

Effects of Fuel Chemistry and Spray Properties on Particulate Size Distributions from Dual-Fuel Combustion Strategies

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ABSTRACT

The effect of direct-injected fuel on particle size distributions (PSDs) of particulate matter emitted from dual-fuel combustion strategies was investigated. The PSD data were acquired from a light-duty single-cylinder diesel engine operated using conventional diesel combustion (CDC) and two diesel/natural gas dual-fuel combustion strategies. Three different direct-injection (DI) fuels (diesel, 2,6,10-trimethyldecane, and a primary reference fuel blend) and two different injector nozzles were studied. The DI fuels were chosen to have similar energy and ignition characteristics (heat of combustion and cetane number) but different physical and chemical properties (volatility, aromatics %, viscosity, density). The two nozzles (with different orifice diameter and spray angle) allowed a wide range in DI fuel quantity for the dual-fuel combustion strategies. The results suggest that the physical and chemical properties of the DI fuel may have a strong impact on PSD distribution shape and accumulation-mode particle concentration for CDC and natural gas combustion with a diesel-pilot-injection strategy. For diesel/natural gas RCCI combustion the PSD was found to be insensitive to the DI fuel when using two-stage dilution with a volatile particle remover. The DI fuel quantity was found to slightly affect the PSD magnitude for dual-fuel combustion strategies.

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INTRODUCTION

Particulate matter (PM) emissions formed during combustion within internal combustion engines is of great concern due to its negative impact on human health; recent research has shown that exposure to ultrafine particles is associated with increased occurrence of cardiovascular events and reduction in lung function [1, 2]. Smaller particles are believed to be potentially more harmful to the human respiratory system than larger particles [3], and these particles may act as carcinogens [4]. Both particle size and chemical composition can be factors in the impact of particulate on human health. Such awareness has led to the development of stricter PM emissions regulations. In the United States, the EPA Tier 3 emissions standards introduce substantial reductions of PM emissions for both light-duty and heavy-duty vehicles [5]. Moreover, number-based PM regulations have been introduced on top of the stringent mass-based PM regulations in some markets. California's Low Emission Vehicle III (LEV III) standard proposed a solid particle number (SPN) limit of 3×10^{12} #/mi measured over the FTP75 Drive Cycle [6]. The European Union established the Particle Measurement Program (PMP) to measure ultrafine particles emitted by engines in a regulatory framework, and number-based engine exhaust particle regulations have been established in Europe [7]. The EU regulation sets a particle number limit at 6×10^{11} #/km.

The stringent regulation of PM emissions motivates research on PM formation mechanisms, which can be achieved, in part, from measurements of particle size distributions (PSD) in the engine

exhaust. The PSD of conventional diesel engine exhaust has been investigated extensively [8, 9, 10]. A bimodal distribution shape has been repeatedly measured and is illustrated in Figure 1. Particles are generally divided into two categories: nucleation mode ($3 \text{ nm} < d < 50 \text{ nm}$) and accumulation mode ($50 \text{ nm} < d < 500 \text{ nm}$) particles. As shown in Figure 1, nucleation mode particles account for a large portion of total particle number, but only account for a small fraction (typically < 20%) of total particle mass.

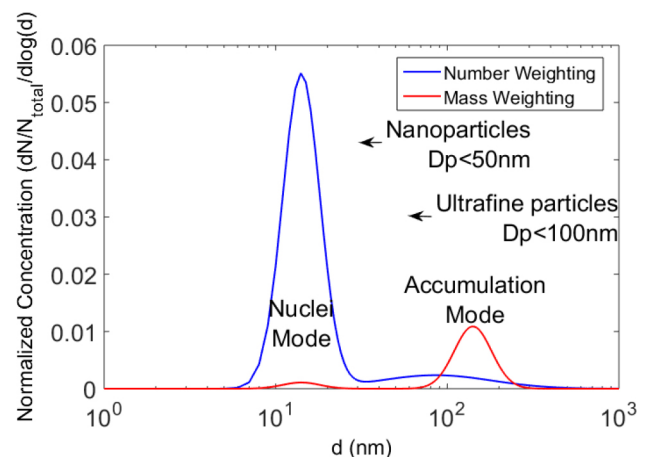


Figure 1. Typical engine exhaust size distribution with both mass and number weightings (derived from [9])

