Gasoline Direct Injection Engines and Particulate Emissions

Nikhil Sharma and Avinash Kumar Agarwal

Abstract Gasoline direct injection (GDI) engines are increasingly used in transport sector worldwide in recent years due to the advantages they offer. These include superior fuel economy and better engine response and control due to introduction of electronic control unit (ECU) and high-pressure fuel injection system. One of the main challenges of using GDI engine vehicles is that they emit particulates, which are not an issue in case of multipoint port fuel injection (MPFI) engines. However, there is potential to further improve GDI engines for lower particulate matter (PM) emissions. Particulates from GDI engines are of different sizes such as coarse, fine and ultra-fine, and they also vary in composition and origin. The particulate of different sizes is known to cause adverse health effects. In this chapter, fundamental aspects of both homogeneous and stratified modes of combustion of GDI engines have been discussed, in addition to wall, spray and air-guided GDI engine concepts. A section of the chapter covers detailed comparison of particulate emitted by GDI and MPFI engines. Various size and concentration-based PM measurement techniques and instruments available commercially are included in this chapter. A discussion on influence of engine load, fuel type and spray characteristics on particulate emissions is elaborated towards the end of this chapter in addition to GDI soot morphological studies.

Keywords Particulate matter · Measuring techniques · Legislation
Health effects

List of abbreviations

BMEP	Brake mean effective pressure
Dp	Diameter of primary soot particle
ECU	Electronic control unit
EGR	Exhaust gas recirculation

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EGT	Exhaust gas temperature
ELPI	Electrical low-pressure impactor
FESEM	Field emission scanning electron microscope
FIP	Fuel injection pressure
GDI	Gasoline direct injection
GPF	Gasoline particulate filter
HRTEM	High-resolution transmission electron microscopy
IARC	International agency for research on cancer
IC	Internal combustion
ICP-OES	Inductively coupled plasma optical emission spectrometry
MPFI	Multipoint port fuel injection
PFI	Port fuel injection
PM	Particulate matter
WHO	World health organization

1 Introduction

GDI engine is considered as one of the most promising gasoline engine technologies for future, since it offers relatively higher BSFC and specific power output compared to existing engine technology, such as MPFI. In addition, GDI offers superior knock resistance characteristics compared to MPFI engines because of the charge cooling effect inside the engine cylinder experienced due to vaporisation of the injected liquid fuel droplets. However, particulate emissions from GDI engines are a major area of concern among scientists and industries because they pose serious health risk [1–4].

Figure 1 shows different zones of human respiratory system affected by particulates of various sizes. Particulate emissions affect human health adversely [5] because they penetrate deep into the human respiratory system (nasopharynx, trachea, bronchi, bronchioles, alveoli) [6, 7] via inhalation and contaminate the respiratory system with various toxic substances, which are adsorbed onto its surface (Fig. 1). As particulate size becomes finer, the severity of health impact increases because of increased surface-to-volume ratio and can eventually cross the cellular membranes to enter the blood-stream [8]. PM_{10} is filtered out in the nose, throat and bronchial tubes. $PM_{2.5}$ can, however, penetrate into the bronchial tubes, and $PM_{0.1}$ can even reach up to the alveoli and enter the blood-stream. Few important health problems due to PM emissions, which may lead to premature death [9] include asthma, irregular heartbeats, decreased lung function, non-fatal heart attack and severe coughing. Hence, there is a need to understand reasons for particulate emissions and their effects on public health, when using alternative/conventional fuels in IC engines and ultimately control their formation in the combustion chamber.

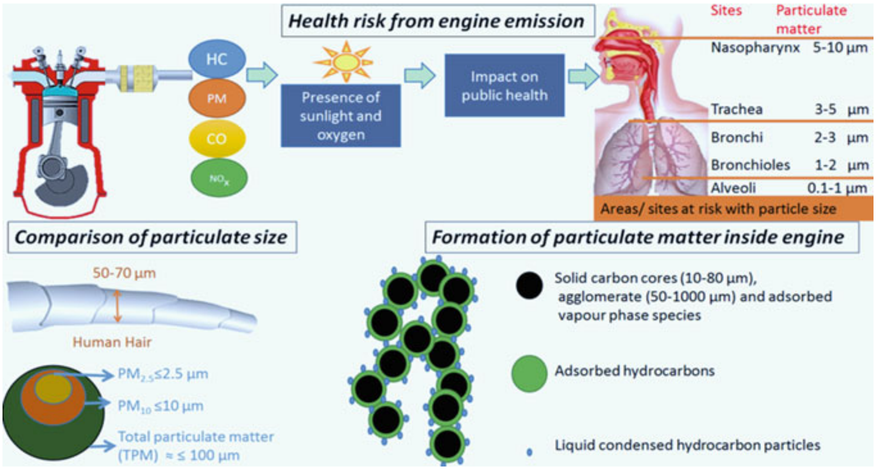

Fig. 1 Particulate emissions from IC engines [42]

