

Particle Number Emissions Reduction Using Multiple Injection Strategies in a Boosted Spark-Ignition Direct-Injection (SIDI) Gasoline Engine

Jianye Su, Min Xu, Peng Yin, Yi Gao, and David Hung
Shanghai Jiao Tong Univ.

ABSTRACT

Spark-ignition direct-injection (SIDI) gasoline engine, especially in downsized boosted engine platform, has proven to be one of the most promising concepts to improve vehicle fuel economy. SIDI engines are also getting a larger share of the gasoline engine market which is traditionally dominated by the port fuel injection (PFI) engines in the U.S., European and Chinese vehicles. However, higher particle number emissions associated with operating the engine at higher loads pose additional challenges for meeting future stringent emissions regulations. In this study, the potential of using multiple injection strategies (double injection and triple injection strategy during the intake stroke in homogeneous combustion mode) to reduce particle number emissions in a 2.0 liter boosted SIDI gasoline engine at 1000 rpm, 11 bar BMEP condition was investigated using Horiba MEXA SPCS1000 PN measurement instrument. To clarify the mechanism for the particle emissions benefit by multiple injection strategies, three-dimensional (3D) Computational Fluid Dynamics (CFD) model of the in-cylinder process was realized using CONVERGE software with the inputs from GT-Power® engine simulation.

Measurements indicate that the double injection strategy causes a 60% reduction in particle number concentration and up to 80% reduction when implementing triple injection strategy as compared to baseline single injection strategy, demonstrating the potential of multiple injections as a promising strategy for lower particle emissions at high load operating conditions. The 3D CFD simulation reveals that double injection is beneficial to the reduction of spray-piston and spray-liner impingement, and the improvement in mixture preparation process, resulting in lower levels of particles. For triple injection strategy, the spray impingement is further reduced, and the fuel is better mixed with air, leading to a significant reduction in particle formation. Regardless of double injection and triple injection strategy, the particle number emissions tend to increase when retarding the final injection timing. While, reducing the first injection mass is beneficial for lower particle number emissions both for double injection and triple injection strategies during the intake stroke.

CITATION: Su, J., Xu, M., Yin, P., Gao, Y. et al., "Particle Number Emissions Reduction Using Multiple Injection Strategies in a Boosted Spark-Ignition Direct-Injection (SIDI) Gasoline Engine," *SAE Int. J. Engines* 8(1):2015, doi:10.4271/2014-01-2845.

INTRODUCTION

Increased global fossil fuel consumption and reduced fuel reserves are driving the automotive industry to further advance engine technologies for enhanced fuel economy. One of the most promising concepts is the downsized boosted spark-ignition direct-injection (SIDI) engines. Compared to port fuel injected (PFI) engines, SIDI engines provide better fuel economy with higher specific torque and power that is achieved from higher volumetric efficiency and higher compression ratio due to the charge cooling effect associated with direct injection [1, 2, 3]. With downsizing the SIDI engines through turbocharger and/or supercharger, fuel economy is further improved as compared to naturally aspirated SIDI engines with the same torque and power levels. Due to the smaller displacement, the downsized engine operates at a

significantly higher mean effective pressure (MEP) at the same torque level; hence the pumping losses are reduced [4]. In addition, a downsized engine operates at more efficient and higher specific torque conditions with reduced relative penalty of frictional losses, especially when the reduction in engine displacement is accompanied by a shift in operating regime to lower engine speeds [5]. The reduced air breathing capacity of smaller displacement is compensated by turbocharging when high output is required from these engines.

However, aerosol particle emissions emitted from SIDI engines are found to be higher than PFI engines [6, 7, 8], and are drawing significant attention due to their negative human health and environmental effects, especially for particles with diameters less than 100 nm (ultrafine particles) [9, 10, 11]. In PFI engines, the fuel is generally injected on the backside of

closed intake valve to take advantage of the warm valve and ports surfaces to help vaporize the fuel spray. When the intake valve opens, fuel vapor and the remaining liquid fuel is carried into the combustion chamber with the charge air and the high charge motion that occurs after intake valve opening promotes excellent air fuel mixing. Therefore, a high degree of mixture homogeneity is achieved at the moment of spark event which results in a clean pre-mixed combustion and lower particle emissions. In SIDI engines, however, fuel is directly injected into combustion chamber. It is more challenging to achieve a sufficiently homogeneous mixture due to the limited time available for fuel spray evaporation and mixing, and increased probability for spray-piston and/or spray-liner impingement. It is believed that the shorter time for mixture preparation and in-cylinder spray-wall impingement are responsible for the higher particle emissions of SIDI engines [7][8][12]. This is even more problematic with boosted SIDI engine operating at high load conditions where a large amount of fuel is injected into the cylinder [8]. As a result, it is necessary to explore effective PM suppression strategies for boosted SIDI engines, and the key to reducing particles is to improve mixture preparation and reduce fuel impingement in combustion chamber.

