

Fuel Pressure and Charge Motion Effects on GDi Engine Particulate Emissions

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ABSTRACT

The focus of this study is investigation of the influence of fuel system pressure, intake tumble charge motion and injector seat specification - namely the static flow and the plume pattern - on the GDi engine particulate emissions under the homogenous combustion operation.

The paper presents the spray characteristics and the single cylinder engine combustion data for the Delphi Multec® 14 GDi multi-hole fuel injector, capable of 40 [MPa] fuel system pressure. It provides results of a study of the influence of fuel pressure increase between 5 [MPa] to 40 [MPa], for three alternative seat designs, on the combustion characteristics, specifically the particulate and gaseous emissions and the fuel consumption. In conjunction with the fuel system pressure, the effect of enhanced charge motion on the combustion characteristics is investigated.

The combustion data shows a systematic effect of fuel pressure increase on reduction of the combustion particulate emissions due to improvement of mixture homogeneity and reduction of tip diffusion flame. The effect of enhanced intake charge motion is a further reduction of particulate emissions for fuel pressures in the range of 20 [MPa] to 40 [MPa]. Injector seat specification exerts an independent influence. The results illustrate a complex relation of the fuel system pressure, the injector specification and the charge motion with the combustion characteristics.

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INTRODUCTION

Figure 1 displays the progression of the GDi high pressure fuel system, since its market introduction in the mid-1990s. The first-generation systems supported stratified combustion and operated in the range of 10 [MPa] fuel system pressure. The broad introduction of turbocharging for GDi engines required extended injector flow ranges which could be accommodated by the variable fuel pressure [1]. The second driver for the fuel pressure increase was the requirement for better atomization and improved mixture formation, primarily brought about by introduction of the spray-stratified (second generation) combustion systems in 2006 [2].

Future legislations for the CO₂ / fuel consumption and emission reduction are spurring the development efforts of the GDi fuel injection system. The reduction of fuel consumption is a primary driver to improve the combustion efficiency. A more effective atomization obtainable with higher fuel system pressure has shown the potential for improvement of the combustion performance for GDi homogeneous systems [3, 4].

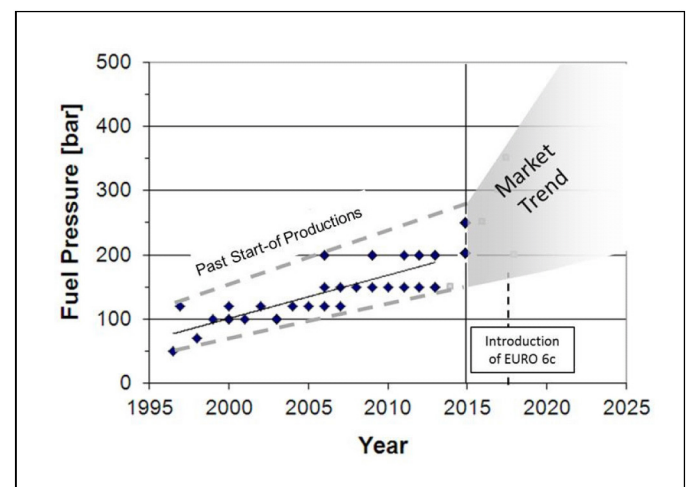


Figure 1. Fuel pressure evolution for GDi systems and future trend

The future emission legislation of Euro 6C [5, 6], becoming effective in Europe in 2017, is another major driver for a GDi fuel system pressure increase. Especially in the case of particulate emissions - mass as well as number - a higher fuel pressure is capable to reduce the engine emissions [7, 8].

The literature on the GDi engines that adopt the homogenous combustion strategy indicate that the primary sources of particulate emissions during the hot engine operation are mixture inhomogeneity and the phenomenon of “injector tip diffusion flame” shown in [Figure 2](#). Evidence suggests that the injector tip diffusion flame is associated with the sac residual fuel and tip wetting process [7], causing fuel absorption into the tip deposit layer in the course of fuel injection and its subsequent release and incomplete reaction (evidenced by the bright flame luminosity of a fuel-rich combustion) after the normal flame propagation during the engine power stroke.