Figure 2 shows the relationships between typical engine exhaust particle numbers, particle mass and particle surface area with respect to particle size. Particle size distribution in this graph can be further divided into nuclei mode particle (Dp: 5–50 nm), nanoparticles (Dp < 50 nm), ultra-fine particles (Dp < 100 nm), accumulation mode particle (Dp: 100–300 nm) and coarse mode particles (Dp < 10 µm). The particulate of different size distributions has different composition, e.g. (a) nuclei mode particles are made of hydrocarbons, which form the nucleation mode particles and (b) soot agglomerates with hydrocarbons condensed

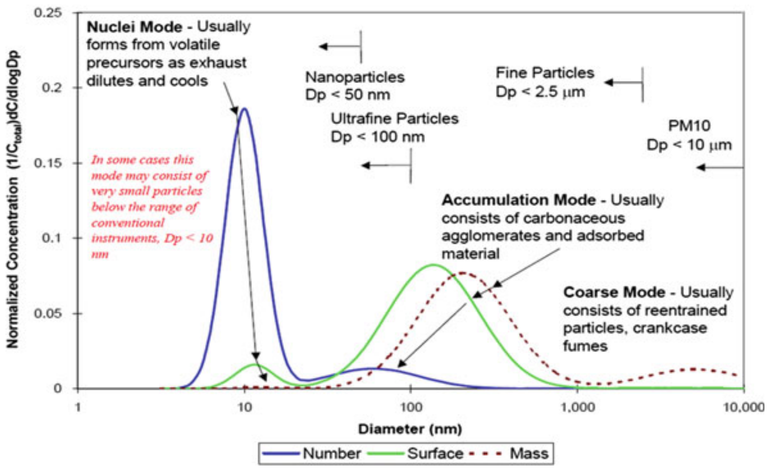

Fig. 2 Typical engine exhaust particle size distribution with particle mass and number weightings [50]

and adsorbed on to the surface form accumulation mode particles. The contribution of ultra-fine particles towards particulate mass is significantly less but towards particle numbers it is very high. Their toxicity increases because of smaller size, and they are prone to cause adverse health effects [10].

In addition to particulate mass, particle number is also regulated for gasoline vehicles with implementation of Euro-VI norms. MPFI engine emits relatively lower particle mass and particle number than the permissible limit, but GDI engine will require significant efforts to meet this emission legislation for particle mass and particle number.

Biofuels are increasingly being used in GDI engine in research laboratories, because of economic and scientific needs of the society and the environment [11–13]. Zhang et al. [14] investigated the effect of particulate emissions from GDI engine fuelled by gasohol blends (ethanol and n-butanol) using EGR and reported that particulate number concentration reduced because of addition of alcohols in gasoline, and the number peak shifted towards smaller sizes in the particulate number–size distribution curve, with increasing percentage of EGR. Higher proportions of finer particles were obtained with increasing percentage of alcohol blended in gasoline. Bai et al. [15] performed investigations using exhaust gas trap (EGT) for controlling the part-load emission characteristics of a GDI engine. They used single-stage injection to obtain homogeneous combustion mode and double injection to obtain stratified combustion mode. They concluded that cyclic variations increase with increasing EGT. They also reported that stratified mixture using the two-stage injection strategy can reduce the cyclic variations and combustion duration, thus improving the thermal efficiency. In this chapter, discussions on GDI engine combustion concept, applicable emission legislations, health effects of PM emission, comparison between MPFI and GDI engines and measurement techniques for particulate have been discussed. Effect of type of fuel, EGR, engine load and EGR on particulate morphology is also discussed.

2 Combustion Concept

GDI technology is regarded as a key technology with huge potential for the transport sector. In comparison to MPFI, GDI engine delivers superior efficiency and specific power output. This difference between the two technologies is essentially due to fuel-air mixture preparation method. In a conventional SI engine, fuel-air mixture is prepared in the intake manifold, outside the combustion chamber. There is sufficient time available to the homogeneous fuel-air mixture preparation. Moreover, MPFI technology-based engine operates on stoichiometric or near stoichiometric fuel-air mixture. On the other hand, mixture preparation in GDI engine is very different from that of MPFI. In a GDI engine, fuel-air mixture is prepared inside the combustion chamber, and the fuel is injected directly inside the engine combustion chamber. GDI engine works on two different combustion modes. Figure 3a shows homogeneous combustion mode, and Fig. 3b shows stratified