Only a few studies have been reported that focus on PSD measurements of advanced combustion strategies. Prikhodko et al. [11] compared PSDs from reactivity-controlled compression-ignition (RCCI) combustion with conventional diesel and diesel premixed-charge compression-ignition (PCCI) combustion. The RCCI results showed lower particle concentrations compared to the other two combustion strategies, and the PSDs for RCCI were dominated by nucleation-mode particles. Dempsey et al. [12] performed PSD measurements for RCCI combustion using a two-stage dilution system where particle sampling was done both before and after the second-stage hot dilution. The results showed that the second-stage dilution process almost completely removed the nuclei-mode particles, suggesting that they were composed primarily of volatile compounds.

The authors' previous published papers [13, 14] addressed the importance of utilizing a single engine platform with consistent measurement environment (non-fuel baseline PSD, dilution conditions, volatile removal method, etc.) for valid PSD comparisons and carried out a comparison of PSD among multiple compression-ignition (CI) combustion strategies at various engine operating conditions. A trend of increased accumulation-mode particle concentration was observed for almost all compression-ignition combustion strategies when transitioning from mainly premixed strategies such as homogeneous charge compression ignition (HCCI) and early injection gasoline compression ignition (GCI), to strategies involving diesel direct-injection (DI), such as conventional diesel combustion (CDC) and diesel low temperature combustion (DLTC). It was also observed that strategies with a very small fraction of DI diesel fuel (~ 10% in mass), such as natural gas combustion with diesel pilot injection (NG DPI), still had a relatively high concentration of accumulation-mode particles - approaching the same order as for CDC.

The objective of this paper is to further investigate the effect of DI diesel fuel on the PSD. PSD data were acquired with CDC as well as two diesel/natural gas combustion strategies: NG DPI and diesel/natural gas RCCI. The details of the combustion strategies have been discussed in a previous paper [14]. In the current work, three different fuels (diesel, 2,6,10-trimethyldodecane (farnesane), and a primary reference fuel (PRF) blend) were used as the DI fuel to investigate the effects of fuel chemistry and physical properties on PSD behavior. The DI fuels were chosen to have similar energy density and ignition characteristics (heat of combustion and cetane number) but different physical and chemical properties (volatility, aromatic content, viscosity, density). Two nozzles with different number of orifices, orifice diameters and spray angles were used in this study to investigate the effect of the spray breakup and fuel atomization process for the DI fuel, and the effect of the DI fuel quantity for the dual-fuel combustion strategies.

EXPERIMENTAL SETUP

Engine Platform

A single-cylinder version of a GM 1.9 L four-stroke light-duty diesel engine with a bore of 82 mm and stroke of 90.4 mm was used in this study. The stock piston with a reentrant piston bowl was utilized. A

schematic of the experimental setup is shown in Figure 2. The engine specifications are listed in Table 1. The intake air pressure was controlled by a series of choked flow orifices and the temperature was regulated within $\pm 2^\circ\text{C}$ with an inline air heater, line heaters, and a tank heater. The engine oil and the coolant were held at 70°C and 80°C , respectively.

For this study the engine was operated with both single and dual-fuel combustion strategies, using both direct and port-fuel-injection (PFI). The intake manifold was equipped with two port-fuel injectors to deliver methane, which was used as a surrogate for natural gas, into the swirl-actuated intake port. The end-of-injection (EOI) of the PFI fuel was set at 180°bTDC . A centrally mounted common-rail injector was located in the cylinder head and was used to deliver the DI fuels. The injection timing and fuel rail pressure were controlled by NI Drivven software. For all combustion strategies, the engine was operated at two different speed/load conditions, referred as Mode 5 (1900 RPM/ 5.7 bar IMEP gross) and Mode 8 (2300 RPM/ 8 bar IMEP gross) for consistency with previous publications.

