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Effect of Engine Load on Size and Number Distribution of Particulate Matter Emitted from a Direct Injection Compression Ignition Engine

Dhananjay Kumar Srivastava[1], Avinash Kumar Agarwal[1*], Tarun Gupta[2]

[1] *Engine Research Laboratory, Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Kanpur – 208016, India*
[2] *Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur – 208016, India*

ABSTRACT

Particle size and number distribution from an engine tailpipe has a direct bearing on the residence time of the particles in the atmosphere and their toxicity. This study presents the number concentration and size distributions of nano-particles emitted from naturally aspirated, water cooled, single cylinder, diesel fuelled direct injection compression ignition (DICI) engine. The engine exhaust particle sizer (EEPS) was used for measurement of number, surface area and mass distributions of soot particles. It measures particle sizes ranging from 5.6 to 560 nm. Reading the size distribution 10 times per second allows for the measurement of transient emissions of soot particles. The experiments were conducted at a constant engine speed (1500 rpm) with varying engine load. It was found that (a) number and size distribution, (b) surface area and size distribution, and (c) mass and size distribution of soot particles varies significantly with the engine load. The width of the emitted particle size distribution increases with increasing engine load.

Keywords: Air Toxins; Aerosols; Diesel aerosols; Characterization; Hazardous air pollutants; Nano-particle measurement.

INTRODUCTION

The merits of diesel engines, compared to other internal combustion engines, include lower fuel consumption, and lower unburned hydrocarbons emissions, due to the overall lean combustion (equivalence ratio of the order of 0.5), and a better fuel efficiency due to controlled non-homogeneous combustion (diffusion flame) at high pressures. Diesel engine is therefore an attractive option to reduce CO_2 emissions from automobiles and counter greenhouse gas effects (Belardini *et al.*, 1998). On the other hand, the existence of fuel-rich high temperature zones lead to fuel pyrolysis, hence a diesel engine also produces soot particle emissions. Given the intensive use of diesel engines and the detrimental effects of soot particles on environment and health (USEPA, 2002), more stringent emissions standards have been imposed (OECD, 2001).

Soot is formed from unburned fuel, which nucleates from the vapour phase to a solid phase in fuel-rich regions of combustion chamber at elevated temperatures. Soot is a solid substance consisting of roughly eight parts carbon and one part hydrogen (Tree *et al.*, 2007). Newly formed particles have the highest hydrogen content with a C/H ratio as low as one, but as soot matures, the hydrogen fraction decreases. The density of soot is reported to be 1.84 ± 0.1 g/cm^3 by Choi *et al.* (1994) and it agrees with values reported elsewhere. Hydrocarbons and other available molecules may condense on, or get absorbed by soot particles depending on the surrounding conditions. Particulates are a combination of soot and other liquid or solid phase materials that are collected when exhaust gases pass through a filter. Particulates are often separated into a soluble (typically in an organic solvent like benzene) and an insoluble or dry fraction. Soot is often estimated by finding the insoluble portion of the particulates. The fraction of soot in particulate from diesel exhaust varies, but is typically higher than 50%. Other particulate matter constituents include partially burned fuel and lubricating oil, moisture, metals from engine parts and fuel-origin sulphates (Ullman, 1989; Lee *et al.*, 1998). The evolution of liquid or vapour phase hydrocarbons to solid soot particles generally involves six commonly identified processes namely: pyrolysis, nucleation, coalescence, surface growth, agglomeration, and oxidation. A sequence depicting the soot formation process is shown schematically in Fig. 1, while oxidation (the sixth process) converts hydrocarbons to CO, CO_2 and H_2O at any point during these five processes.