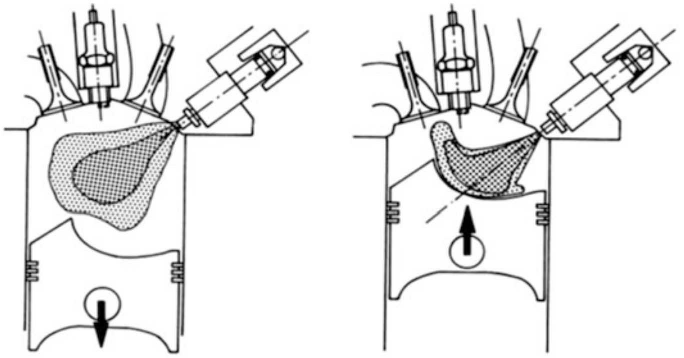

Fig. 3 Two modes of combustion in GDI engine

combustion mode. In homogeneous mode of combustion, mixture is stoichiometric, and in stratified mode of combustion, overall mixture is lean, but the charge is inhomogeneous and stratified. The local fuel-air ratio near the spark plug (at the flame) is richer.

In homogenous mode of combustion, fuel is injected early in the intake stoke so that there is sufficient time available for homogenous fuel-air mixture preparation. On the other hand, in stratified mode of combustion, fuel is injected late in the compression stoke. In both the cases, fuel-air mixture is ignited with the help of a spark plug. Due to comparatively lesser time available, the mixture is stratified, and it essentially leans out spatially with increasing distance from the fuel spray core. Stratified mode of combustion is required when the demand for power is less, and homogenous mode of combustion is required when the demand of power is comparatively higher. Lesser fuel quantity is injected in the stratified mode of combustion, and relatively higher fuel quantity is injected in the homogeneous mode of combustion.

Apart from the two modes of combustion, there are three types of engine designs for GDI engine as shown in Fig. 4 (spray-, wall- and air-guided), which are commercially available.

In the spray-guided GDI engine, the gap between the spark plug and the injector is comparatively lesser. This type of design is typically favourable to create stratified combustion mode by forming ignitable stratified mixtures near the spark plug. The moment fuel is injected, a spark instigates combustion in the richer part of the stratified charge near the spark plug. Parameters such as combustion chamber geometry, spray dynamics, FIP and fuel droplet size distribution are the factors responsible for charge stratification. This design causes spark-plug fouling and soot formation but eliminates wall-wetting. Therefore, fuel spray should be precisely controlled. Minute variation in fuel quantity may result in large cyclic variations and misfiring.

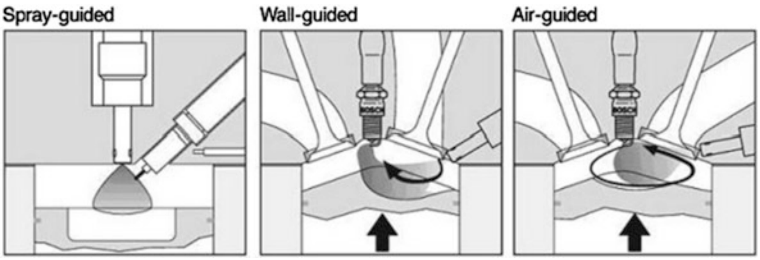

Fig. 4 Different DISI combustion systems [51]

In a wall-guided GDI engine, the injector is mounted on one side, and curved nose shape of the piston guides the charge nearer to the spark plug. There exists sufficient gap between the spark plug and injector. This type of engine is typically used to operate in homogeneous combustion mode. This is because there exist significant cyclic variations in stratified combustion mode for this design. Costa et al. [16] concluded that piston head geometry played an important role in the mixture formation in wall-guided GDI engines. Since fuel directly impinges on the top surface of the piston, this design of engines generates relatively higher soot emissions than spray-guided GDI engines.

In the air-guided GDI engine, interaction between the fuel spray and the motion of air charge inducted in the cylinder is responsible for charge stratification. The fuel is essentially injected into the air, which is directed towards the spark plug. In such designs, shape of inlet port plays an important role to direct the fuel near the spark plug. In this technique, the butterfly valve/throttle controls the mass flow rate of air, and fuel does not wet the piston top or the cylinder.

In a GDI engine, one combustion system and both combustion modes are present. Most recent engines use a combination of wall- and air-guided designs.

A typical torque vs. BMEP curve is presented in Fig. 5. Stratified combustion mode is desirable at low engine speeds and at lower engine torque. Homogeneous combustion mode is required, when the driver demands higher torque and higher engine speed. The amount of throttle pressed by drivers gives a message to the ECU to operate the engine in a specific mode. There is no separate button to change the mode of engine operation.

