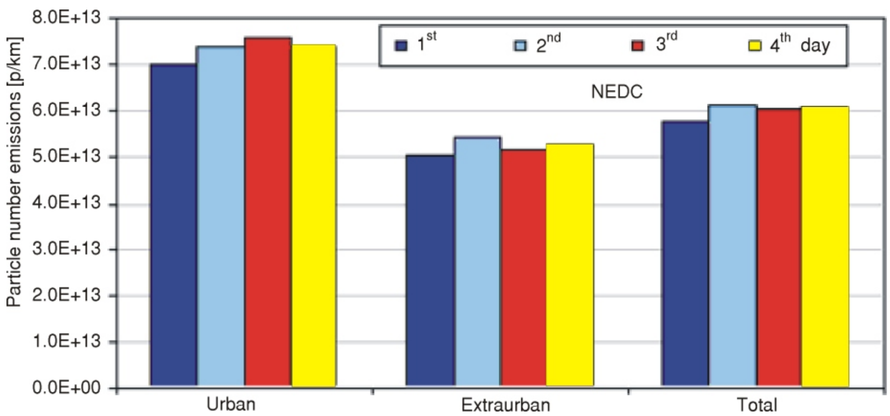

Figure 12. Particle number emission in NEDC (color image see on our web site)

Figure 13 shows particle number concentration of this non-DPF vehicle during NEDC. Increased particles emission can be noticed during the shifting of speed and load (due to acceleration). From picture it can be seen the dominance of emission of fine particles under acceleration at higher load. In the beginning of urban cycle, higher concentration is present, but it is reduced in following urban cycles due to warm up of catalytic converter and oxidation of soot. Anyway, contrary to "golden" vehicle, particle emission of non-DPF vehicle is significant either in first urban or in other urban cycles, as well as in extra-urban cycle [8].

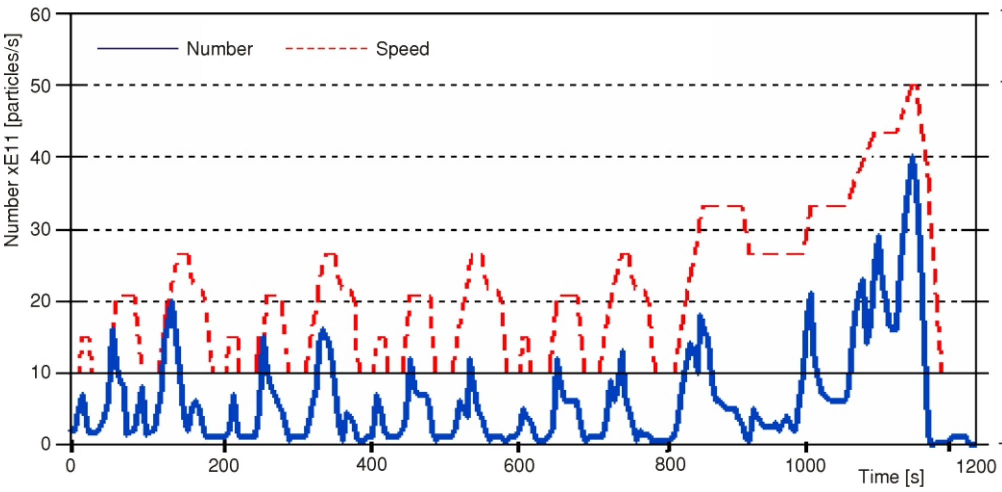

Figure 13. Particle number emissions during NEDC (color image see on our web site)

Interesting conclusion can be obtained after the measurement of particle mass and number concentration levels taken on different engine technologies in nine laboratories. Figure 14 compares the difference in measured particulate mass emissions between "golden" vehicle (DPF G) and other vehicles with engines with different technologies. Particle mass emissions for all vehicles with particulate filter (DPF) are always very low: much bellows 1 mg/km. Though the particle mass emissions repeatability of DPF diesel vehicles is better than the repeatability of "golden" vehicle, it is still very high and its average is about 20%. Mass particulate emission of multi point injection gasoline engines (G MPI) is at the same level with DPF engines and, also, its repeatability is very bad with high CoV (about 40%). The particle mass emission of direct injection gasoline engines (GDI) is almost ten times higher than the PM emission of PDF diesel engines, but the repeatability of test data is much better. GDI CoV range from 2% to 17%. The particulate mass emissions of conventional diesel (DIS) engine (without particulate filter) is almost hundred times higher than emissions of DPF engines, but the results repeatability is much better with CoV mainly bellow 10 (it ranged from 2 to 11%) [10].