These processes may proceed in a spatially and temporally separated sequence as it occurs in a laminar diffusion flame or all of the processes may occur simultaneously as in a well-stirred reactor. In practical combustion systems like diesel

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[*] Corresponding author. Tel.: +91 512 2597982;
Fax: +91 512 259 7408
E-mail address: akag@iitk.ac.in

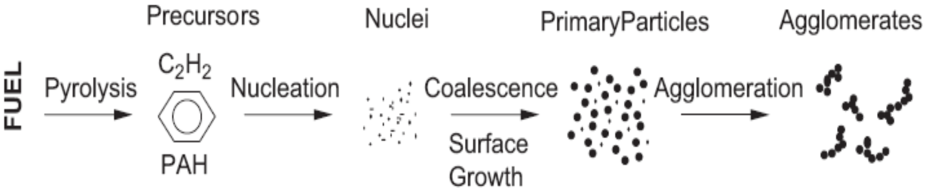

Fig. 1. Schematic diagram of the steps involved in soot formation (Tree *et al.*, 2007).

engines, the sequence of processes may vary between these two extremes.

The residence time of particles in the atmosphere is longest for particles in the diameter range of 0.1–10 µm and is typically about one week. Larger particles are removed from the atmosphere quite quickly by settling process and smaller ones by diffusion and coagulation processes. A typical residence time for 10 nm particles is only about 15 minutes (Harrison, 1996). The main mechanism for removal of these tiny particles is coagulation with particles in the accumulation mode. Atmospheric aerosols also influence the climate by scattering or absorbing sun light and by acting as cloud condensation nuclei (Seinfeld and Pandis, 1998). Particles interact with light by absorption and scattering. For diesel particulates, absorption is much stronger than scattering and is relatively independent of particle size for light in the visible range. These properties depend on particle size, shape, and composition (Scherrer and Kittelson, 1981; Kittelson *et al.*, 1988). The absorption is due to the carbon content of the particles. Light scattering is strongly dependent on particle size and shape and is typically maximum for particles a few tenths of a micron in diameter. The light scattering is mainly due to particles in the accumulation mode size range. Ultra-fine and nano-particles scatter light very weakly. These tiny carbon particles directly affect the Earth's radiation balance by absorbing solar radiation in the atmosphere. This enhances the global warming (IPCC, 2001). Numerical aerosol models predicting the aerosol behaviour in the atmosphere take into account the particle residence time and optical properties. The size and morphology of non-volatile soot particles affect both these factors (Colbeck *et al.*, 1989, 1990). Thus detailed study of the structure, size, and concentrations of particles emitted from different sources is essential for modelling purposes.

Ambient fine particles are of current interest due to their deleterious health effects on population at large (Dockery and Pope, 1994). The aspect of particle size that is attracting the greatest attention is the influence of fine and ultrafine particles on human health. Adverse health effects seem to be linked with smaller particles. The efficiency of deposition in the human respiratory tract depends upon the particle size. In particular, pulmonary deposition increases with decreasing particle size. Recently, special concerns have been raised for particles in the ultra-fine and nano-particles size ranges. Particles that are non-toxic in µm size range may be toxic in nm size range. In addition, the properties of non-volatile soot particles also have been related to adverse health effects (Dasenbrock *et al.*, 1996; Berube *et al.*, 1999; Gehr 2000). There are more than 50 million constant speed direct injection diesel engines operating in India alone in agricultural sector as well as decentralized power generation sector and this number is several times higher than total number of diesel engines used in transportation sector in the country. Therefore, the environmental and health impact of this class of engines is clearly going to much higher than the engines used in transportation sector.

The objective of this study is to characterize the particles number concentration and size distribution from naturally aspirated gen-set engine at different engine loading conditions operating at constant speed. This type of engine is mostly used for decentralized power generation, irrigation and agricultural usage worldwide.

EXPERIMENTAL SET UP

There has been increased interest in obtaining size distribution data during transient engine operation where both particle size and total number concentrations can change dramatically. Till recently, the Scanning Mobility Particle Sizer (SMPS) system was widely used to measure the size distribution of engine generated aerosols. Since the SMPS requires a minimum of 60 sec to make a measurement, its use has been limited to stable engine operating conditions only. A newly developed Engine Exhaust Particle Sizer (EEPS) spectrometer provides both high temporal resolution and size resolution by using multiple charge detectors in parallel. This makes the EEPS ideal for measuring engine aerosols even in transient conditions. It measures particle sizes ranging from 5.6 to 560 nm with a sizing resolution of 16 channels per decade (a total of 32 channels). Reading the size distribution 10 times per second allows for the measurement of transient particulate emissions. The particle mobility measurement is made similar to what is done in the SMPS however multiple electrometers are used to provide simultaneous measurements. A naturally aspirated single-cylinder direct injection water cooled diesel engine was used in this study. The technical specifications of the engine are provided in Table 1.