3 Legislation

Emission legislations play a significant role in improving the urban air quality; therefore, they tend to become increasingly more stringent with time. Although there is no scientifically proven and defined threshold where one can say that PM will not cause adverse health effects. In recent years, strict restrictions have been applied by governments world over to limit emissions from transport sector to improve air quality, especially in urban settings.

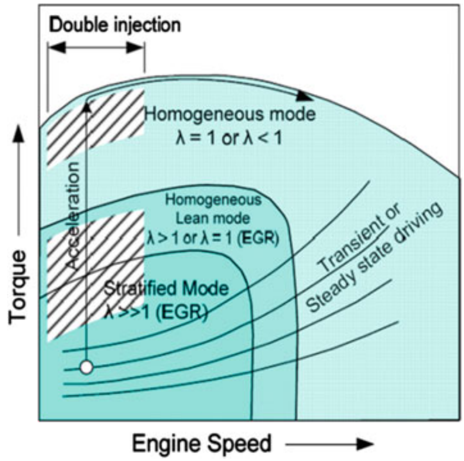

Fig. 5 Speed versus BMEP for different combustion modes

Indian emission legislations closely follow European Union legislations. In case of four-wheelers, Indian emission legislations are behind European legislations by ~5 years in major cities of India and ~10 years behind throughout the nation. However, two- and three-wheeler emission legislations are developed independently by India, depending upon country-specific requirements. At present, many Indian metro cities are struggling with severe air-quality issues. In this context, India has decided to directly move from BS-IV to BS-VI emission legislations by April 2020 in the entire nation. With this courageous decision, India has set a benchmark for other developing nation to also provide a clean and healthy environment for sustainable development of their citizens. There is a PM mass emission limit applicable to all gasoline engines in EU-V emission standards, which limits it to 0.005 g/km. To meet even more stricter emission legislations of EU-VI, GDI engines must be equipped with gasoline particulate filter (GPF).

4 Health Effects of Particulates

Rapid industrialization and urbanization for creating economic growth and job opportunities are the reason for increased PM levels in the metro cities. PM contains solids/liquid droplets which are considered as harmful to the human health because they have long atmospheric retention time and they also travel longer distances. Government implements emission legislations and introduces policies from time to time to reduce PM; however, current levels of PM emissions still cause prominent risk to human health. People with pre-existing heart and lung diseases and children and elderly people are more prone to adverse health impact of PM emissions. Air pollutants in combination with particulates accumulate and increase the severity of adverse health effects. Particulates change the blood circulation in human body and increase the mortality rate [17]. Mortality rate increases with continuous exposure to particulates. It is roughly estimated that exposure to diesel particulates could decrease projected life expectancy between one year [18] to five and half years [19]. In addition to this, the exhaust from diesel engines has been classified as carcinogenic (Group 1) to humans by the International Agency for Research on Cancer (IARC) and WHO [20].

The size of particulates is directly associated with the severity of health problems caused. $PM_{2.5}$ is about 1/28th in diameter to that of a human hair or even smaller. These fine particles can invade lungs and alveolar regions [21], and ultra-fine particles can even enter the blood vessels [22]. Exposure time to these fine particles is another parameter directly associated with health hazard. Longer the exposure time, more adverse effects it may cause to the human health. This is primarily due to increase in cardiopulmonary and lung cancer mortality. Exposure of particulates to children could be even more dangerous. It directly affects lungs and its growth rate [23]. It is reported that exposure to $PM_{2.5}$ is directly linked with the risk of cardiopulmonary mortality by 6–13% per 10 $\mu g/m^3$ of $PM_{2.5}$ [24–26]. In 2005, 130,000–320,000 premature deaths took place in the USA due to high exposure to $PM_{2.5}$. In another study, reduction in long-term exposure to $PM_{2.5}$ in the USA resulted in increased average life expectancy [27]. Various adverse health effects caused by particulates are summarized below in Table 1.

Table 1 Various health effects caused by particulates to humans and animals

Diseases	Causes/remarks
Asthma	Asthma symptoms can be worsened by increase in PM levels in a city [52, 53]
Lung cancer/decreased lung function/lung irritation	Fine particles directly affect the bronchi, which effects health of lungs and results in cancer. It causes lung irritation, leading to increased permeability in lung tissues [54, 55]
Cardiovascular diseases	Fine particulate affects heart and its functions [56]
Premature delivery and birth defects	PM may pass from mother to the child, resulting in a wide range of birth defects. Lowers birth rate [57–59]
Premature death	Higher in regions with high level of particulate emissions [60, 61]
Vascular inflammation	This is a result of plaque in arteries [62]
Atherosclerosis	Arteries become hard, reduce elasticity, plaque builds up in arteries. This leads to heart problems [63, 64]
Inflammation of lung tissues	Releases chemicals, which directly attack heart and reduce its functions [65, 66]
Blood chemistry changes	Results in clots that may lead to heart attack [62, 67]
Sensitivity to viral and bacterial germs	This leads to pneumonia in vulnerable person [68]
Others diseases	Increased blood pressure (BP), increased stress, autonomic imbalance and arrhythmias, prothrombotic and coagulant changes [67]

5 Reasons for Particulate Formation in GDI Engines

Particulates from diesel engines are being studied by researchers for last many decades. Particulate emissions were not a major concern in gasoline engines until GDI came into reality. Figure 6 shows the steps of soot formation mechanism and reasons for soot formation in GDI engines.