The particle number concentration for vehicles with different engine technologies is shown in fig. 15. Trend between mass and number concentration is similar (figs. 14 and 15). Number emissions of diesel DPF vehicles were on level of gasoline engine with MPI injection. It can be expected that number emissions of these vehicles should be bellow 10^{12} particles/km in NEDC test. Direct gasoline injection engine had 10 times higher particles number concentration in comparison with two previous engine technology. Their emissions should be bellow 10^{13} par-

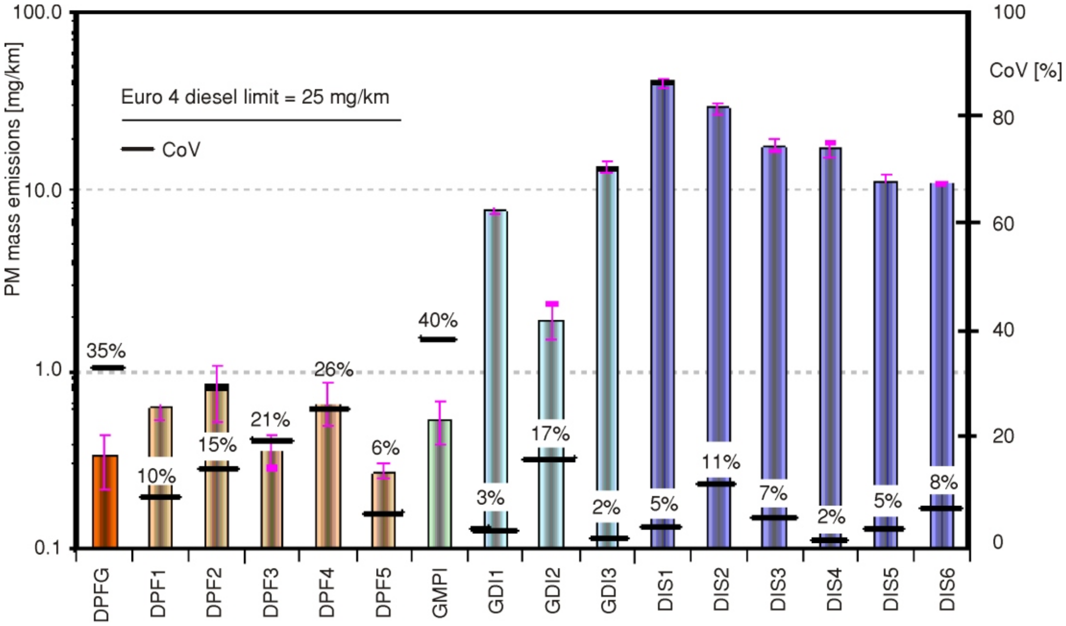

Figure 14. Particulate mass emissions for vehicles with different engine tehchnologies (color image see on our web site)

ticles/km in NEDC test. Diesel EURO 4 vehicles without DPF had hundred times higher particles emissions than DPF vehicles. Their number emissions are bellow 10^{14} particles/km in NEDC test. Test results repeatability (fig. 15) is almost perfect for conventional diesel non-DPF vehicles and their CoV is mainly under 5%. However, the repeatability of DPF vehicles is much worst and their CoV was over 30% [10].

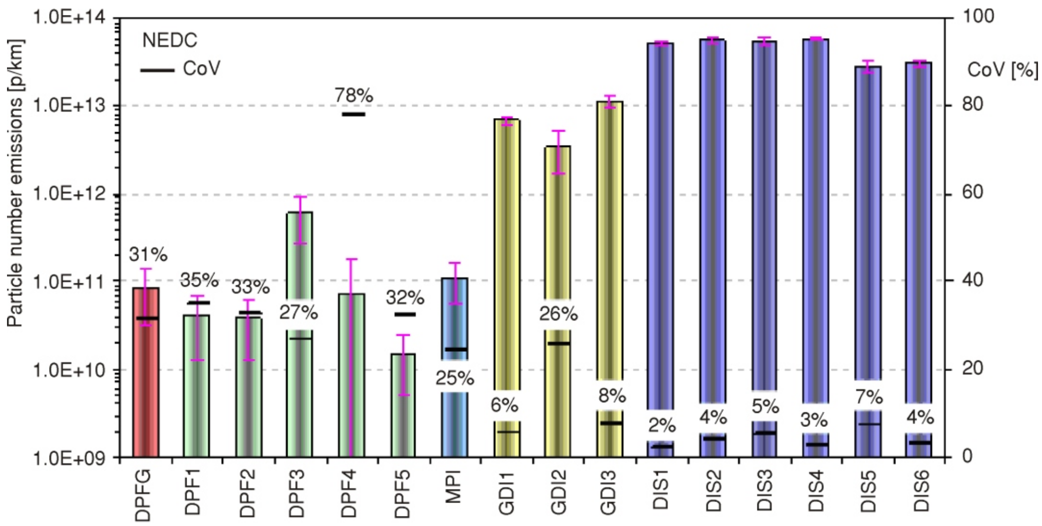

Figure 15. Particle number emissions for vehicles with different engine technologies (color image see on our web site)

