

Particulate Matter Characterization Studies in an HSDI Diesel Engine under Conventional and LTC Regime

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ABSTRACT

Several mechanisms are discussed to understand the particulate matter (PM) characterization in a high speed, direct injection, single cylinder diesel engine using low sulfur diesel fuel. This includes their formation, size distribution and number density. Experiments were conducted over a wide range of injection pressures, EGR rates, injection timings and swirl ratios, therefore covering both conventional and low temperature combustion regimes. A micro dilution tunnel was used to immediately dilute a small part of the exhaust gases by hot air. A Scanning Mobility Particle Sizer (SMPS) was used to measure the particulate size distribution and number density. Particulate mass was measured with a Tapered Element Oscillating Microbalance (TEOM). Analysis was made of the root cause of PM characterization and their relationship with the combustion process under different operating conditions. PM increased with an increase in EGR in conventional combustion regime and decreased with increase in EGR under the Low Temperature Combustion (LTC) regime. The size distribution and number density shows more complex trends. The particulate formation was broadly divided into nucleation and accumulation modes and their relative roles contributing to the final PM characterization are discussed.

INTRODUCTION

Due to their high efficiency, small bore, high speed, direct injection diesel engines are growing in

popularity to power light duty vehicles. Manufacturers are under increasing regulatory pressure to reduce the emissions further to meet future standards.

A major distinction of the diesel engine exhaust is the high particulate matter emissions and is one of the main sources for black smoke traditionally associated with diesel-powered vehicles. Diesel particulate matter (DPM) forms a complex aerosol system as the soluble organic fraction (SOF) compounds like the poly-nuclear aromatic hydrocarbons (PAH) and the nitro-PAH are adsorbed on the surface. These not only contribute significantly to the overall particulate matter carcinogenic effects, but also represent energy lost and thus need to be reduced. Though PM mass has been the priority, particle size and number emissions are gaining importance due to health concerns. This becomes more of an issue as the PM size becomes smaller due to the strategies used to meet the other emission regulations.

SOOT FORMATION PROCESS

Soot constitutes a major part of PM. The characterization of soot has been explained in good detail [1]. It has been summarized here. Soot is the solid carbonaceous phase formed from the gas phase hydrocarbon species. The soot aerosol can be characterized by the total amount of the material in the condensed phase, often expressed as the soot volume fraction, f_v ($\text{cm}^3 \text{ soot}/\text{cm}^3$), the number density of particles, N and the characteristic dimension of the particles, d . The particles also

possess a size distribution. The first particles appear small ($d \sim 2\text{nm}$ and masses of the order of 200 amu, [2]) and at high number density soon after the main reaction zone. The amount of soot, f_v , is initially only a small fraction of the final amount, growing steadily during later part of the combustion. As f_v grows, the particles also grow in size; at the same time their number density decreases. Richer flames produce more soot and larger particles than lean flames. The overall soot formation can be divided into four major processes.

(a) Soot formation begins with particle inception, where the first condensed phase material arises from the fuel-molecules via their oxidation and/or pyrolysis products.

(b) After inception, planar growth, comprising of replicating type growth occurs. This is followed by particle nucleation consisting of coalescence of PAH into three-dimensional clusters, [3].

(c) Soot loading can increase by surface growth. This involves the attachment of gas-phase species to the surface of a particle and their incorporation into the particulate phase. Surface growth reactions lead to an increase in the amount of soot, but the number of particles (N) remains constant. Particle growth (increasing d) is the result of simultaneous surface growth reaction and coagulation.

(d) The stages of particle generation and growth constitute the soot formation process. This is often followed by a phase of soot oxidation in which the soot is burnt in the presence of oxidizing species to form gaseous products such as CO and CO₂. The eventual emission of soot from any combustion device will depend on the balance between these processes of formation and burnout.

The fraction of total soot volume contributed by particle inception is usually low. But the early flame-zone chemistry has a strong influence on the total surface area of the first particles. Therefore, although the particle inception process does not by itself produce much soot, it may have a substantial influence on the extent of surface formation, through the generation of area [1].

The transition from particle inception to particle growth is not sharp. The growth of very large molecules by addition of smaller hydrocarbons also involves the addition of similar species to particles. Similarly, large molecules can react among themselves in the same way as particles coagulate. However, both in premix and diffusion flames, the zones of particle nucleation and of particle growth do

appear to be spatially distinct. New particle formation is restricted to a narrow region near the main reaction zone where the temperatures and radical and primary ion concentrations are highest [4, 5]. Except under weakly sooting conditions (e.g., a premixed flame operating near the sooting limit), the generation of volume fraction by new particle generation is negligible compared with that contributed by surface growth. Surface growth occurs over extended periods as the gases move away from the primary reaction zone, even into relatively cool, otherwise un-reactive zones.

