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# Detailed characterization of particulates emitted by pre-commercial single-cylinder gasoline compression ignition engine

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A B S T R A C T

Gasoline Compression Ignition (GCI) engines have the potential to achieve high fuel efficiency and to significantly reduce both NOx and particulate matter (PM) emissions by operating under dilute, partially-premixed conditions. This low temperature combustion strategy is dependent upon direct-injection of gasoline during the compression stroke and potentially near top dead center (TDC). The timing and duration of the in-cylinder injections can be tailored based on speed and load to create optimized conditions that result in a stable combustion.

We present the results of advanced aerosol analysis methods that have been used for detailed real-time characterization of PM emitted from a single-cylinder GCI engine operated at different speed, load, timing, and number and duration of near-TDC fuel injections. PM characterization included measurements of size and composition of individual particles sampled directly from the exhaust and after mass and/or mobility classification. We use these data to calculate particle effective density, fractal dimension, dynamic shape factors in free-molecular and transition flow regimes, average diameter of primary spherules, number of spherules, and void fraction of soot agglomerates.

The data indicate that the properties of GCI particulates varied markedly depending upon engine load. Under low-load conditions (5.5 bar net Indicated Mean Effective Pressure, IMEP), PM is comprised of a mixture of particles ~70% of which are compact organic particles and ~30% are fractal soot aggregates. The soot aggregates have fractal dimension of 2.11, are constructed of primary spherules with average diameter of 40 nm, and composed of elemental and organic carbon at ~55:43 ratio by weight. Under high-load conditions (14 bar net IMEP), all the particles are fractal soot agglomerates with nearly identical fractal dimension and composition, but constructed of primary spherules with average diameter of 26 nm.



## 1. Introduction

Current internal combustion engine development aims to reduce consumption of limited fuel resources and reduce carbon dioxide ($CO_2$) emissions by increasing fuel efficiency. While diesel engines achieve the highest fuel efficiency, they also generate the highest mass emissions of particulate matter (PM) and oxides of nitrogen (NOx), which are harmful to human health and the environment. Tree and Svensson provided a detailed overview of the combustion processes in compression-ignition engines [1]; here we mention only a few relevant points. PM emissions form mainly from the mixing-controlled phase of the diesel combustion process, during which unburned fuel and combustion products, surrounded by the flame sheath, form a hot, fuel rich region that favors soot growth. The high temperatures in the flame sheath, which is located approximately at the stoichiometric contour lead to high NOx emissions. Therefore, low temperature combustion (LTC) strategies, like homogenous charge compression ignition (HCCI) [2], offer the potential to avoid both high PM and NOx emissions. The basic principal of these strategies is to limit local high-temperature pockets by operating with dilute mixtures (either dilution with air or exhaust gas recirculation (EGR)) and by at least partially premixing the air and fuel, thereby avoiding hot-spots and spreading the heat release over the entire cylinder.

Fuel with higher volatility and resistance to auto-ignition improve mixing, as high volatility promotes rapid evaporation and high resistance to auto-ignition gives the air–fuel-charge more

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time to mix prior to ignition. These considerations favor gasoline over diesel fuels [e.g., 3–7] for low temperature combustion, especially at high loads.

The combustion process in an LTC engine starts when in-cylinder temperatures, during the compression stroke, become sufficiently high to induce significant chemical reaction. Combustion of fuels with low temperature chemistry produces partially oxidized organic species (aldehydes, oxygenated organic compounds, and aliphatic fuel fragments) and is accompanied by low temperature heat release. As temperature builds, autoignition occurs and oxidation proceeds to the high temperature regime producing radicals that split longer chain hydrocarbons into smaller fragments and then proceed to complete oxidation to $CO_2$ [8]. Controlling the combustion kinetics represents the main challenge in LTC combustion. Under lower loads, leaner air–fuel mixtures form and in-cylinder temperatures and pressure are lower, potentially leading to misfire or partial burning of the charge resulting in high emission of unburned hydrocarbons and lower efficiency. Under high loads, the air–fuel mixture may ignite too easily and violently, causing excessive heat release rates and rapid pressure rise-rates that can damage the engine.

A strategy to achieve LTC at high loads relies on multiple fuel injections, forming a low equivalence ratio homogenous mixture during the first injection, and following it with a second injection closer to TDC to achieve stratification and reliable ignition [7,9]. However, at full load excessively high pressure rise-rate at ignition can remain a limiting problem. This is potentially overcome by the use of a third injection near TDC [10], splitting the late injection into two, to yield a heat release process that is spread over a longer period of time [8]. In this scheme, the amount of fuel and the timing of the second injection is used to control the maximum pressure rise-rate and the third injection is used to control the engine load [10]. It is reasonable to expect that complex strategies such as the ones described above lead to broad range of particulate emission characteristics. However, our knowledge on the subject is limited because studies providing detailed characterizations of PM emission from LTC engines are very sparse.

