THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN THERMO AND FLUID DYNAMICS

Particulate Formation in Gasoline Direct Injection Engines

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Cover:
Illustration of particulate formation in a GDI engine

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ABSTRACT

Gasoline direct injection (GDI) engines are facing a great challenge because of the need to comply with increasingly stringent emission regulations while improving fuel economy. GDI engines are popularly known for their high fuel efficiency (by the standards of gasoline engines) and low emissions, enabling higher compression ratios and thus increased volumetric efficiency. Unfortunately, GDI engines tend to produce higher particulate number (PN) emissions than conventional port fuel injection (PFI) engines, mainly due to the challenges of in-cylinder liquid fuel injection. Cold starts, transients, and high loads account for a disproportionately high share of all PN emissions from GDI engines over a certification cycle. Understanding the mechanisms of PN formation during these stages is necessary for the further market penetration of GDI under the constraint of tighter emission standards. This knowledge becomes especially important when in future particles with sizes smaller than 10 nm are measured and legislated.

This work presents experimental investigation of particulate emissions from a naturally aspirated single cylinder metal gasoline engine operated in a homogeneous configuration. The engine was modified to be capable of operating using DI, PFI, or both simultaneously to isolate certain PN formation mechanisms. PFI was configured with a custom inlet manifold to inject about 50 cm upstream of cylinder head, forming a more homogeneous fuel-air mixture than would otherwise be possible. Improved mixing quality with upstream injection together with direct injection could reduce PN emissions by up to a factor of 10 while only modestly increasing fuel consumption. The chemical composition of the fuel could also strongly affect particulate emissions. Therefore, to find alternative ways of reducing PN emissions, experiments were conducted using a gasoline engine with fuel blends containing renewable oxygenates – either 10% (v/v) ethanol (EtOH) or 22% (v/v) ethyl tert-butyl ether (ETBE). It was observed that PN emissions was reduced using oxygenated fuels at low load for both PFI and DI operation, but not at higher loads where PN increased instead. Measurements of solid PN (SPN) emissions revealed that more soot was formed at high load along with an increase in emissions of volatile organic compounds (VOC).

PN measurements were conducted using a DMS500 fast particle spectrometer supplied by Cambustion. In addition, solid particulate measurements were performed by passing exhaust samples through a thermodenuder and a catalyst to remove most of the volatile organic compounds (VOCs) from the raw emissions. The results indicated that wall-wetting is the dominant particulate formation mechanism inside the cylinder: fuel-wall interactions with the piston, cylinder walls, and valves during the fuel injection period account for a significant fraction of the PN content of raw exhaust.

Keywords: Gasoline Direct Injection, Particulate Number, Alternate fuels, PM, Volatile organic compounds

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following publications:

Publication A	Etikyala, S., Koopmans, L., & Dahlander, P. "Particulate Emissions in a GDI with an Upstream Fuel Source" in *WCX^{TM} 19: SAE world congress experience, Detroit, MI, US*, https://doi.org/https://doi.org/10.4271/2019-01-1180
Publication B	Etikyala, S., Sharma, N., Sjöblom. J., Karvo. A., Keskiväli. J., Kolehmainen. T., Koopmans, L., & Dahlander, P. "Particulate Emissions from GDI Engines fueled with Gasoline and Renewable Fuel Blends", submitted to *Fuel Journal Elsevier.*

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This project relies heavily on measurements of the particulate contents of engine exhausts, and anyone who has performed such measurements will be able to tell you how challenging and complicated it can be. I would therefore like to thank Docent Jonas Sjöblom and Dr. Timothy Benham for sharing their expertise and helping with the measurement equipment. I would also like to thank Tim for helping with the emission equipment whenever needed and his endless patience. I am also hugely grateful to Alf hugo, Robert, Patrik, and Anders for being so understanding and always willing to help me.

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Contents

1 Introduction

1.1 Motivation

Internal combustion engines are widely used in transportation due to their high efficiency and reliability and have played a major role in shaping both public lifestyles and the global economy over the 150 years since they were first developed. Unfortunately, the increased usage of internal combustion engines in the automotive sector and elsewhere has a disadvantage in terms of emissions. Particulate emissions due to road transportation have attracted particular interest and concern in recent years because several medical studies have shown that that particulates can adversely affect human health. For instance, particulates in inhaled air goes into the lungs and enters the blood system through alveoli. Thus, in addition to their contributions to air pollution and global warning, vehicular emissions can cause significant health and environmental problems.

Over 25% of all ultrafine particulates emitted into the atmosphere originate from road transportation, with major vehicular sources including internal combustion engines, brakes and sometimes also tires, as shown in Figure 1.1. Because they are a public health hazard, stringent regulations on particulate emissions have been introduced. The need to reduce particulate emissions has motivated extensive research on control mechanisms for internal combustion engines and improvements in engine technology.

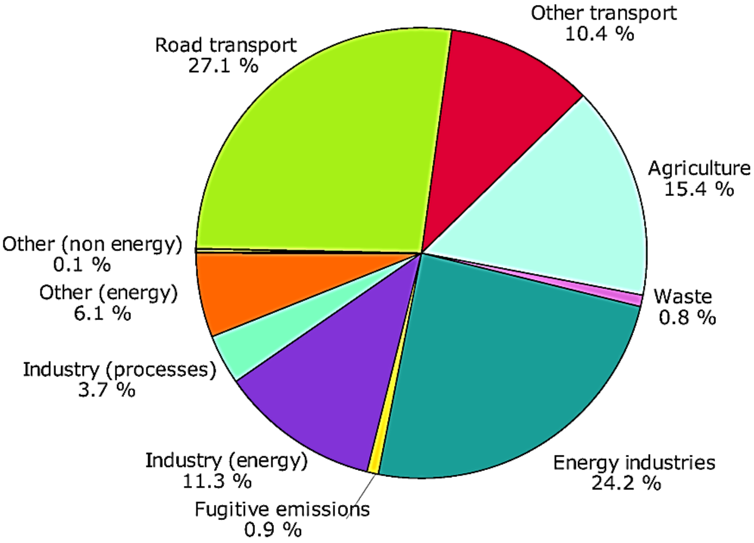

Figure 1.1: *Sector split emissions of primary and secondary fine particulate emissions by particulate mass (PM10) [Source: EAA 18]*

Gasoline engines use a pre-mixed combustion process that produces less soot than similarly powerful diesel engines that rely on diffusion combustion. This is particularly true for modern port fuel injection (PFI) engines, which achieve excellent mixture quality under stationary operating conditions. Since their introduction in 1996, gasoline direct injection (GDI) engines have been widely used by automotive manufacturers because of their high efficiency. Most gasoline DI engines operate using a stoichiometric air/fuel mixture formed by injecting the fuel early during the intake stroke. GDI engines are a key enabler for reducing CO2 emissions from gasoline-powered vehicles. In contrast to Port Fuel Injection (PFI) engines, GDI engines have higher compression ratios and lower charge temperatures which deliver higher volumetric efficiencies with lower fuel consumption. [1, 2]. Because of these benefits and the potential for further reductions in fuel consumption and emissions, there is strong interest in developing improved DI gasoline engines, despite their greater cost compared to PFI engines. GDI engines also have the potential to deliver considerable reductions in emissions during cold starts by avoiding the formation of liquid fuel films on the intake port walls [3]. However, particulate emissions from GDI engines tend to exceed those of PFI engines under standard operating conditions due to the formation of fuel-rich zones and wall-wetting.