The engine was coupled with a single phase, 220 V AC

Table 1. Engine specifications.

Maker/Model	Kirloskar/DM10
Bore x stroke	102 / 116 mm
Compression ratio	17.5:1
Displacement volume	0.9481 L
Rated Power	7.4 kW @ 1500 rpm
Start of fuel injection	26^0 BTDC
Nozzle opening pressure	200-205 bar

alternator. The alternator was used for loading the engine through a resistive load bank. The load bank consists of eight heating coils (1000 W each). A variac was connected to one of the heating coils so that load can be controlled precisely by controlling voltage in that particular coil of the load bank. Fig. 2 shows the schematic of experimental setup.

Experimental Procedure

All experiments were carried out at constant engine speed (1500 rpm) with varying engine load. Commercially available diesel was used for these experiments. At each engine operating condition, engine was stabilized for 10 minutes and then the measurements were made. Experiments were done at three different engine loads (0 kW, 3 kW and 5 kW). For measuring particle size distribution in the diesel engine exhaust, EEPS (Make: TSI, USA; Model: 3090) was used. Working principle of EEPS is described in detail by Gupta *et al*. (2010). A part of exhaust from engine was drawn from the exhaust pipe. Dilution of this exhaust gas was carried out using rotating disc thermo-diluter (Make: Matter Engineering; Model: 379020) to reduce the particle concentration to a value, which is within the measurement range of the EEPS. For the present set of experiments, exhaust gas was diluted by a dilution ratio of 111:1. Particle concentrations and number distribution data was stored in computer for further analysis and this dilution factor was accounted for before presenting all the results.

RESULTS AND DISCUSSIONS

The measurement of soot size distribution was made after the stabilization of engine and under optimum running conditions. All the results presented in this paper are average of sixty data points and its corresponding standard deviation is also reported. The process of soot formation and release in diesel engines is strongly influenced by the localised temperature distribution and fuel/air ratio, which vary greatly inside the combustion chamber. The variations in temperature and fuel/air ratio affects the rate of soot formation and release. In the fuel rich spray zones, the rate of soot formation is greater than the rate of soot oxidation, which leads to formation of new soot, while in the lean zones, the rate of oxidation is more than the rate of formation, therefore, the net effect is a reduction in the soot concentration in these zones.

Fig. 3 shows the particle number and size distribution at different engine loads. It can be seen that smaller particles in the size range of 40–50 nm dominate at no load. As the load is increased, dominating size range decreases and particles in the size range of 20–25 nm have the highest number concentration. On increasing the engine load further, the number of smaller size particles reduce significantly and particles in the size range of 60–70 nm start dominating.

Temperature inside the combustion chamber increases as load on the engine increases. Temperature has the greatest effect among all parameters of the soot formation process as it increases all the reaction rates involved in soot formation and oxidation reactions. As temperature of combustion chamber is increased, the rate of oxidation increases more rapidly than the rate of soot formation (Glassman, 1988).

It can be seen that the number distribution obeys log-normal distribution pattern and distribution width increases with increasing engine load (Fig. 3). Harris *et al.* (2001) conducted experiments on diesel engine and examined soot particle distribution under various engine operating conditions. They also observed that distribution of soot particles follow nearly log-normal distribution. At higher engine loads, the combustion chamber temperature and the amount of injected fuel are also higher, while the air/fuel ratio is on the lower side. These conditions increase the initial soot formation and also accelerate the agglomeration process. Due to faster agglomeration process, the peak of the number distribution is towards larger particles at higher load. Broadening of the particle size distribution with engine load is also in agreement with Virtanen *et al.* (2004).