Storey et al. [11] analyzed the composition of PM collected on filters and reported that 95% of the PM emitted by a HCCI engine operated at low load was comprised of partially burned fuel, composed of organics like aldehydes and PAHs, and that the concentrations of both were significantly higher than emissions produced by conventional diesel engines. The same study characterized emissions from a premixed charge compression ignition (PCCI) engine, in which fuel is injected later than in the HCCI engine, and found that for this engine the PM emission at low loads were similar to conventional diesel engine. The size distributions of particles generated by the PCCI and the HCCI engines were also very different, with majority of particles emitted by the HCCI engine being smaller than 10 nm, while the PCCI PM size-distributions peaked at 23 and 46 nm, depending on the load.

The Gasoline Compression Ignition (GCI) operating strategy offers the potential to achieve low fuel consumption while reducing both NOx and PM emissions, with its success being highly dependent upon direct injection of gasoline near-TDC, the timing and duration of which can be tailored to speed and load to create an optimized air–fuel charge distribution that results in stable, staged combustion. Recent studies by Ra et al. [9,10] characterized the performance of a GCI test engine and demonstrated the ability to operate near 18 bar net IMEP using a triple injection fueling strategy, while achieving low NOx and PM emissions (<1 g/kg fuel), low gross indicated specific fuel consumption (around 180 g/kW h), and maximum pressure rise rates less than 10 bar per crank angle degree.

Single particle mass spectrometers (SPMSs) have previously been used to characterize particulate emissions from vehicles [see for example: 12–17]. SPMSs yield information on the size and compositions of large numbers of individual particles, in situ and in real time, with high temporal resolution. Moreover, unlike the Aerodyne Aerosol Mass Spectrometer (AMS), which yields average mass concentrations of the semi-volatile compounds of aerosol particles *only* [e.g., 18], single particle mass spectrometers provide information on the size and composition of both the refractory and non-refractory fractions in each particle.

This paper presents a detailed in situ characterization of PM produced by GCI engine under a range of operating conditions. It uses SPLAT II, our SPMS, [19] to measure individual particle compositions and vacuum aerodynamic diameters ($d_{va}$); a scanning mobility particle sizer (SMPS) to measure PM mobility number size distributions; a differential mobility analyzer (DMA) to select particles with narrow distributions of mobility diameters ($d_m$), and an aerosol particle mass analyzer (APM) [20] to measure particles' mass, and select particles with narrow distributions of mass ($m$), to yield, in addition to individual particle composition, particle $d_m$, $d_{va}$, and $m$. These particle attributes are sufficient to determine particle size, fractal dimension, average primary spherule diameter ($d_p$), effective density ($\rho_{eff}$), mass ($m$), number of spherules, void fraction, and flow-regime dependent dynamic shape factors as function of agglomerate size [21]. To the best of our knowledge, the study presented here is first of its kind in its detail and clearly first on this type of engine.

## 2. Experimental

A schematic of the experimental setup used in this study is depicted in Fig. 1. The GCI engine used in this study is a single-cylinder version of a General Motors (GM) 1.9 L, 4 cylinder light-duty diesel engine described in detail in separate publications [9,10]. Here we provide the main characteristics of the engine, fuel injection system, and fuel specifications (Tables 1–3, respectively).

Based on recent numerical and experimental studies of the GCI engine [9,10] 6 different engine operating conditions of interest were identified and used in the present study. Table 4 shows an overview of the engine parameters for the different conditions. Four of the conditions with an IMEP of 5.5 bars are labeled as low-load conditions (LL1–LL4), as shown in Fig. 2. For these conditions, the timing of the second injection, specified as start of injection (SOI2) in crank angle degrees before top dead center (°bTDC), was varied from 39 °bTDC to 33 °bTDC. Furthermore, for the fourth condition (LL4), the engine speed was increased to 2500 rpm as compared to 2000 rpm for all other conditions. In addition, two high-load conditions (HL1 and HL2), also shown in Fig. 2, were studied, at an IMEP of 14 bar. For both high-load conditions, the injection timing of the second injection was set to 21 °bTDC. For HL2, a third injection was performed at 10 °bTDC. The first injection for all conditions took place early in the intake stroke at 350 °bTDC.

The engine exhaust is drawn through a surge tank and part of the sample flow is sent to the Horiba emission bench that provides information on concentrations of $CO_2$, NOx, carbon monoxide (CO), oxygen ($O_2$), and hydrocarbons (HC). Another exhaust sample flow is drawn through a micro-diluter (Rupprecht and Patashnich Series 6100), where the sample is diluted by a factor of ~10 and sampled by the emission bench and PM characterization system. The second $CO_2$ measurement of the diluted flow is used for dilution ratio (DR) calculation. The DR ratio determined from the controller for the micro-diluter is also recorded. This DR is based on measured air mass flow rate in the controller and the micro-diluter calibration, and is found to be within ±10% of $CO_2$-measured DR. The sampling temperatures for the 5 bar 2000 rpm runs, 5 bar 2500 rpm run, and the 14 bar runs were 150 °C, 172 °C, and 191 °C, respectively. Table S1 lists all relevant emissions for all 6 operating conditions.