Techniques such as exhaust after-treatment, recirculation of exhaust gas into the cylinder, and fuel reformulation to increase oxygenation have been used to reduce soot emissions [4, 5]. For instance, gasoline particulate filters (GPF) are widely used to capture soot from engine exhaust [6]. Current GPFs are less efficient at removing soot than diesel particulate filters (DPFs), but intensive research efforts to improve their performance are ongoing. Pressure build-up in the exhaust manifolds of vehicles can be avoided by periodically regenerating GPFs. Unfortunately, expensive GPFs will impose increased costs: they increase fuel consumption by raising the engine's backpressure, and may also increase maintenance costs if they must be replaced frequently [7]. Active regeneration would need a lean air-fuel mixture at certain high temperatures (but not too high) and can be critical in the presence of catalysts. Compared to PFI systems, DI fuel injection systems are more likely to produce less homogeneous fuel-air mixtures at ignition because they yield shorter mixing times and may cause fuel impingement on the combustion chamber and cylinder walls, the piston, or the valves. This leads to the formation of fuel-rich regions and cyclic variation, both of which tend to increase soot formation [8, 9, 10]. Particulate formation in gasoline engines is usually attributable to inadequate air-fuel mixing [3]. Increasing mixture homogeneity in SI engines generally improves combustion quality, which is essential for minimizing particulate emissions. Because particulate emissions from GDI engines depend on many different factors whose interrelationships are not well known, research is needed to develop a detailed knowledge of the processes that control mixture homogeneity and particulate formation/degradation in order to guide the development of robust strategies to minimize particulate emissions.

Alternative fuels for gasoline direct injection engines have also drawn a lot of attention recently. Recent studies showed that particulate formation and emissions from GDI engines can be reduced by replacing some part of conventional fossil gasoline with alternatives such as ethanol (EtOH), methanol, butanol, or methane. Several alternative fuel blends for spark ignition engines are widely available: E5 (5% ethanol and 95% gasoline by volume) is now common in Europe (European Committee for Standardization 2008), E10 blends are ubiquitous, and E20 is entering the market for newer vehicles in the USA (U.S.C. §7546).

Table 1.1: EU emissions standards for particulate emissions from GDI-powered vehicles.

Emissions	**Units**	**Euro 5a**	**Euro 5b**	**Euro 6b**	**Euro 6c**
		Jan 2009	Jan 2013	Sept 2015	Sept 2018
PM	mg/km	5	4.5	4.5	4.5
PN	#/km	-	-	6.0 x 10^{12}	6.0 x 10^{11}

Table 1.1 shows the evolution of EU regulations governing particulate emissions from GDI engines. To comply with regulations relating to particulate mass (PM) emissions, the exhaust is commonly filtered to remove larger particulates. However, PN emissions tend to be dominated by low-diameter particles. Future legal limits on PN emissions and the sizes of particles emitted by GDI engines will almost certainly be more stringent than those currently in force, and GPFs can only reduce PN emissions by 60–80%. This margin is too small to ensure that existing technologies will be sufficient to achieve compliance with future legal requirements. Identifying ways to minimize particulate matter formation in GDI engines will also enable the design of effective GPF systems to remove the remaining particles without creating a detrimental back-pressure. For all these reasons, there is a clear need to better understand the mechanisms of soot formation in GDI engines.

1.2 Objective and thesis outline

The objective of this work is to identify, isolate, and study the mechanisms of particulate formation in GDI engines. An additional objective is to use the resulting knowledge to develop effective ways of reducing particulate number (PN) emissions from GDI engines. More concisely, the project's objectives are to:

- Identify the mechanisms governing soot formation in homogeneous SI engines, and
- Develop counter strategies for minimizing this soot formation.

To a greater degree than other regulated emissions, particulate emissions are sensitive to and dependent on many parameters. Similarly, there are several ways of reducing PN emissions. This study aims to quantitatively compare the benefits of these techniques in terms of their effects on different (and particularly, dominant) particle formation mechanisms. For instance, the impact of wall-wetting on PN is so substantial that it masks the effects of all other PN formation mechanisms under almost all driving conditions [8].

The potential for reducing PN emissions under various driving conditions by replacing gasoline with alternative fuels was also investigated. Experiments using gasoline blends containing renewable oxygenates provided new insights into their ease of use and the extent to which they can reduce PN emissions while driving in urban areas. The impact of blend composition on engine performance and emissions was studied experimentally using a AVL single cylinder engine with a Volvo prototype cylinder head.

This thesis is divided into five sections. This introductory section is followed by section 2, which provides detailed background on particulate formation. Section 3 explains the experimental set-up, including the injection strategies and operating conditions, measurement and equipment setup. Section 4 presents results relating to PN measurements, particulate size and distribution, total numbers of particulates, and solid particulates. Finally, section 5 summarizes the conclusions that were drawn.

2 Background

GDI is a key technology for modern gasoline engines whose purpose is to reduce CO2 emissions while simultaneously improving torque and power output. Direct injection is often implemented in downsized turbocharged engines. However, the PN emissions of GDI engines are higher than those of conventional PFI engines; in fact, a car with a GDI engine and no particle filter may emit significantly more harmful particulates than a comparable diesel engine with a particle filter. This has resulted in new legal limits on PM and PN emissions from direct injection SI engines. To satisfy current regulatory requirements, automakers have now started to use GPFs.

2.1 Particulates from GDI engines

To fully understand the particulate emissions from GDI engines, it is important to consider real driving emissions (RDE) in a typical drive cycle. Figure 2.1 shows the variation in PN emissions from 1.6 L GDI and PFI engines over the New European Driving Cycle (NEDC) [4]. As shown in the plot, there are three key phases of a drive cycle during which PN emissions from the GDI engine are particularly high:

- cold starts/engine warmup,
- transients, and
- high loads.

2.1.1 Cold Starts

The cold start engine condition is an important influencing factor for PN emissions from GDI engines. During a cold start, particle number emissions are significantly higher than those observed once the engine has warmed up to its normal operating temperature [11]. This is because heat losses are higher and the surface temperature is considerably lower during cold start and engine warm-up conditions; this in turn reduces the extent of fuel vaporization and air-fuel mixing, creating a heterogeneous charge with localized fuel-rich regions [12]. Consequently, cold-start particulate emissions account for more than half of the total PN emissions from a GDI engine over a drive cycle [13]. As the engine warms up, PN emissions start to decrease.