PFI of gasoline results in significantly lower PM emissions compared to GDI engines. This is because PFI results in strongly premixed and almost homogeneous charge resulting in stoichiometric mixture inside the combustion chamber. Hence, there are no fuel-air rich mixture zones in the combustion chamber; therefore, PFI results in negligible soot formation. On the other hand, homogeneity of fuel-air charge in GDI engine is relatively lower. The reason for relatively lower fuel-air mixture homogeneity is due to limited time available for fuel droplets to evaporate in the combustion chamber. This also results in high-temperature zones where there is relatively lower amount of oxygen present and higher concentration of

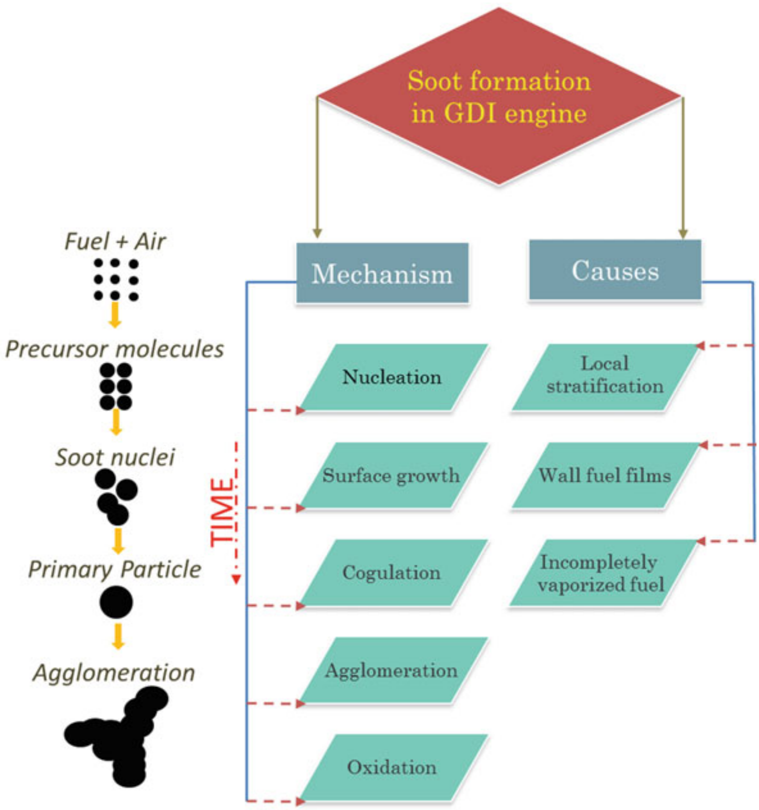

Fig. 6 Mechanism and steps responsible for soot formation in GDI engines

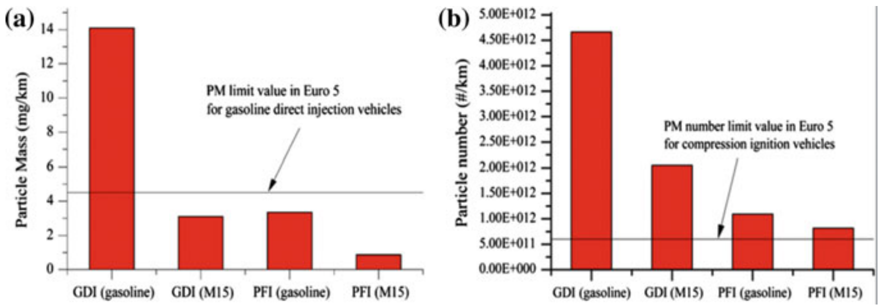

Fig. 7 **a** PM mass emissions using gravimetric measurement method. **b** total PN emission using ELPI [28]

hydrocarbon fuels. This may result in endothermic pyrolysis reactions, which in turn lead to soot formation. Another aspect, which is responsible for relatively higher particulate emissions from GDI engines, is fuel spray impingement on the piston surface (Leidenfrost effect). A fuel vapour film forms on the piston top surface, which reduces the heat transfer rate. Therefore, evaporation of subsequent fuel spray droplets is relatively lesser due to this vapour film formation, leading to diffusion combustion. This may also lead to locally fuel-rich combustion, which results in particulate formation.