More stringent emission standards are also driving the introduction of the particle suppression strategies to boosted SIDI engines. In Europe, a particle mass limit of 5 mg/km has been defined for SIDI powered vehicles for the first time. According to a proposal issued by the European Commission, particle number limits over the New European Driving Cycle (NEDC) for SIDI powered vehicles will limit particle number to 6.0×10^{11} particles/km in 2017 [13]. Sabathil et al. [12] investigated the particle number emissions from current PFI powered vehicles and concluded that most natural aspirated PFI engines can meet the particle number limit of 6.0×10^{11} particles/km even without any challenges. However, some turbocharged PFI engines and SIDI engines exceed this limit. A recent research on particle emissions from three types of SIDI gasoline engines (naturally aspirated wall-guided, turbocharged air-guided, and naturally aspirated spray guided SIDI engines) powered vehicles over the NEDC indicated that none of those were able to satisfy the proposed EURO 6 particle number regulations of 6.0×10^{11} particles/km [9]. In order to meet these stringent emission standards, future gasoline engines, especially for boosted SIDI engines, need to be optimized by effective lower particle emission strategies.

Multiple injection strategy has been applied to production SIDI gasoline engine as a catalyst heating strategy. Under cold start condition, retarding spark timing is an effective way to reduce HC (Hydrocarbons) emissions and enable the catalyst to reach the operation temperature quickly. However, this benefit is limited by deteriorated combustion stability. With double injection strategy (one injection during intake stroke, another injection during compression stroke), combustion stability is

improved which allows more retarded spark timing, thus the cold start performance is improved [14][15]. Two studies [7][8] to reduce particle emissions at cold start engine condition indicated that multiple injection strategies (double injections, triple injections, 4 injections, and 5 injections) help to improve the mixture preparation process and decrease fuel impingement through reducing spray penetration. As a result, particle emissions are significantly reduced. For example, compared to single injection, two orders of magnitude lower particle number concentration was achieved by the 5-injection strategy [7]. In addition to the improved cold start performance, multiple injection strategy is also investigated to suppress knock tendency and enhance lean stratified combustion. A study by Yang and Anderson [16] demonstrated that fuel injection timing during the intake stroke is required to improve volumetric efficiency, however, a retarded injection timing during the compression stroke is required to reduce knock tendency. As a result, double injection is proposed to as a compromise for the two competing requirements, and to further increase engine full load torque output. Experimental results from a spray-guided SIDI engine under lean combustion concluded that double injection strategy provided the potential to increase combustion efficiency, improve combustion stability, and reduce NOx (Oxides of nitrogen) emissions as compared to single injection strategy [17].

The above-described studies provide insight into the role of multiple injection strategies in cold start, knock combustion, fuel economy and NOx emissions, but there appears to be very little information provided regarding the particle emissions reduction by multiple injection strategies at high load conditions. A numerical analysis by Bonandrini et al. [18] evaluated the advantages of multiple injections during intake stroke in terms of spray impingement and mixture preparation in a SIDI engine, but no particle emissions data was presented. The objective of this study is to experimentally explore the particle number reduction potential with multiple injection strategies and conduct a 3D CFD analysis to clarify the reasons for the observed improvements in particle number emissions in a boosted SIDI engine at high load condition.

EXPERIMENTAL SETUP

Engine

A 2.0 L SIDI gasoline engine configured with turbocharger was used in this investigation. The engine specifications are provided in [Table 1](#). The high-pressure injectors were located below the intake ports (side injection) with a fuel injection pressure up to 15 MPa. Downstream of the turbocharger, an intercooler controlled the intake-air temperature to $38 \pm 1^\circ\text{C}$ at the engine operating condition. The ETAS hardware along with INCA software were used to communicate with the engine controller, providing the flexibility required to fully optimize the engine performance at each operating condition.

Table 1. Engine specifications

Engine Type	L-4
Displacement	1.998 L
Bore/Stroke	86/86 mm
Connecting Rod Length	145.5
Compression Ratio	9.3
Fuel System	Direct Injection (side)
Fuel Injector	Bosch 6-hole HDEV5
Boosting System	Twin-scroll turbocharger

An AVL AC dynamometer system was used to maintain the desired engine speed. An inlet air conditioning system along with an intercooler conditioning system was used to maintain the inlet air temperature, humidity, and pressure at desired values. An AVL 733s fuel system and an AVL 753C fuel temperature control system were used to measure the fuel flow rate. The AVL PUMA control and data acquisition system interfaced with the facility and instrumentations on the engine tests bench were used to collect and process the data.