2.1.2 Transients

During load transients in a GDI engine, there is a sudden change in the mass of fuel injected into the cylinder, leading to abrupt changes in PN emissions. The increased fuel intake causes considerable wall-wetting, increases the abundance of fuel-rich zones, and reduces mixture homogeneity, all of which tend to increase PN emissions. A sudden increase in load can also cause pool fires to occur before steady state conditions are established, further increasing PN emissions [14]. Engine transients also often reduce the

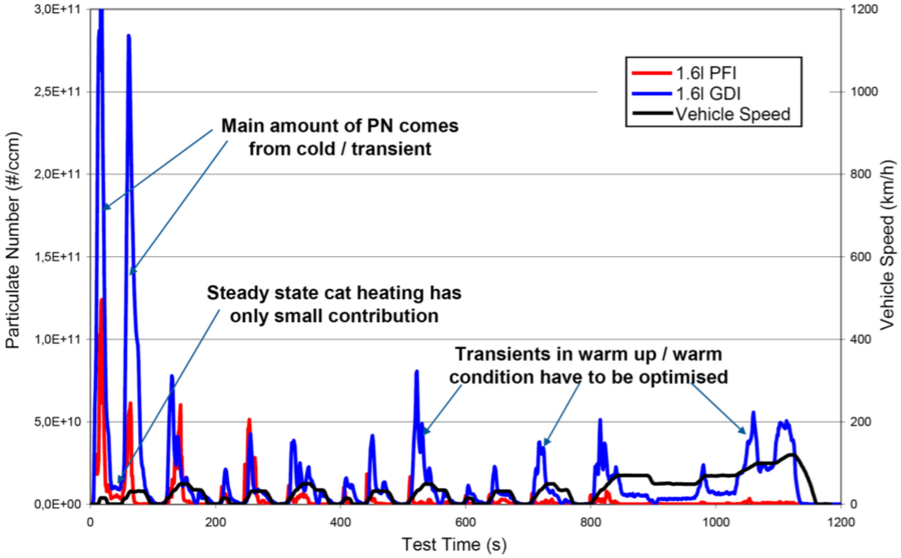

Figure 2.1: *The NEDC drive cycle test sequence together with PN (particle number) emissions from PFI and GDI engines with equal swept volumes. PN emissions are particularly high during cold starts, engine warm-up, transients, and high load drive phases [Source: Whitaker et al. 2011].*

air-fuel ratio (AFR), which is another key determinant of PN emissions. PN emissions tend to be high at rich or stoichiometric AFRs – up to an order of magnitude higher than under lean conditions. Finally, alcohol fuels exhibit poor vaporization during load transients, reducing mixture homogeneity and thus increasing PN emissions.

2.1.3 High Loads

In all engine types, high loads typically necessitate the injection of a greater quantity of fuel and thus cause higher PN emissions. Fuel–wall interactions are a major cause of PN formation, and increasing the quantity of injected fuel increases the potential for such interactions. Injecting large amounts of fuel also necessitates longer injection duration, increasing the likelihood that liquid fuel will interact directly with the piston as it moves from BDC towards TDC. This issue is exacerbated by the high fuel injection pressures used in many modern engines, which increase liquid penetration and thus increase the likelihood of liquid fuel reaching the walls or piston. Any unburnt fuel that remains in the cylinder after the end of combustion will also increase PN emissions. At relatively high loads, the tumble and turbulent kinetic energy are strong, leading to enhanced mixing. Nevertheless, achieving a completely homogeneous air-fuel mixture in direct injection engines can be challenging, and imperfect homogenization may cause the presence of fuel-rich regions in the mixture, favoring soot formation. The fuel spray may also be deflected by strong tumble motion, further reducing mixing quality.

2.2 Particle formation mechanisms

Particle formation occurs during the combustion of fuel in the combustion chamber of an internal combustion engine. The formed particles may subsequently grow via nucleation of supersaturated vapors in the exhaust gas after-treatment system [14, 5]. Particulate emissions from GDI engines include ultrafine particles that are < 100 nm in size. Particles in this size class have come under intense scrutiny in recent years because of their adverse effects on human health.

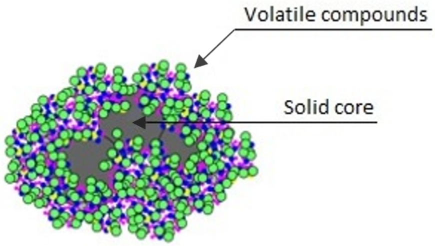

Figure 2.2: *Illustration of a typical particulate found in engine exhaust [Source: PMP 18]*

Ultrafine particles contribute little to particulate emissions by mass but account for a large fraction of particulate number emissions. Particles emitted from engines typically have complex structures featuring a solid core that forms first and is subsequently coated with volatile compounds (see Figure 2.2). Volatiles including sulphates, nitrates, and volatile organic compounds (VOC) account for almost 90% of the mass of ultrafine particulates [8, 14, 6]. Most PN formation mechanisms contribute to the formation of both the solid core and the volatile coating.

In-cylinder mechanisms that cause particulate formation

2.2.1 Spray interactions

Any fuel that is injected into the cylinder but not promptly vaporized will inevitably get in contact with the piston or the cylinder walls. The interactions of the fuel spray with the cylinder walls, piston, and valves contribute significantly to particle formation, so studying these interactions can provide important insights into the mechanisms by which particulates are formed. Figure 2.3 shows an image of a fuel spray being injected into the cylinder of a GDI engine with a start of injection (SoI) of -320 CADbTDC, which is a typical value for a GDI engine. In the figure, the fuel spray can be seen to interact with various surfaces, resulting in valve impingement, cylinder wall impingement, and piston wall-wetting. All three types of interaction are known to cause PN formation in GDI engines, although their relative and absolute importance are temperature-dependent.

Fuel films on the combustion chamber wall also contribute to PN formation in GDI engines. Fuel deposited on the wall cannot be adequately mixed with air before the flame arrives, creating localized fuel-rich zones with elevated levels of particulate formation [7]. Fuel films also dilute the oil films on the cylinder walls that ease piston movement.

Figure 2.3: *Image of a fuel spray injected into the cylinder of a GDI engine (SOI: -320 bTDC)*

2.2.2 Mixing quality

Several factors make it impossible to form a perfect air-fuel mixture inside the cylinder. Piston wetting can generally be avoided by adjusting the SOI timing. However, the SOI timing must also be set so as to provide a mixing period long enough to enable adequate air-fuel mixing. The choice of injection timing is therefore a compromise between avoiding piston wall-fuel interactions and ensuring adequate mixing time. The formation of a very well-mixed charge would avoid these problems and thus minimize PN emissions. PFI systems allow longer mixing times than GDI systems, and thus tend to produce more homogeneous fuel-air mixtures even when the GDI system is operated in homogeneous mode. It is possible that by combining GDI and PFI, one could retain the benefits of GDI while producing lower PN emissions than would be achieved with GDI alone.