Also, it should be mentioned that the correlation between measured particles mass and number concentration (fig. 16) does not exist for vehicle with DPF (either for "golden" vehicle in nine laboratories or for other tested DPF vehicles). Evidently, problem is extremely low measured values and unstable fraction of ultra-fine particles. Correlation is much better for GDI vehicles, as well as for conventional diesel engines without particulate filter (fig. 17), because they have higher emissions of stable solid fine particles [11].

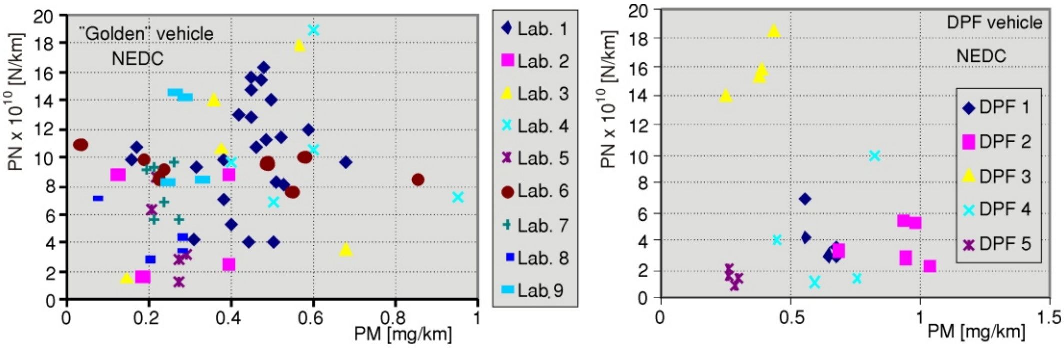

Figure 16. Correlation between measured particles mass and number concentration for DPF vehicle (color image see on our web site)

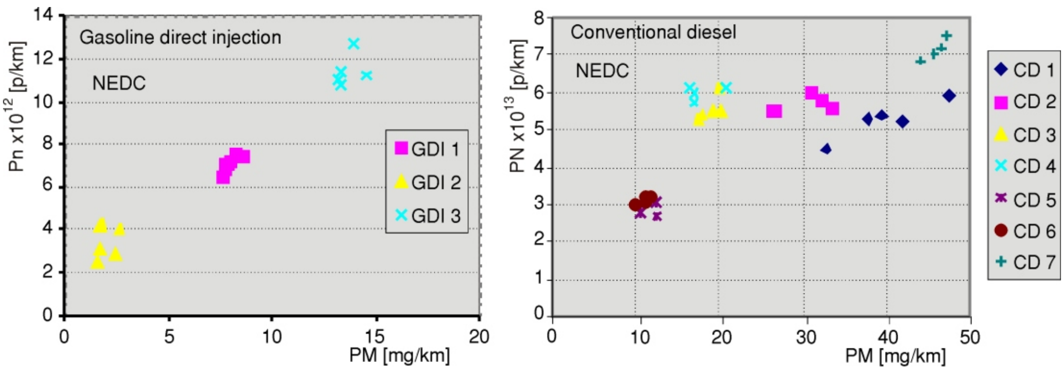

Figure 17. Correlation between particles mass and number emissions for GDI and non-DPF vehicle (color image see on our web site)

At the end, fig. 18 shows some results of particle number emission measurements outside of PMP inter-laboratory correlation exercise in different laboratories and with different engine technology, but using PMP measurement procedure in NEDC. Shaded results were got using Matter/TSI instruments and unshaded used Horiba SPCS system. Some of the vehicles were tested using both. The results are almost identical as in PMP testing. Particle number emission of DPF vehicles ranged from 10^{11} to 10^{12} p/km, for MPI gasoline engines it ranged from $5 \cdot 10^{10}$ p/km to $5 \cdot 10^{11}$ p/km, for GDI engines it was from 10^{12} to 10^{13} p/km, and for conventional diesel engines without DPF it ranged from 10^{13} to 10^{14} p/km [12].