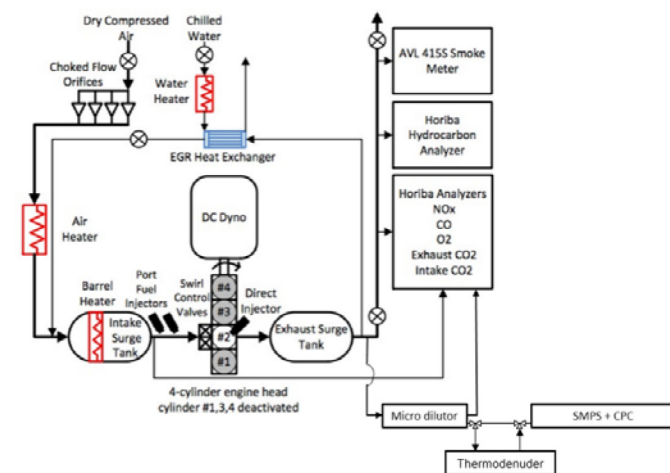


Figure 2. Schematic of the engine experimental platform

Table 1. Engine geometric specification

Base Engine	Single-cylinder version of GM 1.9 L 4-cylinder DI Diesel
Bore $\times$ Stroke	82.0 mm $\times$ 90.4 mm
Connecting Rod Length	145.54 mm
Displacement	0.477 L
Compression Ratio	16.7:1
Intake Valve Opening/Closing	$344^\circ/-132^\circ$ aTDC
Exhaust Valve Opening/Closing	$112^\circ/388^\circ$ aTDC
Swirl Ratio	1.5
Piston Bowl Type	Re-entrant bowl

Data Acquisition System

National Instruments LabView software was utilized for system control and data acquisition. A Kistler 6125A pressure transducer together with a Kistler 5010 charge amplifier were used to measure the in-cylinder pressure. A 0.25 crank-angle degree (CAD) resolution

optical shaft encoder was used for timing. Pressure data were acquired for 300 cycles at each experimental point. Horiba gaseous emissions benches were used to measure CO₂ concentrations in the raw and diluted exhaust to determine dilution ratio for particulate sampling. Filter smoke number (FSN) was measured with an AVL 415S smoke meter.

Particulate Sampling System

Particulate matter was sampled from the exhaust after the exhaust surge tank and diluted using a two-stage micro-diluter (Dekati FPS-4000). Exhaust dilution is used to achieve appropriate inlet conditions for the scanning mobility particle sizer (SMPS) used to measure the PSDs. A heated probe extracted a sample from the exhaust flow that was sent to a heated perforated-tube primary diluter. The primary dilution air was heated to prevent condensation of volatile species. The secondary dilution occurred in an ejector diluter that utilized HEPA filtered room temperature air for the dilution process. The temperature profile along the dilution process was monitored and recorded for measurement consistency. The overall dilution ratio (DR) was determined by CO₂ measurements in both the diluted and undiluted exhaust samples and was computed as:

$$DR = \frac{[CO_2]_{diluted} - [CO_2]_{background}}{[CO_2]_{undiluted} - [CO_2]_{background}} \quad (1)$$

Where $[CO_2]_{diluted}$ is the CO₂ concentration in the diluted sample, $[CO_2]_{background}$ is the background CO₂ concentration in the intake and dilution air, and $[CO_2]_{undiluted}$ is the CO₂ concentration in the undiluted exhaust stream. In this study an overall dilution ratio of ~20:1 was used for all combustion strategies.

A thermodenuder (TD, Dekati) was installed between the micro diluter and the SMPS to remove volatile particles. The thermodenuder first vaporizes volatile compounds in an aerosol heater, which heats the sample to 250 °C, then the sample enters the absorber section, where the vaporized compounds are adsorbed by the activated charcoal filter. A particle loss correction given in the manufacturer's manual was applied during the data processing to data taken with the thermodenuder.

The SMPS system consisted of a long differential mobility analyzer (DMA, TSI model 3081) controlled by an electrostatic classifier (EC, TSI model 3025A). An aerosol neutralizer (TSI model 3077A) was used to establish the bipolar charge distribution on the particles. The particle sample, sized by the DMA, was measured using a condensation particle counter (CPC, TSI model 3025A). The system has the capability of resolving particle mobility diameters from 7 nm to 300 nm (the scan range used in the current study). Before entering the SMPS, the sample aerosol went through an inertial impactor with a 600-nm cut-point diameter to remove large particles. TSI Aerosol Instrument Manager (AIM) software was used to acquire and process the PSD data. Corrections for particle diffusion losses in the SMPS and multiple charging of the particles were applied to the current data set.