Emission Measurement

The Particle Measurement Programme (PMP), organized under the Working Party on Pollution and Energy (GRPE) of the United Nations Economic Commission for Europe (UN/ECE), proposed a particle number measurement protocol that has been adopted by current light duty vehicle emission regulations in Europe [19]. PMP recommended that particle number instrument should have counting efficiencies of 50% $\pm$ 12% and > 90% for particles with electrical mobility diameter of 23 ± 1 nm and 41 ± 1 nm, respectively. In this study, the particle number concentration was measured by Horiba MEXA-1000SPCS which was designed based on the PMP recommendation to determine particle number concentration [20]. As shown in Figure 1, engine exhaust was sampled directly from post-TWC (three-way catalyst), followed by a heated sampling line maintained at $191 \pm 7^\circ\text{C}$, a pre-dilution unit (PDU), a particle transfer tubing maintained at $47 \pm 5^\circ\text{C}$, a particle pre-classifier (PCF), and a volatile particle remover (VPR) upstream of a laser-based condensation particle counter (CPC). The PDU firstly diluted the sample with a dilution ratio of 10:1. Larger particles with diameter greater than $2.5 \mu\text{m}$ were removed by the particle pre-classifier. The VPR was designed to suppress particle nucleation within the sample and remove the soluble organic fraction (SOF) and sulfur component. The VPR comprises a particle number diluter (PND1), an evaporation tube (ET) and a second diluter (PND2) in series. The PND1 was operated at a (wall) temperature $150 \pm 10^\circ\text{C}$ and a dilution ratio of 50:1. The evaporation tube was operated with a wall temperature $350 \pm 10^\circ\text{C}$. The PND2 was operated at a (wall) temperature $25 \pm 1^\circ\text{C}$ and a dilution ratio of 15:1. After VPR, the sample was introduced into CPC

where butanol condensed onto particles in the sample flow, creating droplets large enough to be detected efficiently using a light-scattering technique. Data are collected at a sampling rate of 10 Hz for 60 s and subsequently averaged for results presented in this paper.

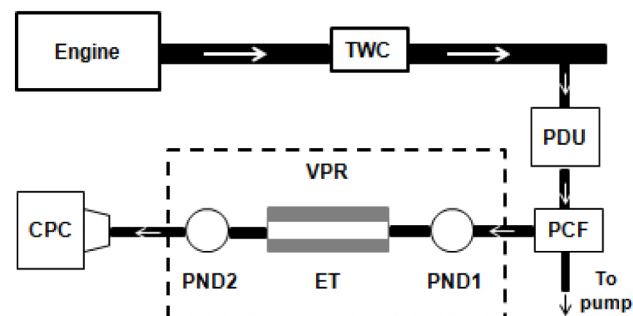


Figure 1. Schematic of particle number counting system.

Engine Operating Condition and Test Procedure

The evaluation of the effect of multiple injection strategies on particle number emissions was conducted at a fixed fuelling (approximately 11 bar BMEP), 1000 rpm, and lambda value of one. Fuelling was fixed while the throttle and turbocharger wastegate were adjusted to maintain lambda at unity. The total injected fuel mass for each strategy was unchanged. In the evaluation of each strategy, other parameters (i.e., spark timing, lambda, fuel pressure, etc) were kept constant at the baseline settings, as summarized in Table 2, to better isolate the effects from other parameters on particle emissions. Since fuel mass is kept constant during different injection strategy, BMEP varies slightly around 11 bar.

Table 2. Engine operating condition

Speed (rpm)	1000
BMEP (bar)	11(nominal)
Fuel Mass (kg/h)	4.8
Injection Pressure (MPa)	11
Spark Timing ($^\circ\text{BTDC}$)	7.5
Lambda	1
Intake Temperature ($^\circ\text{C}$)	38 ± 1
Engine Out Coolant Temp. ($^\circ\text{C}$)	90 ± 1
Oil Sump Temp. ($^\circ\text{C}$)	90 ± 1

CFD Analysis

The CFD analysis was carried out using the commercial software CONVERGE. The calculation domain included that combustion chamber, intake and exhaust ports, as shown in Figure 2. A moving-mesh method was used to trace the movements of valves and piston. The maximal size of the moving mesh was 2 mm.