The smallest identifiable solid particles observed in luminous flames have diameters in the range of 1.4 to 2 nm and masses of the order of 200 amu at the start of the luminous zone, [2]. Particles observed in flames just sooting have similar sizes. The generation of such particles from the gas phase reactants constitutes the particle inception process. Typical production rates are of the order of $10^{15} \text{ cm}^{-3} \text{ s}^{-1}$. The PAH growth reactions, in order to produce the spherical units as small as 1.5 nm, must eventually lead to a departure from planar PAH molecules. Growing into the third dimension is achieved through the side chains and interactions of these with other PAH.

In addition, surface growth rates are higher for smaller particles [4], than for the chain forming larger particles, which are already tempered and exhibit reduced surface growth activity. The young soot particles are highly disorientated and possess many radical sites, factors that may make the internal mobility of younger particles significant. Typically it is found that particle collisions are effectively coalescent for particle diameters up to several tens of nanometers, beyond which they appear to be more chain forming [6].

The process of coagulation leads to the establishment of a particle size distribution. For coalescent collisions in the absence of surface growth, a self-preserving size distribution is predicted. This distribution is distorted and is no longer self preserving when gas to particle conversion by surface growth also occurs. The surface of hot soot readily accepts hydrocarbons from the gas phase. This is clearly demonstrated by the appearance of macroscopic changes when soot particles are held (e.g., by electric fields) in the carbon formation zone. For a given species this can occur at rather lower temperatures than the generation of the particles themselves [1]. Surface growth can also continue at hydrocarbon concentrations below the lower limit required for the inception of sooting.

COMBUSTION PROCESS & PARTICULATE MATTER

The formation of soot particles in combustion environments involves a complex series of chemical and physical processes, which control the conversion of fuel carbon to carbonaceous particles. Since soot formation is a chemically kinetic limited process, the effects of temperature and pressure would be important [1].

Soot emitted from typical pyrolysis and combustion systems is found to consist agglomerates of a number of primary spheres whose diameters are typically in the range of 10 to 250 nm for different conditions and exhibit a size distribution. Soot is typically carbon but may contain around 1% by weight of hydrogen. Soot is formed from the fuel injected into flames and burnt gases [7]. There are numerous possible pathways, but the important feature is that an initial aromatic structure provides the foundation for the build of larger aromatics by the addition of non-aromatics such as C_2H_2 [4,8].

EXPERIMENTAL SETUP

The experiments were conducted on a single cylinder, 4-valve, direct injection, 4 stroke cycle, water cooled, diesel engine equipped with a common rail fuel injection system capable of delivering fuel pressure up to 1350 bar. The engine specifications and the fuel properties are given in appendix. A water-cooled Kistler 6043A60 piezoelectric pressure transducer is used to measure the cylinder pressure.

The intake and exhaust gases are fed to and from the engine through large plenum chambers, with a volume of approximately 100 times the engine displacement. The plenum chambers are connected to head through short, 20 cm runners. This arrangement was designed to reduce the gas dynamic effects during gas exchange process of the single cylinder engine. This ensured that the pressure, temperature and EGR fluctuations resulting from the intake and exhaust dynamics of the single cylinder engine were maintained at a minimum.

The EGR system is designed by connecting the exhaust and intake manifolds of the engine with a flow control valves. An external compressor equipped with an air heater controls the intake air temperature. The backpressure in exhaust surge tank simulates actual turbocharged conditions. EGR ratio was calculated by measuring CO_2 emissions at intake and exhaust.

The intake tangential and helical ports were throttled to different degrees by using a gate valve that varied the swirl ratio from 1.44 to 7.12. All results reported in this paper are at an IMEP of 3 bar, engine speed of 1500 rpm, intake temperature of 150° F (339K) with the Location of Peak of Premixed Combustion (LPPC) of the rate of heat release (RHR) at 5° after TDC. This is equivalent to that the fuel quantity and injection time are adjusted such that peak heat release occurs at 5° after TDC. This assured that the combustion phasing with respect to TDC was constant and the same for all the experimental data presented in this study.

A six hole, 320 micrometer orifice diameter, mini-sac nozzle has been used in these tests. The engine is instrumented with intake and exhaust manifold pressure transducers, intake and exhaust thermocouples, coolant and oil outlet thermocouples. The fuel used for this study was low sulfur diesel fuel with less than 15 ppm of sulfur. The fuel properties are given in appendix A.

A Bosch smoke meter EFAW 68A was used to measure the engine out soot emission. Dekati micro dilution tunnel along with a Dekati FPS was used to dilute the exhaust and control the temperature during dilution process. A Rupprecht and Patashnick TEOM series 1105 particulate monitor was used to measure particulate mass concentration.

A TSI Scanning Mobility Particle Sizer (SMPS) consisting of an Electrostatic Classifier (3080) long Differential Mobility Analyzer (DMA) (3081) and nano DMA (3085) along with Condensation Particle Counter (CPC) (3025A) was used to measure the particulate size distribution and number. The long DMA provides a wide size range of 10 to 1000 nm. The Nano DMA is optimized for the size range below 20 nm. However, it covers a broad range of particle diameters from 2 to 150 nm. Therefore for better understanding the size distribution was obtained with both long DMA and nano DMA. A third scan with long DMA at a low flow was taken for a better understanding of the larger nano particles.