Nearly whole surface area of individual nuclei that comprise the agglomerates is available for adsorption. Thus,

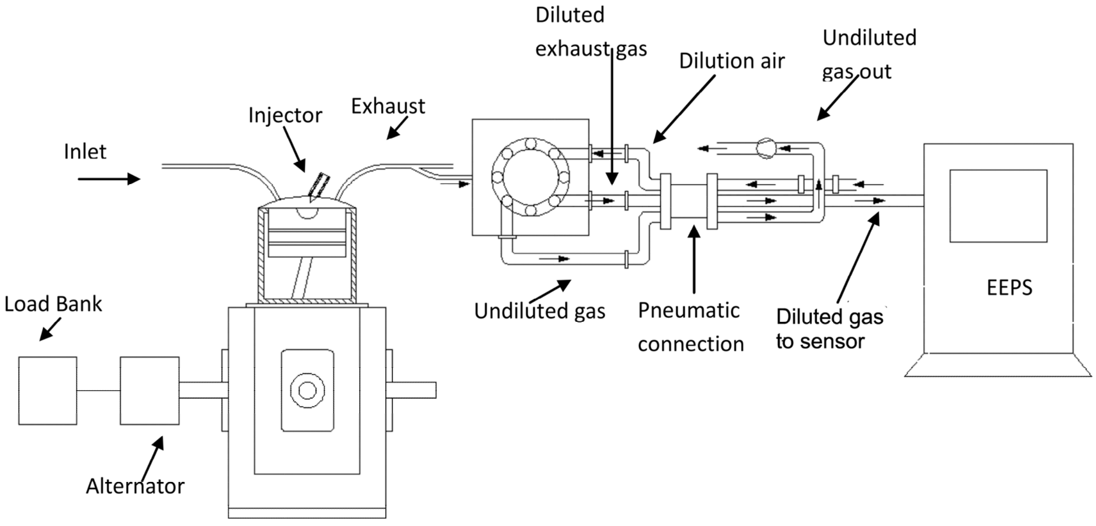

Fig. 2. Schematic of experimental set up.

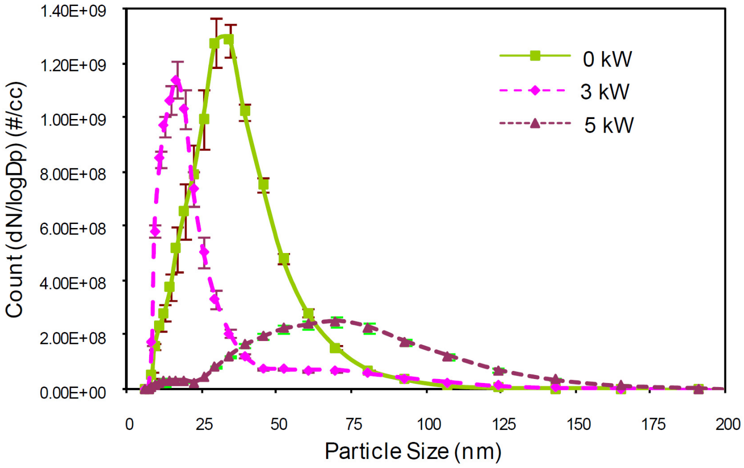

Fig. 3. Particle size and number distribution from a diesel engine at different engine loads.

the surface area of diesel particles is probably more a function of the size of the individual nuclei in the agglomerates rather than the agglomerate size (Kittelson, 1998). This surface area may be available for atmospheric reactions. In the atmosphere, various atmospheric constituents will compete with exhaust constituents for this surface area. Smaller particles tend to have significantly higher surface area per unit particle mass compared to larger particles, thus offering larger surface area for condensation/adsorption of toxins such as VOC's and PAH's. Therefore, smaller particles tend to become more hazardous for human health compared to larger particles.

Fig. 4 shows the surface area distribution of soot particle at different engine loads. Surface area of particles depends on diameter and number distribution. It can be seen that the surface area of particles in the dominating size range (40–50 nm) is highest. When the load increases to 3 kW, the dominating surface area reduces because the size of the particle now reduces to 20–25 nm. The particles in the size range of 75–85 nm dominate the surface area, inspite of lower number density. At 5 kW load, particles in the size range 80–110 nm dominate.