RESULT & DISCUSSION

DI Fuel Substitution

To investigate the DI fuel's impact on the PSD shape, the first part of this study is focused on a DI fuel substitution study. Farnesane (FAR) and a PRF blend (n-heptane and iso-octane) were used to replace #2 diesel as the DI fuel in CDC and the two diesel/natural gas dual-fuel combustion strategies. The fuels have similar ignition characteristics, but different physical and chemical properties. Farnesane has similar viscosity compared to diesel and the boiling point of farnesane is within the distillation curve of diesel. The density of farnesane is between that for diesel and the PRF. A major difference between farnesane and the diesel fuel used is the chemical composition. As a single-component alkane species farnesane does not contain aromatics, which are recognized as promoter of soot formation in diesel combustion. The PRF blend, on the other hand, has significantly different chemical and physical properties; it has much lower density and viscosity and much higher volatility compared to both diesel and farnesane, hence it undergoes a faster spray breakup and vaporization during injection compared to the other DI fuel candidates. It also does not contain aromatics as it is a blend of two single-component alkane species. The DI fuel substitution study will therefore help connect the PSD behavior with one or more properties of the DI fuel. Some important fuel properties are listed in Table 2, and the distillation curves for the fuels used are shown in Figure 3.

Table 2. DI fuel properties

Fuel	Diesel	Farnesane	PRF Blend
CN	53	58	53
Aromatics (% vol)	24.2	-	-
LHV (MJ/kg)	43.2	43.5	44.3
Density (kg/m ³)	831	770	681
Viscosity (cSt)	2.69	2.33	0.39

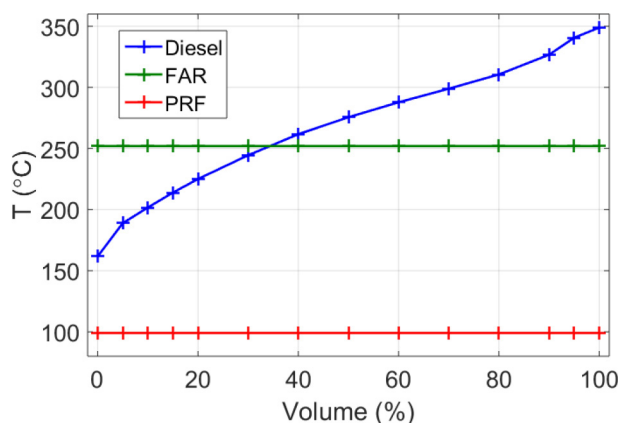


Figure 3. Distillation curves for DI fuels

Conventional Diesel Combustion

The engine was operated with CDC at 1900 RPM and 5.7 bar IMEP, hereafter referred as Mode 5 for all three fuels. The engine operating conditions as well as the pressure and heat release rate are shown in Table 3 and Figure 4.

Table 3. CDC Mode 5 operating conditions

		CDC Mode 5		
Fuel		Diesel	FAR	PRF
DI%		100%		
Intake Temp.	°C	50		
Intake Pressure	bar	1.3		
Exhaust Pressure	bar	1.34	1.35	1.35
Injection Pressure	bar	950		
Injection Timing	aTDC	-7.5	-7.5	-7.5
CA 50	aTDC	6.5	6.5	6.25
FSN		0.09	0.05	0.03

For all three fuels the engine performance is quite similar. The pressure and heat release rate data shown in Figure 4 are well matched. A trend of reduction of FSN with increasing volatility was noticed. Groendyk and Rothamer [15] have observed a similar trend in their previous study, and attributed this to the fuel chemical structure, i.e., the aromatic content and the molecular chain length.