Liang et al. [28] compared PM emissions from GDI vehicles and PFI vehicles fuelled by M15 and gasoline using electrical low-pressure impactor (ELPI) and mass emission measurements using gravimetric method. It was found that for each vehicle, PM obtained from gravimetric analysis estimated that PM mass from M15 fuelling was comparatively lower than gasoline fuelling. Similar trends were obtained for PN emissions. For both fuels, PM and PN emission from GDI engine were found to be relatively higher than the PFI engine.

It is reflected by Fig. 7 that GDI engine fuelled by M15 resulted in 78% reduction in PM mass and 56% reduction in PN compared to GDI engine fuelled by gasoline. The presence of oxygen in methanol resulted in more complete combustion, which reduced soot formation. Moreover, methanol did not contain aromatic components which were the building blocks for soot formation.

6 Measuring Techniques

There are numerous instruments available in market for measuring size distribution of particulates. Important instruments measure particle concentration and particle size distributions [29]. Figure 8 shows various methods and instruments used for measurements of particulates.

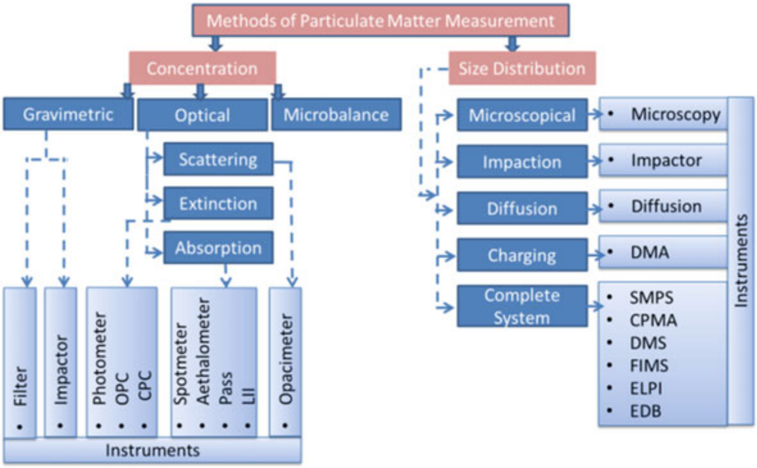

Fig. 8 Various methods for measurement of particulates

a. Concentration Measurement Methods

The particulate concentration can be measured in terms of particulate mass (*m*), particulate number (*N*) and particulate surface area (*S*) distributions with particulate size. There are several correlations used in such instruments. These measuring instruments work on different principles.

i. Gravimetric Method: In this method, particulate sampling is done on a quartz filter paper in a dilution tunnel for a fixed time. Particle mass concentration is found by weighing the quartz filter paper before and after the sampling. This offline measurement technique is time-consuming and costly.
ii. Optical Methods: In these methods, light (visible, infrared or laser) is made to pass through exhaust gas, where each single particle scatters the incident light in all directions. Each scattering signal is detected by a photo-diode. Optical instruments generally work on the principles of light extinction, or scattering, or absorption. These methods have an advantage of measuring particles of several sizes simultaneously. The estimation of particle size is based on many assumptions related to characteristics of particles. Particle diameter obtained is equivalent diameter for particles with the same refractive index as that of the calibration particle of the instrument employed. Details of such instruments are given by Giechaskiel et al. [30].
iii. Microbalance Method: Such methods use a vibrating substrate to collect soot particles. The frequency of oscillations of vibrating substances changes with changing amount of particulate collected on the substrate. This change in frequency is used to calculate the mass concentration. Giechaskiel et al. [30] described this measurement technique in detail.

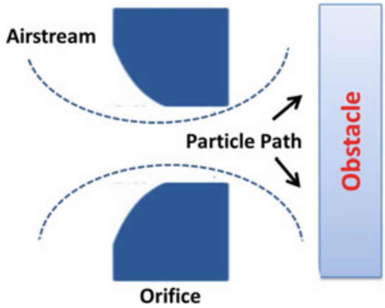

Fig. 9 Typical design of an impactor-based segregation scheme

b. **Size Distribution Measurement Methods**

i. Microscopy: In this technique, soot samples are collected on a filter paper through a dilution tunnel. Further, samples are prepared for SEM and TEM analysis. The time spent for microscopic analysis is significantly higher than other measuring techniques.
Impactor: An impactor consists of a series of orifices or circular slots and an obstacle designed for the collection of size-segregated particulates. A typical impactor is shown in Fig. 9. Particles larger than specific aerodynamic size strike the obstacle surface, while smaller particles proceed through the sampler [31]. Smaller particles are collected in the next stage with smaller orifice sizes. This process continues until the smallest particles get filtered out through the impactor. The particles get separated based on their inertia [32].