2.2.3 Injector tip-wetting

Wetting of the injector tip is another important cause of particulate emissions in GDI engines. In endurance tests, where the engine is initially equipped with clean injectors and operated under stationary conditions for several hours, PN emissions are often observed to increase before reaching a high but stable level. Under these stabilized conditions, the injector tip surface is usually covered with a thin layer of carbon-based deposits, as shown in Figure 2.4 [9, 10]. It is assumed that this layer forms if liquid fuel remaining on the injector tip after the end of injection cannot fully evaporate before the onset of combustion; when the flame reaches this residual fuel, high temperatures and a lack of oxygen lead to the formation of particulate matter and deposits on the tip surface [15]. Deposit formation on the injector tips may also compromise spray quality because

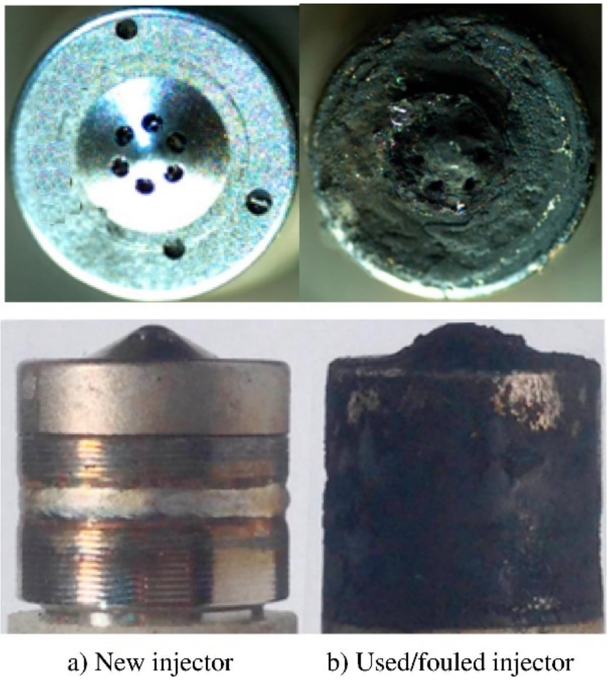

Figure 2.4: *Photographs of a GDI fuel injector before and after usage [Source: Zhou et al. 2018]*

the porous nature of the deposited material allows it to store liquid fuel and retard its evaporation, thereby accelerating further deposit growth until an equilibrium between deposit formation and removal is reached.

2.2.4 Particulates from Oil

The engine exhaust also contains particulates originating from the engine lubrication oil. Lube oil (also known as engine oil, motor oil, and engine lubricant) coats the piston and cylinder walls. The desorption of semi-volatile organic compounds (SVOC) from this coating layer during the exhaust stroke is both a major pathway of oil loss and an important contributor to PM emissions [16]. It is well-known that lube oil is continually consumed in the combustion chamber. Although its rate of consumption in modern engines is low – values of 0.2% [17] and 0.1% [18] are common – it can nevertheless contribute significantly to overall particulate matter emissions [19, 20]. Particles derived from lube oil were estimated to account for almost a quarter of the total PM emissions from gasoline-powered vehicles, and PM emissions during transient operation were strongly dependent on the composition of the lube oil [20]. It was also found that the concentration of additives (Zn, Mg, P and S) in the lube oil correlates positively with PN emissions and that lube oils with high contents of Zn, Ca, Mg, and S were associated with elevated PM emissions [14].

2.3 PN measurements

Particulate emission measurements are unfortunately highly sensitive to the choice of sampling system. Therefore, a robust measurement protocol such as that used in the Particulate Measurement Program (PMP) with a volatile particle remover (VPR) should be used. While several standards for measuring particles from combustion sources have been developed, the one most commonly used for certification in the automotive sector is that specified in UNECE regulation no. 83 [21]. The sampling system should be able to prevent particle formation by nucleation and agglomeration downstream of the engine. As noted above, particulates have both solid and volatile components. Unfortunately, particulate measurements become highly variable when volatiles are involved because their instability can cause measurements to fluctuate widely.

Measuring solid particles is also challenging because the engine exhaust sample must be depleted of volatiles in a way that has little or no effect on solid particles. The engine emissions at a sampling point must be in a “frozen” state for solid particle measurements. Because of these difficulties, PN measurements are not always reproducible and depend strongly on the sampling system. Therefore, the sampling equipment must be kept in a constant state to produce comparable measurements.

Raw exhaust PN emissions from gasoline engines can be classified based on particle size: the “nucleation mode” and “agglomeration mode” comprise particles with diameters of 3-30 nm and 20-500 nm, respectively [6]. The nucleation mode accounts for almost 90% of all PN emissions but only 10% of the total particulate mass, and consists predominantly of volatiles. There are also semi-volatiles, which are defined as particles of varying size surrounding solid core particles with dimensions of 1-5 nm [22].

2.3.1 Interpreting particulate size distribution graphs

The particulate content of exhaust samples is quantified in terms of particle number and size distributions, which are displayed by plotting the number concentrations of particles per unit flow (dN/dLogDp/cc) against particle size (5 to 300 nm). Figure 2.5 shows a typical particle size distribution from a gasoline engine operating at a reference load point.

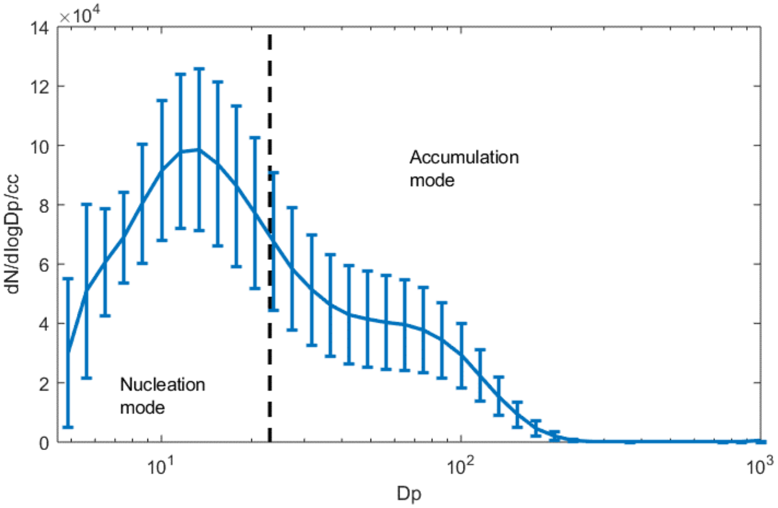

Figure 2.5: *Particle size distribution for a GDI engine at a load of 5 bar IMEP and an engine speed of 1500 rpm. The dashed line indicates the regulatory limit of 23 nm for PN emissions.*

2.4 Current techniques for PN reduction

This section briefly reviews some established solutions for reducing PN emissions from GDI engines.

2.4.1 Injection pressure tuning

The fuel injection pressure strongly affects PN emissions. Raising the injection pressure enhances air-fuel mixing because higher injection pressures produce smaller fuel droplets, which evaporate more rapidly than larger ones. At a given load, increasing the injection pressure makes homogeneous flame front propagation faster and raises the peak pressure [23]. Higher peak pressures imply higher in-cylinder temperatures, which is beneficial for soot oxidation. The results presented in this thesis (see chapter 4 and Paper I) support the conclusion that higher pressures reduce particulate emissions, partly because they increase the momentum of fuel droplets [8]. These findings are consistent with previously reported studies on the effects of varying the injection pressure in GDI engines [2, 24, 25]. Because of these benefits, manufacturers of gasoline engines for passenger cars have begun using higher injection pressures in their engines: Volkswagen's engines operate at typical maximum injection pressure of 350 bar and others are aiming for even higher pressures such as 700 bar.