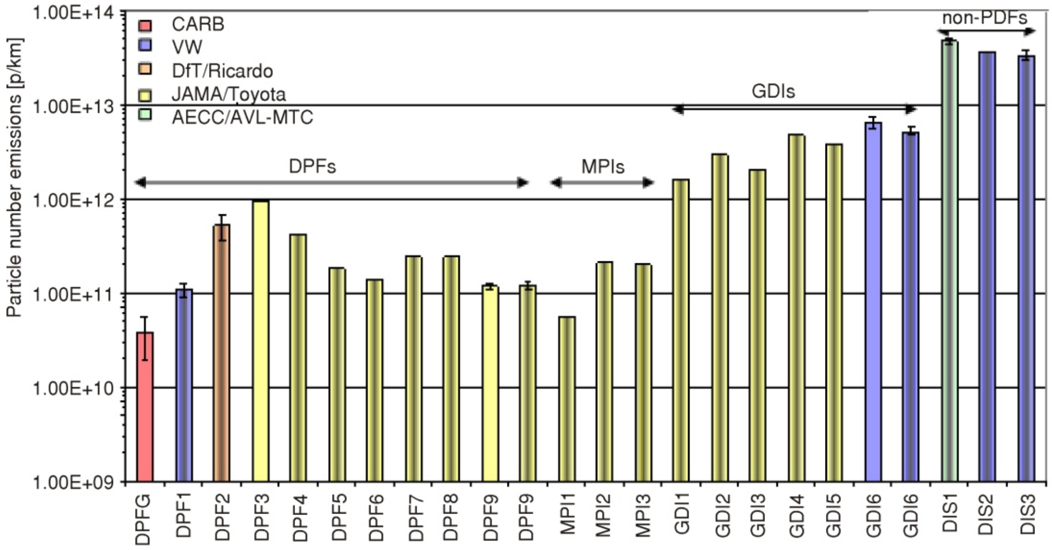

Figure 18. Particle number emissions for vehicles tested outside PMP (color image see on our web site)

Conclusions

As concerns the particle character and size, emitted particles from diesel engines can be divided in three groups: nano, fine, and coarse particles.

(1) Phase of coarse particles are particles above 2.5 μm. They are mostly formed in engine with obsolete system of injection, insufficient mixing of air and fuel and incomplete combustion. Coarse particles contain ash and swarf. Those particles have large mass but small concentration. New engines that meet EURO 4 limits haven't any coarse particles emission.

(2) Phase of particle accumulation is made of particles smaller than 2.5 μm. They are made by agglomeration solids carbon particles in chains able to absorb volatile organic compounds and inorganic components (likely sulphur compounds). Those particles are 80-90% in particles mass and 20-40% in number concentration. Beside their stabile structure, their number depends on measures applied for particle reduction (exhaust gas after treatment).

(3) Phase of nucleation involves ultra fine particles with diameter less than 100 nm and nano particles with diameter less than 50 nm. They are made by condensation sulphuric and nitro compounds and heavy hydro-carbons in exhaust system. They are present in 5-10% of all particle mass, but 60-90% in their total number. Also, their number in highly unstable due to conditions in exhaust system manifold.

Particles might have harmful effects on environment especially on humans, because most of them carry toxic organic and inorganic material. Some of negative manifestations are eye irritation and decrease in lung function. Coarse particles are kept in the nose and upper part of lung, but particles smaller than 2.5 μm are found deep in the lung, and even in the liver and the brain.

Taking in account the ability of particle diffusion in lungs, particle mass is not primary target any more, as it is: number, active surface, and size distribution. Active surface is most important characteristic to defining its ability to carry hazardous components on particle surface. Diameter is value of particle size. There is no universal parameter (diameter) to define all particles. Geometrical diameter is the diameter of spherical particle with the same mass as real particle, but it doesn't represent particle size character. Aerodynamic diameter represent sphere particle of same unit density with same settling time as real one. Mobility diameter is diameter of imaginary sphere particle with same diffusion properties as real one. Which diameter will be used is defined by operational procedure of instrument. Total number of particles and number of solids particles are particle properties which are the most interesting for measurement. In sum of total particle number are included volatile (liquid drops) particles. Number of volatile particles is influenced by various factors such as humidity, number of vehicles and their speed. Distribution on particle mass or size is interesting parameter which define the structure of emitted particles, average diameter as well the influence parameters on particles number in forming phases.