The mass of soot particles emitted by engines is very important from emission legislation point of view. As of now, the total mass is the indicator used and the size distribution is not at all important from emission legislation point of view. The mass distribution of particles with size is shown in Fig. 5. It can be seen that mass distribution essentially depends on the engine load. Higher is the engine load, larger particle size range dominates the mass spectrum.

CONCLUSIONS

The size, surface area and mass distributions of soot particles were investigated in the exhaust from a single cylinder direct injection compression ignition engine for different engine loads ranging from no load to full load at constant engine speed in a typical engine used in agricultural/decentralized power generation sector. It was found that the shape of the size distribution curve of soot particles depends on the engine load. Size range of the particles increases as engine load is increased. Smaller particle in the size range of 40–50 nm dominate at no load while at full load, particles in the size range of 60–70 nm

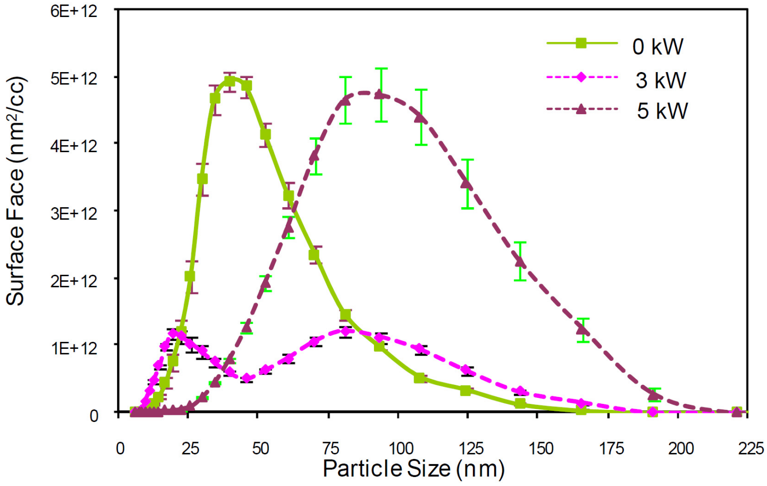

Fig. 4. Particle surface area and size distribution from a diesel engine at different load.

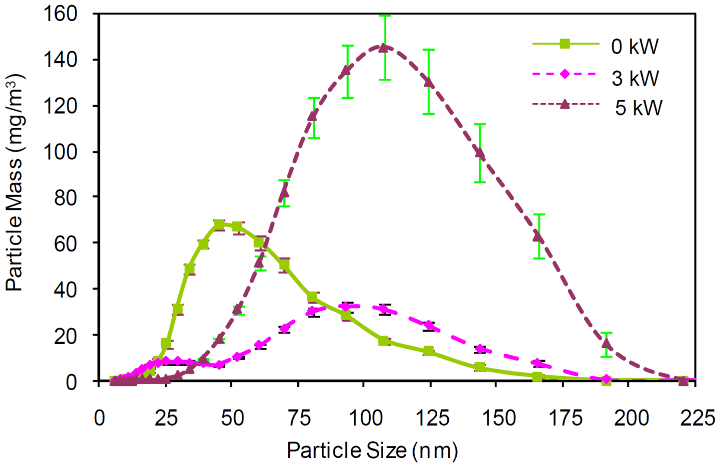

Fig. 5. Particle mass and size distribution from a diesel engine at different loads.

dominate. The number distribution obeys log-normal distribution pattern. Peak of the surface area distribution shifts towards the larger size range of the particles as engine load was increased. Mass distribution of the particles also depends on the engine load. Coarser particles dominate the mass spectrum at the higher engine loads.

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REFERENCES

Belardini, P., Bertoli, C., Ciajolo, A., D'Anna, A. and Del Giacomo, N. (1992). Three Dimensional Calculations of D. I. Diesel Engine Combustion and Comparison with in Cylinder Sampling Valve Data. *SAE* 92225.

Berube, K.A., Jones, T. P., Williamson, B.J., Winters, C., Morgan, A.J. and Richards, R.J. (1999). Physicochemical Characterization of Diesel Exhaust Particles: Factors for Assessing Biological Activity. *Atmos. Environ.* 33: 1599–1614.