2.4.2 Optimizing injection timing

The injection timing in a GDI engine must be optimized to strike a good balance between achieving an adequate mixing time and avoiding piston wetting. In a GDI engine operated in homogeneous mode, fuel is injected in the intake stroke. If injection is too early, there is a risk of fuel interfering with the piston. However, if the injection occurs too late in the cycle, there will be insufficient time for mixing, resulting in poor mixture quality. Figure 2.6 shows how the PN emissions of a GDI engine vary over an SOI sweep with a fixed injection pressure. In this engine, advancing the SOI from 350 °bTDC to 330 °bTDC causes a dramatic reduction in PN emissions, which fall to a minimum at 270 °bTDC. This is consistent with the findings of an earlier study [26] in which pool fires were found to occur throughout the combustion process when early injection timings were used but were eliminated entirely by using later injection timings. Pool fires generate very large numbers of particulates, so to minimize PN emissions it is essential to use an SOI timing that prevents their occurrence.

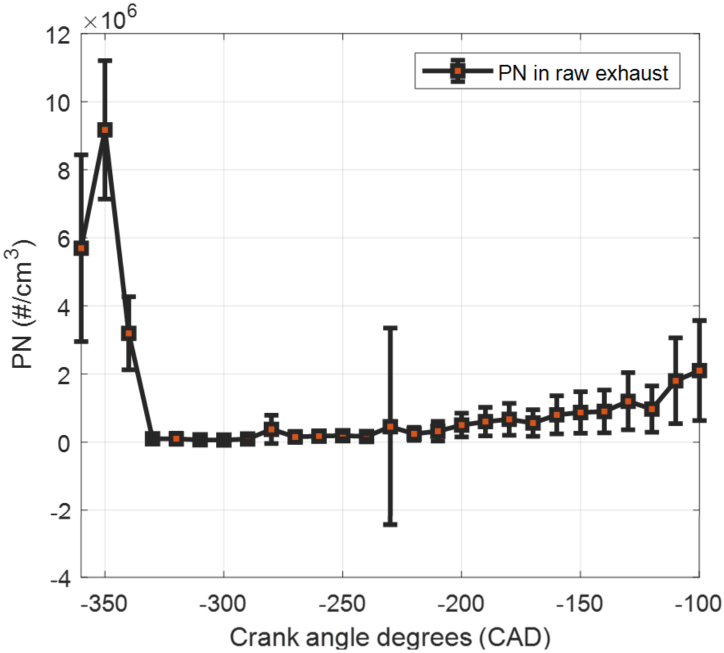

Figure 2.6: *Influence of fuel injection timing (SOI) on particulate (PN) emissions at an engine load of 5 bar IMEP at 1500 rpm*

2.4.3 Split Injection and Multiple Injection

During split injection or multiple injection operation, fuel is injected in a small sequence of injections rather than a single large injection. Because the mass of fuel injected at any one time is reduced, the momentum of the individual fuel jets is lower. This in turn reduces the liquid penetration length and enhances the spread of the spray, leading to reduced wall-wetting and a lower spray density. Both of these phenomena reduce PN emissions [23]. Split injection can also improve mixing and increase combustion stability, further reducing PN emissions.

2.4.4 Optimization of Spray targeting

Another way of reducing PN formation is to reduce the interaction between the fuel and in-cylinder surfaces. This can be achieved by using injectors with specific spray targeting so that the fuel spray does not directly hit the piston. However, spray optimization is not a generic solution; each spray targeting scheme is specific to a given engine type and design. The objective of spray targeting is to guide the liquid fuel such that it does not directly hit a surface such as a valve or the cylinder walls. Spray targeting also ensures proper charge homogenization, thus controlling the formation of fuel films on the combustion chamber walls and increasing atomization. Recent developments have enabled improvements in spray optimization for all types of GDI engines, for instance by using side- and center-mounted injection systems.

2.4.5 Gasoline Particulate Filters

The density of particulates in gasoline exhausts is typically an order of magnitude lower than that in raw diesel exhaust. Therefore, a soot cake forms rapidly in diesel particulate filters (DPFs), allowing them to achieve PN filtration efficiencies of >99%. The lack of a soot cake on GPFs unfortunately leads to relatively low PN filtration efficiencies. The efficiency of a GPF during a driving cycle varies between 75 and 80% if the filter is coated, and between 45 and 50% for a non-coated filter. In both cases, the back-pressure is typically 5-10 kPa, so the increase in fuel consumption is relatively modest. In late October 2017, a prototype three-way catalyst with a coated GPF achieved a particulate filtration efficiency of 99%. However, the back-pressure generated by this system was very high, resulting in a significant increase in fuel consumption. Additionally, the system's filtration efficiency and back-pressure increased significantly over its lifetime, presumably because an ash layer was gradually built up (from oil ash residuals) on the filter channel wall.

2.4.6 Renewable fuels

Sweden wants to replace fossil fuels with renewable fuels by the year 2030. Several studies have shown that replacing conventional fossil fuels with oxygenated alternatives reduces soot formation. A rule of thumb for drop-in fuels (e.g., gasoline with 30–40% butanol) is that they will reduce engine-out soot emissions by around 50%. However, only a few combinations of renewable fuels have been investigated in this context. The energy content of alternative fuels is typically lower than that of fossil fuels and their latent heats are higher, both of which necessitate longer fuel injection periods. This may influence the combustion process and soot formation. Soot formation when using these fuels may also be affected by fuel properties that influence spray atomization, such as vaporization behavior, the adiabatic flame temperature, viscosity, and surface tension. Spray properties (for example, droplet size and liquid penetration rate) may vary with the alternative renewable fuel considered/employed. However, the effects of these properties on soot formation are unclear. A better knowledge of their effects (or lack thereof) is therefore needed to develop soot-reduction strategies tailored to specific renewable fuels. In addition, the potential benefits of renewable and drop-in fuels on the emissions of sub-23 nm particulates remain to be determined.

3 Experimental Setup and Methods

3.1 Engine

The experimental investigations were conducted on a single cylinder research engine equipped with a four-valve cylinder head fitted with intake ports designed to generate moderate tumbling gas motion. Fuel was delivered to the cylinder through a) a six-hole solenoid injector mounted centrally in the cylinder head and/or b) a port fuel injector (PFI) mounted 50 cm upstream of the intake port in the inlet manifold, as shown in Figure 3.1. The two injection systems were used both simultaneously and separately. The engine specifications are listed in Table 3.1.