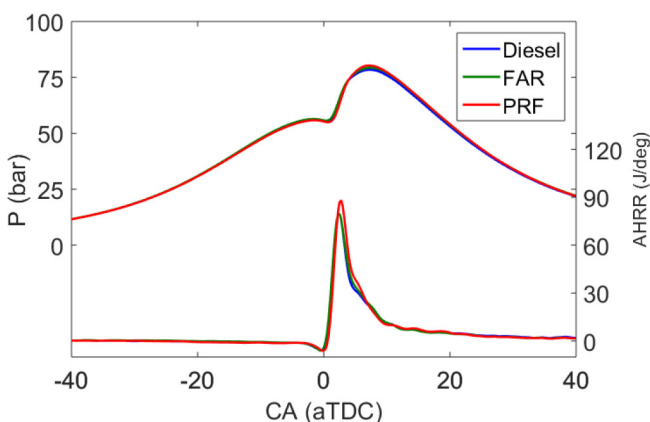


Figure 4. Pressure and heat release rate for CDC Mode 5 (1900 RPM/ 5.7 bar IMEP)

Particle size distribution measurements were carried out for all three fuels. All PSD data were collected at a dilution ratio of ~20:1. Previous studies have shown that this dilution ratio together with the use of a TD is sufficient to remove most of the volatile materials in the sampled exhaust. For the CPC used in this study, the 20:1 dilution ratio was used to avoid measuring at low raw counts, hence it provided better measurement confidence compared to high dilution ratio conditions.

In Figure 5, the solid lines represent the PSD average for 7 scans of data collected consecutively at steady-state engine operation. The dashed lines indicate the upper and lower the 95% confidence intervals for the averaged PSD data based on the 7 scans. In Figure 5, a reduction of accumulation-mode particle concentration is clearly observed when going from diesel to FAR to PRF. In the nuclei-mode

particle range an opposite trend is found. Using PRF as the DI fuel led to higher nuclei-mode particle concentration. However, the uncertainty in the nuclei-mode particle diameter range is higher than for the accumulation-mode particle range. Overall, the observation from Figure 5 suggests that the PSD shape for CDC is impacted by fuel properties. In particular, the higher sooting tendency for fuels containing aromatics and alkane fuels with longer chain length appear to result in higher concentrations of accumulation mode particles. Additionally, due to the lower density of farnesane and the PRF fuel they are expected to result in slightly higher air entrainment during the injection process, which impacts the local equivalence ratios and likely also impacts the PSD.

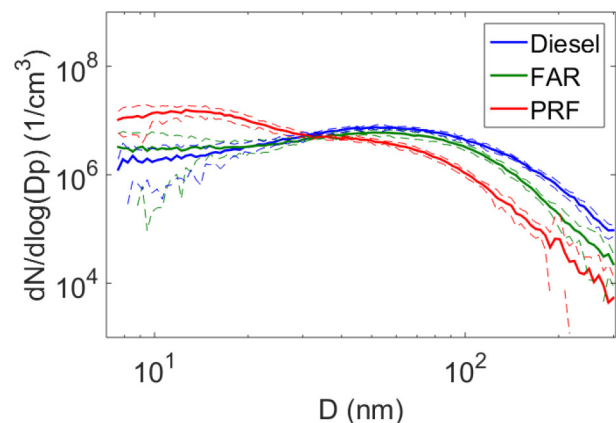


Figure 5. PSD comparison at CDC Mode 5 (1900 RPM/ 5.7 bar IMEP)

Natural Gas with Diesel Pilot Injection

In NG DPI combustion, a small amount of DI fuel is injected late during the compression stroke. The DI fuel acts as the ignition source and the surrounding NG/air mixture, is consumed via flame propagation. The engine operating conditions and combustion performance for the NG DPI conditions are presented in Table 5 and 6 and Figure 6 and 7. The engine was operated at both Mode 5 (1900 RPM/5.7 bar IMEP) and Mode 8 (2300 RPM/8 bar IMEP).

Table 4. DPI Mode 5 operating conditions

		DPI Mode 5		
Fuel		Diesel	FAR	PRF
DI%		11%		
Intake Temp.	°C	40		
Intake Pressure	bar	0.82		
Exhaust Pressure	bar	1.13	1.13	1.12
Injection Pressure	bar	600		
Injection Timing	aTDC	-14.3	-14.1	-17.5
CA 50	aTDC	8	7.75	8.5
FSN		0.02	0.02	0.02