SAMPLING FOR PM ANALYSIS

The dilution process plays an important role in measuring diesel exhaust aerosols by affecting the saturation ratio, temperature and volatile fractions of diluted exhaust. Dilution air lowers the temperature at sampling zone and filter face. It also attenuates flow rate fluctuations inherent in exhaust. The dilution process considerably affects the particulate matter measurements and is a potential source for artifact generation.

To minimize uncertainties in sample measurements, dilution of the exhaust can be obtained in one or two stages. During primary dilution the raw sample mixes with heated dilution air. The dilution ratio of the primary dilution stage can be adjusted by changing the dilution airflow into the primary diluter. The secondary dilution stage draws the sample from the primary dilution stage and dilutes it further. Dekati FPS allowed particulate measurements spanning from high concentrations to hot and humid conditions. Adjusting the dilution ratio in two phases temperature control and rapid dilution allow predictable sample transfer from vehicle exhaust.

The first dilution was conducted close to the sampling point. This method assists in obtaining reproducible results and prevents losses. This was done in hot conditions. With hot dilution condensation of volatile species was prevented. The second phase is an ejector type diluter, which is located downstream of the primary dilution. The ejector diluter acts as a pump sucking a known amount of a diluted sample from the primary dilution.

Thus most of the critical parameters of the dilution are controlled and simultaneously monitored. Consequently, a sample is transferred from high temperature and high concentration to moderate levels in a controlled manner. Most importantly, a controlled nuclei formation prevents volatile or semi volatile compounds from nucleating on the surface of the solid particles and therefore the uncertainties of the particle size are minimized. Overall dilution ratios of 60 have been used for the particulate matter analysis sampling and converted back to engine out emissions data during post processing.

LOW TEMPERATURE COMBUSTION (LTC)

“Modulated Kinetics, MK” combustion strategy [9] by Nissan is a LTC regime known to reduce NO_x and Soot by having combustion at relatively lower temperatures (Low temperature combustion) by applying high EGR rates, and injecting the fuel late during the expansion stroke. To increase the combustion rate, late in the expansion stroke, MK strategy applies high swirl ratios.

Due to the high EGR ratios used during Low temperature combustion (LTC) the ignition delay is increased. To compensate this, the injection timing is advanced. This may contribute to an increase in the wall impingement. Higher injection pressures, employed to reduce smoke may increase this trend. Also, the high EGR ratios, limit the applicability of LTC strategy to light loads. When optimized during steady state testing, LTC strategy exhibited

efficiencies comparable to that of conventional combustion (fuel penalty was observed to be less than 5%).

The effect of various operating parameters on regulated and unregulated gaseous emissions has been discussed in a lot of studies [10,11]. Particulate matter is found to increase with increase in EGR in conventional combustion regime, and decrease with an increase in EGR while operating in low temperature combustion regime [8,12,13,14]. This paper investigates the factors that contribute to the particulate matter characterization in the conventional and LTC regime, and the effect of swirl ratio and injection pressure on the engine out emissions.

EFFECT OF SWIRL IN LTC REGIME

The tests were conducted with an injection pressure of 600 bar and EGR of 64% at different swirl ratios while location of peak of premix combustion (LPPC) was kept constant at 5 CAD after TDC. Fig. 1a gives the Bosch Smoke Number (BSN) and mass concentration data. Fig. 1b shows the PM number density. Fig. 1c shows the change in mean diameter with Swirl Ratio. Fig. 1d, Fig. 1e and Fig. 1f, show the size distribution while sampling with nano DMA, long DMA in high and low flows respectively. Table 1 gives the injection timing and injection duration for the tests conducted to investigate the effect of swirl.

Table 1: Injection timing data for effect of swirl

Swirl	SOI	Inj. duration
1.44	-10.375 CAD	446 μ s
2.59	-13.250 CAD	468 μ s
3.77	-15.250 CAD	470 μ s
4.94	-15.875 CAD	470 μ s
7.12	-17.500 CAD	472 μ s

With increase in swirl the mean diameter was observed to decrease (Fig. 1c). There is a sharp fall in PM mass with increase in swirl ratio from 1.44 to 2.59, after which PM mass remains relatively constant (Fig. 1a). The number density (Fig. 1b) increases, when swirl ratio (R_s) changes from 1.44 to 2.59. With further increase in swirl ratio to 3.77 a big drop in number density is observed, after which, it remains relatively constant up to $R_s = 7.12$.

Swirl ratio 1.44 is observed to have high soot mass, (Fig. 1a) and mean diameter (Fig. 1c). This is an indication of high accumulation mode PM. This can be explained as follows. Due to low swirl, the