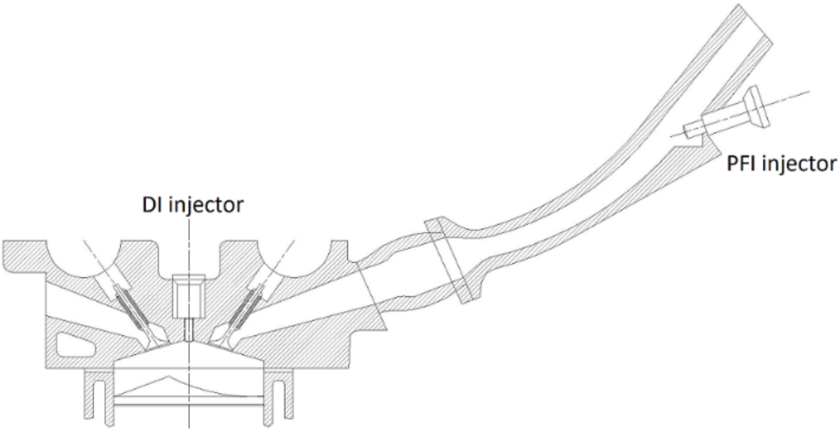

Figure 3.1: *Schematic depiction of the dual injector setup showing the centrally mounted DI injector and a PFI injector mounted 500 mm upstream in a custom manifold.*

The location of the PFI injector was chosen to be relatively far from the cylinder head so that any fuel delivered via this injector can be assumed to be well-mixed with air when it reaches the combustion chamber. The quantity of fuel injected into the cylinder was quantified in terms of the mass of fuel injected. In cases where both injectors were used, the total fuel mass injected into the cylinder at a given load was kept constant. All tests were run under stoichiometric conditions with maximum break torque (MBT) combustion phasing (MFB50 = 8 CADaTDC).

Table 3.1: Engine Specifications

	Single-cylinder engine	
Cylinder volume	500	cc
Bore	82	mm
Stroke	90	mm
Engine head	Four valve SGDI	
Spark plug	Single electrode	
Injector for DI	Six-hole solenoid injector	
Injection pressure for DI	200	bar
Injector for PFI	Conical Spray type injector	
Injection pressure for PFI	3.5	bar
Intake air temperature	35	°C
Coolant temperature	80	°C
Inlet Valve Opening	356	CADaTDC*
Inlet Valve Closing	578	CADaTDC*

*TDC implies TDC combustion

3.2 Measurement Setup

A Cambustion DMS500 MkII fast particle analyzer was used to monitor the particle distribution and number of particles emitted from the engine by measuring the electrical mobility of individual particles. The DMS500 has a built-in dilution system consisting of primary and secondary diluters. The secondary dilutor was operated at a dilution factor of 1 to maximize signal strength. The primary diluter was heated to its maximum temperature of 150 °C. To avoid condensation and possible losses of material due to temperature gradients, the sampling line was also heated to a uniform temperature of 150 °C along its full length (from the engine to the DMS) using an external heating system. The PN distributions reported here were generated by analyzing the exhaust with the DMS500 for at least three minutes at a frequency of 5 Hz under stable engine operating conditions and then averaging the results to maximize reproducibility.

Particulates in the exhaust were measured with and without passage through a volatile particle remover (VPR). This was achieved by placing two switchable valves between the engine exhaust manifold and the DMS500 or SMPS, as shown in Figure 3.2. A Dekati thermodenuder (TD) acting as a VPR and a monolithic catalytic stripper (CS) were used to remove volatiles and thus enable solid particulate measurement. The TD and CS were heated to 350 °C and the exhaust was sampled a short distance (approximately 15 cm) downstream of the exhaust port. Although the VPR specified by the PMP standard relies on dilution, external dilution was not used here because it reduced signal strength unacceptably.

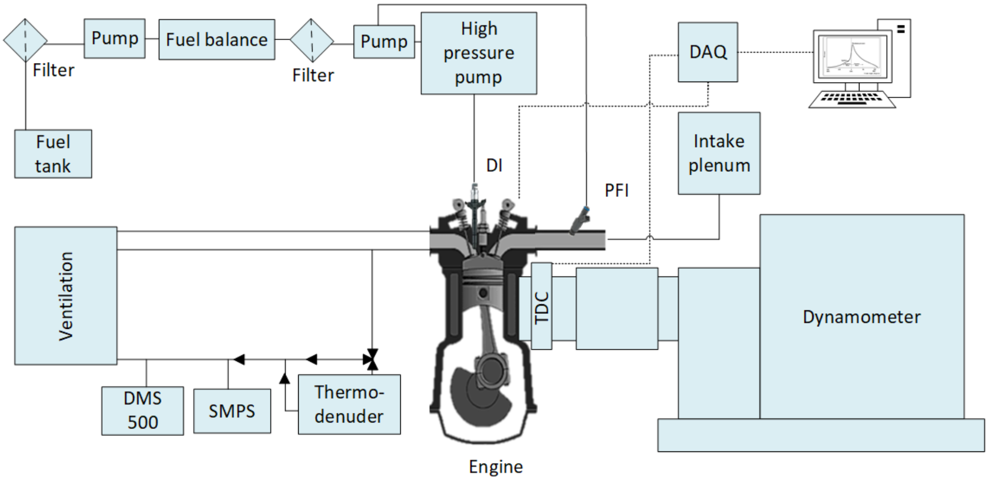

Figure 3.2: *Schematic depiction of the experimental apparatus showing the valve system used to sample engine exhaust with and without prior passage through the thermodenuder.*

The thermodenuder removes volatiles from the exhaust in two key steps: first the incoming exhaust is heated to induce evaporation of volatile compounds, then the resulting dry exhaust is passed through an adsorbing carbon cartridge surrounded by cooling water (see Figure 3.3). At the beginning of each experimental campaign, the carbon cartridges were replaced with fresh ones to ensure adequate adsorption of volatile compounds [27]. Note that measurements of particulates in raw exhaust samples are referred to simply as PN measurements whereas measurements of particulates in exhaust samples after passage through the TD are referred to as solid PN measurements.

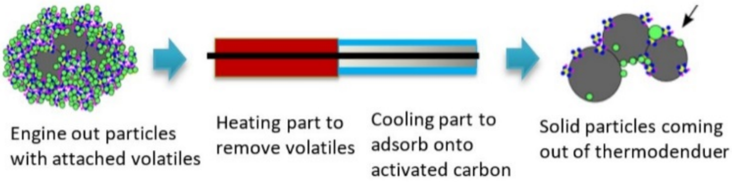

Figure 3.3: *Working principle of a thermodenuder showing the removal of volatile organic compounds from engine out particles*

The DMS500 was cleaned daily to eliminate measurement errors due to accumulation. The flow through the thermodenuder was maintained at the recommended value of 15 lpm. All measurements were conducted under stable steady state operating conditions with a coefficient of variance (CoV) in IMEP <1.5% where possible. However, when using

100% PFI at high load, it was impossible to reduce the CoV in IMEP to much less than 3%.

The experimental data were analyzed using a model based on design of experiments and partial least squares (PLS) regression. Analytical models based on DOE require scalar input data. To generate suitable scalars from the raw DMS500 data, we summed the average counts for each particle size class considered in this work over the measurement duration. This approach is consistent with the method for characterizing particulates specified in the PMP standard [21]. The DMS500 has a measurement threshold of 103 particles per unit flow (dN/dlogDp/cc); the iso-lines indicating 0 PN in some of the plots from the analysis correspond to exhaust samples whose particulate content was below the detection limit of the DMS500.

3.3 Engine operating conditions

This work focused primarily on high load and low speed engine operating points that produce relatively high amounts of PN emissions. Figure 3.4 illustrates the range of engine operating conditions considered. Design of experiments (DoE) was used to generate a factorial experimental design with three independent variables: the engine speed, the load, and the injection split between DI and PFI. The latter variable ranges from 0 to 100, and its value is equal to the percentage of the total fuel mass injected per cycle that is delivered via PFI. The use of a factorial design made it possible to minimize the number of testing points in the matrix while still providing a robust foundation for statistical analysis. The results obtained from the factorial design were analyzed using MODDE (a DOE software package for statistical analysis) to generate a response surface.