The details of few other size distribution measurement methods with their measuring principles and schematic are given in open literature [33–36].

7 Impact of Fuel Composition/Properties on PM Emissions

There are many fuel properties/composition which can effect PM emissions. The following fuel properties are the prominent ones:

(1) Aromatic content
(2) Olefin content
(3) Sulphur content
(4) Volatility
(5) Oxygen content

(1) Aromatic content: Aromatic hydrocarbons are those hydrocarbons, which have sigma bonds and delocalized pi electrons between carbon atoms forming a circle. Higher aromatic hydrocarbons have very high octane number, and they

reflect poor quality of mineral diesel. Increasing the aromatic content in the fuel exacerbates fuel pyrolysis, yielding more soot [37]. Hence, particulate emissions increase with increasing aromatic content of the fuel. Combustion characteristics such as heat release rate and the cylinder pressure are not affected significantly by the aromatic content of the fuel [38].

(2) Olefin content: The class of hydrocarbon compounds that has at least one carbon–carbon double bond in the linear chain is called olefins. Due to the presence of double bond, these olefins are more reactive than paraffinic or aromatic compounds present in gasoline. Olefins have higher formation potentials, and their quantity in gasoline is legislated by the specifications/government. Moreover, olefins have a lower octane number, and they are known to cause carbon deposits in engines. High olefin content in the fuel can lead to plugging of the nozzle holes in the fuel injector and valves deposits due to higher particulate emissions.

(3) Sulphur content: Sulphur exists naturally in small quantities in petroleum products. However, oil companies have to remove fuel sulphur because of two reasons. First reason is that it combines with oxygen to produce sulphur dioxide, which is a catalyst poison and ruins engine's catalytic converter system. The other reason is that it causes acid-rain. SO_2 emissions contribute to formation of secondary inorganic aerosols, and fine particles, which are harmful to the human health. The sulphur compounds are primarily converted by the engine to SO_2, which is not really a problem to be resolved by the automotive manufacturers. This needs to be resolved by the petroleum refiners, who are responsible for removing fuel sulphur. SO_2 gets convert into sulphuric acid under atmospheric conditions in the presence of moisture and sunlight, which encourages gas-to-particle conversions and ultimately soot formation. Hence, SO_2 becomes important for the automotive manufacturers because the diesel oxidation catalysts (DOCs) convert SO_2 into sulphuric acid, which encourages particulate formation that the dilution tunnel filter captures.

(4) Volatility: Volatility is a measure of the tendency of a fuel to vaporize and change from liquid to vapour. Different fuels have different volatility, and this further depends on in-cylinder pressure and temperature. PM emissions are highly dependent on fuel volatility. Lesser the volatility of fuel such as biodiesel, higher will be particulate emission generated by it under identical engine operating conditions. PM emissions are related to both, FIP and fuel volatility. If the fuel volatility is higher, lower FIP can produce lesser particulate emissions from the engine. This is because higher volatility enhances fuel-air mixture, resulting in relatively lesser particulate formation. Fuel film formation on the piston of wall-guided GDI engine is also reduced in case of higher volatility fuels. They also result in reduction in PM emission from a GDI engine.

(5) Oxygen content: PM is generally formed when fuel does not completely oxidize due to insufficient oxygen availability because of some reason [39]. If a fuel contains inherent fuel oxygen content, then more complete combustion can take

place. Oxygenated fuels such as ethanol, methanol, butanol and propanol are usually blended with gasoline to increase fuel oxygen content. These alcohols can be added in various proportions to the gasoline. Inherent oxygen present in ethanol helps oxidize particles and ultimately reduce PM emissions [40].

8 Impact of Engine Load on PM Emissions

In-cylinder temperature and pressure change with changes in engine load. At lower engine loads, in-cylinder temperature is low as well because lower amount of fuel is injected into the combustion chamber. With increasing engine load, amount of fuel injected in the cylinder also increases, which increases the peak in-cylinder temperature. Cylinder pressure also increases with increasing engine load. Both the peak temperature and in-cylinder pressure of the engine combustion chamber have a significant influence on particulate formation and emissions. Higher engine loads shorten the ignition delay, which advances the start of combustion in the expansion stroke, resulting in higher peak in-cylinder pressure. Xing et al. [41] reported that with increasing engine load, the relative percentages of soot emission increased, while the relative percentages of organic particles decreased. Sharma et al. [42] reported that particulate emissions were higher at no load and decreased at intermediate loads to again increase at high loads.