Choi, M.Y., Hamins, A., Mulholland, G.W. and Kashiwagi, T. (1994). Simultaneous Optical Measurement of Soot Volume Fraction and Temperature in Premixed flames. *Combust. Flame* 99: 174–86.

Colbeck, I., Appleby, L., Hardman E.J. and Harrison, R.M. (1990). The Optical Properties and Morphology of Cloud-processed Carbonaceous Smoke. *J. Aerosol Sci.* 21: 527–538.

Colbeck, I., Hardman, E.J. and Harrison, R.M. (1989). Optical and Dynamical Properties of Fractal Clusters of Carbonaceous Smoke. *J. Aerosol Sci.* 20: 765–774.

Dasenbrock, C., Peters, L., Creutzenberg, O. and Heinrich, U. (1996). The Carcinogenic Potency of Carbon Particles with and without PAH after Repeated Intratracheal Administration in the Rat. *Toxicol. Lett.* 88: 15–21.

Dockery, D.W. and Pope, C.A. (1994). Acute Respiratory Effects of Particulate Air Pollution. *Auun. Rev. Publ. Health* 15: 107–132.

Gehr, P., Geiser, M., Hof, V.I. and Schurch, S. (2000). Surfactant-Ultrafine Particle Interactions: What we can Learn from PM_{10} Studies. Philos. *Trans. R. Soc. London, Ser. A* 358: 2707–2718.

Glassman, I. (1988). Soot Formation in Combustion Processes, Proceedings of the 22nd International Symposium on Combustion, The Combustion Institute, p. 295–311.

Gupta T., Kothari A., Srivastava D.K., and Agarwal A.K., (2010), Measurement of Number and Size Distribution of Particles Emitted from a Mid-sized Transportation Multipoint Port Fuel Injection Gasoline Engine. *Fuel* 89: 2230–2233.

Harris S.J, and Maricq M.M., (2001), Signature Size Distributions for Diesel and gasoline Engine Exhaust Particulate Matter. *J. Aerosol Sci.* 32: 749–764.

Harrison, R.M. (1996). Airborne Particulate Matter in the United Kingdom, Third Report of the Quality of Urban Air Review Group, The University of Birmingham, Edgbaston, England.

IPCC (2001). Synthesis Report (www.ipcc.ch).

Kittelson, D.B., (1998). Engines and Nanoparticles: A Review. *J. Aerosol Sci.* 29: 575-588.

Kittelson, D.B., Kadue, P.A., Scherrer, H.C. and Lovrien, R. (1988). Characterization of Diesel Particles in the Atmosphere, Final Report, Coordinating Research Council.

Lee, R., Pedley, J. and Hobbs, C. (1998). Fuel Quality Impact on Heavy Duty Diesel Emissions—A Literature Review. *SAE* 982649.

OECD (2001). Réduire les émissions des Véhicules/Vehicle Emission Reductions. Proceedings of the European Conference of Ministers of Transport (ECMT), Paris, 92-82-11363-9.

Scherrer, H.C. and Kittelson, D.B. (1981). Light Absorption Cross Sections of Diesel Particles. *SAE* 810181.

Seinfeld, J.H. and Pandis, S.N. (1998). *Atmospheric Chemistry and Physics, From Air Pollution to Climate Change*, John Wiley & Sons: New York.

Tree, D.R., and Svensson, K.I., (2007), Soot Processes in Compression Ignition Engines. *Prog. Energy Combust. Sci.* 33: 272–309.

Ullman, T.L. (1989). Investigation of the Effects of Fuel Composition on Heavy-duty Diesel Engine Emissions. SAE 892072.

USEPA (2002). Air Quality Criteria for Particulate Matter, Third External Review Draft EPA/600/P-99/002aC, Research Triangle Park, NC.

Virtanen, A.K.K., Ristimaki, J.M., Vaaraslahti, K.M., and Keskinen, J. (2004). Effect of Engine Load on Diesel Soot Particles. *Environ. Sci. Technol.* 38: 2551–2556.

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