The optimal injection timings for the two injection modes (PFI and GDI) were determined separately by performing start of injection (SOI) timing sweeps while monitoring PN emissions. The injection timings that gave the lowest PN emissions at the reference operating point (5 bar IMEP load and an engine speed of 1500 rpm). As a result, SOI timings of -270 CADbTDC and -90 CAD bTDC were identified as optimal for DI and PFI respectively, and these timings were used in all of the other experiments.

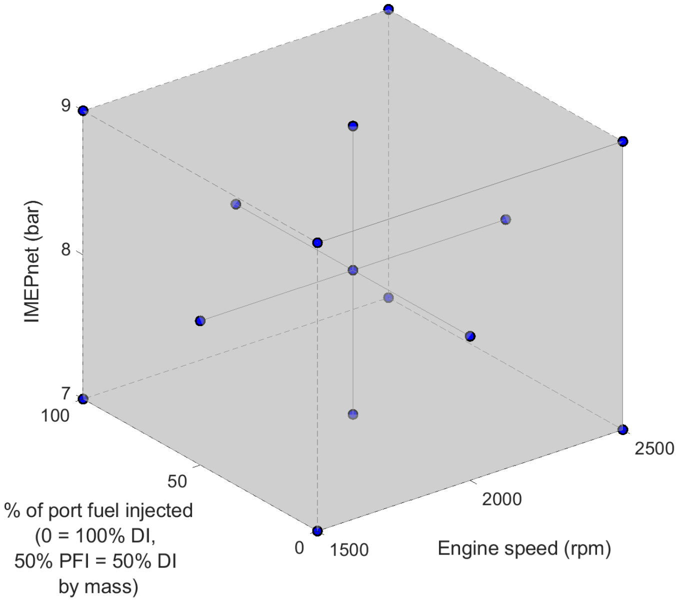

Figure 3.4: *Measurement matrix showing Central Composite Face design comprising full fractional factorial for experiments. All test points are shown in blue.*

3.4 Fuels

The experimental matrix was also used as a reference when testing the effects of alternative fuel blends on particulate emissions. Results obtained with three fuels are presented in this thesis. The base fuel in all the studied blends was a non-oxygenated gasoline. Experiments were conducted using this fuel without additives and also using two blends of this fuel with oxygenates complying with the EN 228 standard – one blend containing 10% ethanol (EtOH) and one containing 22% (v/v) ETBE. These blends are referred to as g+EtOH and g+ETBE, respectively. Both oxygenates were added to the maximum levels permitted by the EN228 gasoline standard. The specifications of the tested fuels are shown in Table 3.2. SOI optimization was achieved by performing an SOI sweep at the reference operating point for each fuel to identify the range of SOI values that minimized PN emissions. An SOI of 270 °CADbTDC was ultimately chosen for subsequent experiments. At each tested engine operating point, the PN emissions observed with each blend were compared by performing experiments in which the amount of fuel injected was varied between blends so as to keep the amount of injected energy constant.

Table 3.2: Properties of the tested fuels*

Property	**Non-oxygenated gasoline** $^{+}$	**g+EtOH**	**g+ETBE**
Oxygenate content	No oxygenates	10 vol-% EtOH	22 vol-% ETBE
Oxygen (wt-%)	<0,05	3,14	3,65
RON	96,1	96,6	97,2
MON	86	86,1	86,8
Vapor pressure (kPa)	68,9	72,3	65,9
Sulphur (mg/kg)	10	8	6
Aromatics (vol-%)	30,5	29,2	26,3
Olefins (vol-%)	14,4	11,4	9,1
Density (kg/m3)	737,3	745,1	742,4
Carbon (wt-%)	86,49	83,51	82,95
Hydrogen (wt-%)	13,49	13,37	13,41
Lower Heating Value (MJ/kg)	43,202	41,722	41,442
Stoichiometric (A/F) ratio	14.58	14.65	14.68

* Values obtained from suppliers or the literature

$^{+}$ Reference fuel

4 Results

4.1 Summary of Paper I

A GDI engine was made flexible to run both direct injection and port fuel injection in combination. Combining a low-pressure port fuel injector with a high-pressure DI injector opens up new strategies for injecting fuel into an engine (as illustrated by Audi's 2.0-liter EA888 Gen3 engine and Toyota). For example, combining DI with PFI can minimize diffusion flame formation, thereby reducing the number of possible sites of soot formation. The effects of varying the fuel injection pressure and the start of injection (SOI) on PN were studied independently to identify optimal values to use in subsequent experimental campaigns comparing PN emissions under different operating conditions. The DI fuel injection pressure was set to 200 bar because lower pressures resulted in higher PN emissions at all operating points.

Particulate emissions from this engine were measured under a range of operating conditions using different splits between PFI and DI. PN emissions in raw exhaust and solid PN emissions were measured separately by performing sequential exhaust sampling with and without passage of the samples through a volatile particle removal system comprising a thermodenuder and a catalytic stripper. Design of experiments was used to construct a factorial experimental matrix for PN measurements under engine conditions spanning a wide range of engine speeds and loads as well as PFI injection splits ranging from 0 to 100%.

The use of upstream fuel injection in a GDI engine was shown to reduce PN emissions by up to a factor of 10 (relative to pure GDI operation) with only a small penalty in fuel consumption. Solid PN emissions decreased almost linearly as the proportion of the fuel mass injected upstream increased, independently of the engine speed. However, PN emissions increased with engine speed because higher speeds result in shorter mixing times. The large mass of fuel injected at high load resulted in high PN emissions, even with upstream PFI, indicating that the use of PFI improved mixing under these conditions but was not sufficient to form a completely homogeneous mixture. Sub23 PN emissions behaved similarly to total PN in raw exhaust, suggesting that strategies for reducing total PN emissions will also be effective at reducing sub23 emissions. However, particles in this size range were found to be predominantly volatiles.

4.2 Summary of Paper II

This paper investigated the effect of fuel oxygenation on PN emissions (including legislated solid PN) from gasoline engines. Gasoline blends with and without added oxygenates were studied in both PFI and DI engine configurations at 4.5 and 9 bar IMEP. The oxygenate contents of the tested blends complied with the current European standard (EN-228). Experiments were performed using both PFI and DI to verify that the observed trends in PN emissions were due solely to differences in fuel properties rather than physical effects such as differences in liquid wall film formation. In PFI mode, fuel properties had load-dependent effects on PN emissions and the PN size distribution. In all cases, PN emissions increased with load. However, because overall PN levels were low at low load, variation in fuel properties had little effect under these conditions. At high load, the use of PFI increased PN emissions by generating a thicker wall film in the inlet runner.