Terefore, the main conclusions are:

- Though the particulate emission of new diesel engines is reduced considerably, the fine particles emission can be critical from human health point of view, because human organism does not posses defense mechanism to stop them.
- Measured particles number concentration can be affected by many factors, such as: sampling conditions (temperature of sample, dilution ratio, sampling time), sampling place, working conditions, measurement instruments, way of removing volatiles components, sulphur content in fuel and exhaust gas after treatment.
- PMP/GRPE/ECE/UN group has proposed measurement method and installation which is a compromise by which are measured and particle mass, on classical way using filter, and number concentration of solid particles. In that method, after dilution in CVS tunnel, larger particles than 2.5 μm are removed, as well as evaporative components, and then particle number is optically counted.
- Measured particles number concentration on vehicle with DPF is less than 10^{11} particles/km and mass PM = 0.25 mg/km (what is less than in GDI engine). Euro 4 vehicle without DPF has $7 \cdot 10^{13}$ particles/km and mass PM = 18 mg/km in NEDC.
- Working conditions during test cycle with high particle emission are first urban cycle after cold start (because of intensive condensation of liquid particles) and extra urban cycle with high acceleration (due to higher engine load and lack of particles agglomeration at high gas flow). In conventional diesel engines, without DPF, the appearance of high number concentrations is always obtained during the acceleration close to engine full load.
- Reproducibility of particle emission results between different laboratories is much better with engine without DPF than with engine with particulate filter.
- In conventional diesel engines without particle filter there is good correlation between particles mass and number concentration. That is not the case in diesel engines with DPF.
- Repeatability of measured particle number concentration results is good for conventional diesel engines, but it is much worse for diesel engines with DPF. Main reason is that the emission of an engine with DPF is too low with appearance of volatile organic compounds which are sensitive on sampling condition.

Acknowledgments

Special thanks to Professor Zizis Samaras who enabled to me to participate in Particulate Measurement Program and supported my work on M. Sc. thesis. Great thanks to all technical stuff at Laboratory for Advanced Thermodynamics in Aristotle Polytechnic Academy of Thessalonica, Greece. Friendly thanks to Thanasis Mamakos and Savas Gazivanidis.

Abbreviations

CoV – coefficient of variations

CPC – condensation particle counter

CVS – constant volume sampler
ECE – Economic Commission for Europe
DIS – diesel
DPF – diesel particulate filter
ECE – Economic Commission for Europe
GDI – gasoline direct injection
GRPE – Group of representatives for pollution and energy
HC – hydrocarbon
MPI – multi point injection
NEDC – new European driving cycle
NO_x – nitric oxides
PM – particulate mater
PN – particle number
PNC – particle number counter
PND – particle number diluter
PMP – particulate measurement program
VPR – volatile particles remover
UN – United Nations

References

[1] Gorham R., Air Pollution from Ground Transportation, UN, 2002
[2] Ntziachristos, L., Mamakos, T., Samaras, Z., Overview of the European Particulates Project on the Characterization of Exhaust Particle Emission for Light Duty Vehicles, SAE International Congress, 2004
[3] Ntziachristos, L., Samaras, Z., Performance Evaluation of a Novel Probe and Measurement System for Exhaust Particle Characterization, SAE International Congress, 2004
[4] ***, Programme on Fine Particulate Emissions from Passenger Cars, ACEA, part II, 2003
[5] ***, Report of the GRPE PMP, Government Sponsored Work Program, Informal document, UN/ECE, 2003
[6] Kittelson, D., Engines and Nano Particles, a Review, University of Minnesota, Minneapolis, Min., USA, 1997
[7] ***, Health Effects of Diesel Particulates, Diesel Net Technology Guide, 2004
[8] Petrović, V., An Approach on the Investigation of Diesel Engine Particulate Emission, M. Sc. thesis, Faculty of Mechanical Engineering, University of Belgrade, Belgrade, 2006
[9] ***, Inter-Laboratory Correlation Exercise: Framework and Laboratory Guide, UN-GRPE PMP, Phase 3, Informal document no. GRPE-PMP-14-1, 2005
[10] Anderson, J., *et al*., Update on the PMP Phase 3 Inter-Laboratory Correlation Exercise, Working Paper No. GRPE-PMP-17-4, 2006
[11] Anderson, J., *et al*., Particle Measurement Programme (PMP), Light-Duty Inter-Laboratory Correlation Exercise (ILCE_LD), Final Report, Informal Document No. GRPE-PMP-18-2, 2007
[12] ***, Compilation of Existing Particle Number Data from outside PMP Inter-Labiratory Correlaton Exercise (ILCE), GRPE-55-16, 2008

Authors' address:

V. Petrovi}
IMR – Institute
7-13, Patrijarha Dimitrija,
11000 Belgrade, Serbia

E-mail: velipetr@eunet.yu

Paper submitted: March 13, 2008
Paper revised: April 11, 2008
Paper accepted: May 15, 2008