9 Effect of EGR on PM Emissions

Influence of EGR on the PM emissions is a complex phenomenon [43–45]. EGR is one of the most common techniques employed to control NO_x emissions. With addition of EGR to the combustion chamber, amount of oxygen available in the engine cylinder decreases, which increase the PM emissions. This also results in reduction in peak power output. Therefore, EGR valve should not be opened, when peak power output is required. EGR can be employed in the engine as hot EGR or cold EGR. Alger et al. [46] reported a reduction in PM and PN emissions by employing cooled EGR from a turbocharged PFI engine. Zhao [47] reported that EGR increased nucleation mode particle emission and decreased accumulation mode particle emission. Lattimore [48] reported opposite trend to the one reported by Zhao [47] for nucleation and accumulation mode particles. PM emissions change with changing EGR rate and engine operating condition.

10 Influence of Spray Characteristics on PM Emissions

In order to improve the combustion characteristics and combustion efficiency of a GDI engine, it is important to understand the influence of fuel spray characteristics on the particulate emissions. Parameters such as in-cylinder pressure, temperature, fuel-air mixture flow-field and CAD position of piston play a critical role. In addition, parameters such as FIP, SoI, ST, which are dependent on engine load and speed, influence PM emissions. These parameters control the fuel injection system and affect the PM emitted from the engine. These parameters must be therefore calibrated for all engine loads and speeds.

Fuel injection pressure and spray penetration length: Higher FIP enhances spray atomization and decreases fuel droplet size. This also enhances fuel-air mixture by increasing the surface area of fuel droplets in contact with the ambient air. Spray penetration length is dependent on FIP.

In a wall-guided GDI engine, fuel impingement on the piston is intentional which results in relatively higher PM. In a spray-guided GDI engine, there is comparatively less impingement on the piston hence lesser PM is produced. PM emission in spray-guided GDI engine is a result of fuel impingement on the valves and liner. Fuel penetration length should be optimized, which depends on FIP and spray break-up length at different engine operating conditions. Atomization and spray break-up are related to turbulence kinetic energy of injected fuel quantity and shear force between fuel spray and the ambient air.

11 Particulate Morphology

The term particulate morphology refers to the structural features of the soot particles such as diameter, area, inter-lamellar distance, periodicity, as well as length and tortuosity of the soot particles. The first step towards finding this is to collect the soot particles on a quartz filter paper through a dilution tunnel. The loaded filter paper can further be analysed using various analytical instruments. The term "analytical instruments" here refers to a broad category of equipment used to evaluate the composition of soot particles such as trace metals in particulate, structure (amorphous or crystalline) and morphology of soot particles for various test fuels at different engine operating conditions. FE-SEM, HR-TEM, ICP-OES are some of the analytical instruments.

HR-TEM is the most advanced technique available for characterizing nanoparticles as of now. Liati et al. [49] studied the characteristics of the soot particles collected from a GDI engine using HR-TEM images. Figure 10 shows the presence of nearly concentric multi-core particles, graphene lamellae interrupted by amorphous material (disordered atomic arrangements). Amorphous material appears due to discontinuous incorporation of organic compounds, which originates during growth of particles. Core in the above figure consists of randomly arranged graphene lamellae.

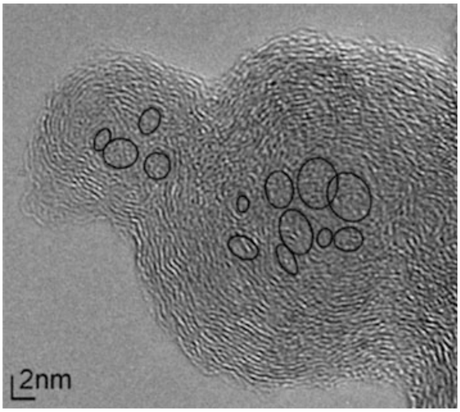

Fig. 10 HRTEM image showing: **a** multi-core particles (cores outlined for clarity); **b** crystallites in the particles [49]

12 Conclusions

Scientists from different fields are constantly working on assessing and reducing the adverse health effects caused by particulates from GDI engines. Investigations such as type of fuel, engine operating conditions, EGR give insights into methods as to how the particulate emissions from GDI engine can be reduced. Based on the research findings of various scientific studies, recommendations are made to limit the particulate emissions for the next set of emission legislations. Asthma, lung cancer/decreased lung function/lung irritation, cardiovascular diseases, premature delivery and birth defects, premature deaths, vascular inflammation, atherosclerosis, inflammation of lung tissues, blood chemistry changes, sensitivity to viral and bacterial germs are some of the important adverse health effect caused by engine particulates. A comparative analysis GDI and PFI engine technologies gave more insights of fundamental differences between gasoline-origin particulate formation processes. A discussion on the advantages of different types of GDI engine designs is also included in this chapter. Different types of particulate measuring technique/principles (mass based and concentration based) have been discussed, and instruments available commercially for such measurements are also touched upon briefly.

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