The SOI timing was optimized to minimize PN emissions in DI mode. Wall wetting is unlikely when using DI at low load, so the PN emissions for the tested fuels were expected to be similar under these conditions. However, Zhang et al. [28] found that oxygenate addition generally suppresses soot precursor formation and thus reduces PN emissions at low load; this finding was supported by the results obtained here. Larger amounts of fuel had to be injected at high load, which increased wall wetting and thus resulted in higher PN emissions. The g+EtOH blend yielded higher raw and solid PN emissions than the other blends, whereas the g+ETBE blend produced similar PN emissions to non-oxygenated gasoline. For lower particulate diameters (especially for sub23 PN), g+ETBE yielded substantially lower PN emissions than the other fuel blends. The oxygenated fuel blends were more dense than non-oxygenated gasoline, which can lead to higher PN emissions [29]. The consistency of the results from the DI and PFI tests suggest that slight changes in fuel properties do not greatly contribute to PN formation. However, the impact of fuel effects was found to be stronger in DI mode at low loads.

Large quantities of low-diameter (i.e. sub23 and nucleation mode) particulates were formed under all tested conditions. Consequently, exhaust samples were passed through a thermodenuder to remove volatiles and enable measurement of solid PN emissions, in accordance with the PMP protocol. At low load (4.5 bar IMEP), both the oxygenated blends emitted the lowest solid PN, while the reference non-oxygenated gasoline generated the lowest solid PN emissions at the higher load of 9 bar IMEP. The robustness of protocols for measuring legislated PN emissions is highly dependent on the ability to accurately measure solid PN emissions. However, artefacts are common when measuring solid PN, so it is important to consider both total and solid PN emissions to properly understand the effect of fuel properties. Oxygenated fuel blends provide a good way of reducing PN emissions in raw exhaust because most passenger vehicles are mainly driven under partial load. However, under high load conditions, non-oxygenated gasoline emits lower PN. The results at high load suggest lower burn temperature for the oxygenated blends indicating slower rate of soot oxidation. However, oxygenates may have different or weak effects at high load, presumably because of a possible increase in the formation of polycyclic aromatic hydrocarbons (PAH), which act as soot precursors [30].

5 Summary and Conclusions

Particulate formation is a complex process that is sensitive to several engine parameters and variables. The effects of key variables and processes affecting in-cylinder PN formation, such as the fuel injection pressure and mixture formation, were isolated and investigated using a dual PFI/GDI injection strategy. In addition, the influence of fuel composition and the use of renewable oxygenates on PN was investigated using fuel blends that comply with the gasoline EN 228 standards and can thus be used as drop-in replacements for conventional gasoline. The experimental results indicated that piston wall-wetting affects PN emissions more strongly than all other factors considered to date.

- A single cylinder SI engine was used to conduct experiments to identify, isolate, and study the major causes of PN formation in GDI engines.
- The first investigation revealed wall-wetting to be a more important PN formation mechanism than mixing, the effects of which were isolated by mixing PFI and DI.
- The use of upstream PFI made it possible to isolate the effects of direct interactions between liquid fuel and the piston.
- The second investigation using EN228-compliant gasoline blends with oxygenates shed light on factors affecting PN emissions at low and high loads in GDI engines.
- The differences in PN emissions between the fuel blends were modest relative to the effects of variation in the engine load.
- Overall, oxygenated fuels generally yielded lower PN emissions than non-oxygenated gasoline.

Further investigation is required to understand the effect of engine load on PN emissions more thoroughly.

6 Contributions

Contributions among the work done so far in the project can be summarized two-fold with two major experimental campaigns respectively.

Paper – I

"Particulate Emissions in a GDI with an Upstream Fuel Source"

Particulate formation is still an actively sought-after topic in the industry. Designing experiments to isolate serval influencing mechanisms that occur simultaneously inside the cylinder is a difficult task. This work used the flexibility between injecting the fuel at different locations to manage and change the quality of mixture formation. By doing so, the mechanism of wall-wetting where the liquid fuel interacts with solid surfaces inside the cylinder stood out as the dominating PN formation mechanism. The main author has designed and carried out the experiments, setup and post-processed the data to realize this outcome. Main author wrote the manuscript with support from the other authors and fabricated the concept of upstream fuel injection as a source of relatively well mixed air-fuel mixture.

Paper – II

"Particulate Emissions from GDI Engines fueled with Gasoline and Renewable Fuel Blends"

The concept of using alternative fuels has been well-established so far in many developed as well as developing countries. Right now, the blend of renewable fuels with a fossil fuel is being the subject of persuasion in most parts of the world as it would require no additional cost of infrastructure in the vehicles. The idea of studying PN from blends of oxygenates with gasoline that comply with the current gasoline EN228 standard was made possible with this campaign. The main author devised the project, the main conceptual ideas and proof outline with the help of supervisors and other authors. Author has also worked out almost all the technical details and designed the suggested experiments using DoE. Author conducted experiments with different blends. The main author wrote the manuscript, verified the PN results from two measurement instruments by implementation with the help of co-authors expertise in designing after-treatment technology.

7 Future work

Diffusion flames inside the cylinder generate PN emissions at high load and during transient operation when load increases sharply. To investigate their influence more thoroughly, in-cylinder spray-wall interactions will be studied using an endoscope and a high-speed camera together with a suitable lighting system. A modified cylinder head supporting endoscope visualization has been provided by Volvo Cars. Simultaneous exhaust PN measurement using the DMS500 system will enable correlation of the visualization data with trends in PN emissions. The results of these metal engine experiments will be very relevant to road-driven engines fueled with gasoline.

Study of transients will also be extended to renewable fuels such as E85 and blends that may be used in future when EU gasoline standards permit the use of larger quantities of oxygenates. The relationship between PN emissions and engine load will be studied systematically to better understand why PN emissions rise with the load. This investigation will also be conducted using the endoscope-equipped metal engine. In addition, injector tip wetting is known to contribute to PN generation. Therefore, experiments will be designed in such a way as to isolate this phenomenon from other major PN formation mechanisms to better characterize its contribution.

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Abbreviations

AFR Air to Fuel Ratio

AVL Anstalt für Verbrennungskraftmaschinen List

CAD Crank Angle Degrees

CADaTDC CAD after TDC

CADbTDC CAD before TDC

CERC Combustion Engine Research Centre

CoV Coefficient of Variance

CS Catalytic Stripper

DoE Design of Experiments

DPF Diesel Particulate Filter

E10 Gasoline + 10% (v/v) Ethanol

E20 Gasoline + 15% (v/v) Ethanol

E5 Gasoline + 5% (v/v) Ethanol

ETBE Ethyl Tert-Butyl Ether

EtOH Ethanol

GDI Gasoline Direct Injection

GPF Gasoline Particulate Filter

MBT Maximum Break Torque

MFB50 50% Mass Fraction Burnt

Mg Magnesium

NEDC New European Driving Cycle

P Phosphorus

PFI Port Fuel Injection

PLS Partial Least Squares

PM Particulate Mass

PMP Particulate Measurement Program

PN Particulate Number

RDE Real Driving Emissions

S Sulphur

SoI Start of Ignition

SPN Sold Particulate Number

SVOC Semi Volatile Organic Compound

TD Thermodenuder

TDC Top Dead Centre

UNECE United Nations Economic Commission for Europe

VOC Volatile Organic Compound

VPR Volatile Particule Remover

Zn Zinc

List of Figures

List of Tables

Appended Publications A–B