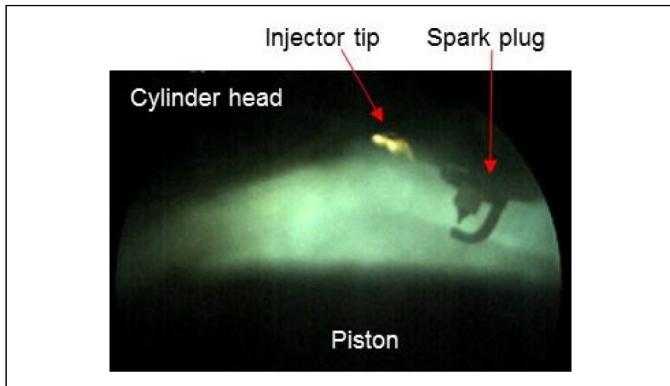


Figure 2. GDi injector tip diffusion flame (yellow) image

With regards to the GDi combustion characteristics, the role of charge motion requires clarification. In GDi engines, the intake port design and optimum tumble charge motion differ substantially between the “spray stratified” and “homogeneous” ($\lambda = 1$) combustion concepts. The engines that employ the “spray stratified” concept employ low charge motion in order to preserve the charge stratification and minimize the heat losses to the engine coolant. In contrast, the GDi engines that adopt the “homogenous” combustion strategy employ high tumble charge motion (often in conjunction with sophisticated valve phasing) to promote spray vaporization and charge homogeneity, in order to minimize formation of combustion emissions.

The present study extends a previous investigation of the influence of fuel pressure increase on the spray and combustion performance of GDi multihole fuel injection systems [9] through inclusion of the influence of tumble charge motion variation. In the previous study, single-cylinder engine (SCE) combustion tests were carried out for investigation of the effect of fuel pressure increase from 5 [MPa] to 40 [MPa] on the combustion characteristics, primarily the particulate and gaseous emissions and fuel consumption. The base GDi SCE in [9] was equipped with an intake system for low tumble charge motion generation, optimized for the “spray stratified” combustion strategy. In order to investigate the effect of high tumble charge motion, commonly employed in the current GDi “homogenous” combustion systems, the SCE intake port has been modified to produce two levels of induction tumble charge motion. The influence of large-scale charge motion is of particular interest with respect to its promotion of mixture homogeneity and, consequently, the reduction of the particulate emissions. This study enables a direct comparative

investigation of the influence of charge motion, in conjunction with the fuel system pressure, on the mixture preparation and engine combustion characteristics.

In the following sections, the influence of fuel injection increase between 5 [MPa] and 40 [MPa] on the spray characteristics -structure, penetration and atomization - are presented and the effects with respect to mixture preparation are discussed. The effect of fuel system pressure on the combustion characteristics is of primary interest: in this context, SCE combustion data for three GDi multi-hole injectors - with different combination of static flow and spray patterns - operating at different fuel pressures are presented. Simultaneously, the effect large-scale charge motion is studied: combustion data is provided for the base engine (the standard intake port) and two enhanced intake charge tumble levels representative of to the “homogenous” combustion systems. The focus of the study is on hot engine particulate emissions. The cold engine start-up phase is not addressed, since the engine crank time is not sufficient to buildup high fuel system pressures. (It is expected that a fuel system pressure of 6 MPa is achieved with the current engine start-up calibration practice.)

In addition to the combustion data, the effect of fuel pressure increase on the injector tip diffusion flame is investigated and its correlation with the engine-out particulate emissions is illustrated. Finally, a summary of the main findings of this study is provided.

FUEL INJECTION SYSTEM

High Pressure Fuel Injector

The fuel injector is a key component of the GDi fuel injection system. It must possess excellent dynamic and hydraulic performance for precise fuel metering and outstanding spray atomization characteristics in order to improve the fuel economy and reduce pollutant emissions of the future gasoline engines. [Figure 3](#) presents the Delphi Multec14 GDi multi-hole injector with 40 [MPa] fuel system pressure capability.



Figure 3. Delphi Multec14® GDi inward-opening multi-hole injector 40 [MPa] fuel system pressure capable

Delphi Multec14 employs an electro-magnetic coil-actuation compatible with the current GDI current-controlled drive schemes. The design features and performance targets of the Delphi Multec14 injector have been described in the literature [9]. Therefore, here only the influences of fuel system pressure on the spray characteristics, which are of particular importance with respect to the mixture preparation process, are discussed.

Spray Structure and Penetration

Figure 4 displays the effect of fuel pressure on the spray structure with the aid of Mie images of spray at the end of fueling (i.e. visible end of injection) for four fuel system pressures of 5, 10, 20 and 40 [MPa]. The injected quantity is 11 [mg/pulse] and pulse duration is adjusted to deliver the same quantity for all fuel pressure conditions.

The imaging data shows marginal effect of fuel system pressure on the spray penetration at the end of injection of an identical quantity. However, there is substantial increase of the plume spread angle, underscoring the enhancement of the spray air entrainment with the fuel pressure increase. This - in conjunction with improvement of spray atomization - is of notable importance with respect to the spray evaporation and mixing characteristics.

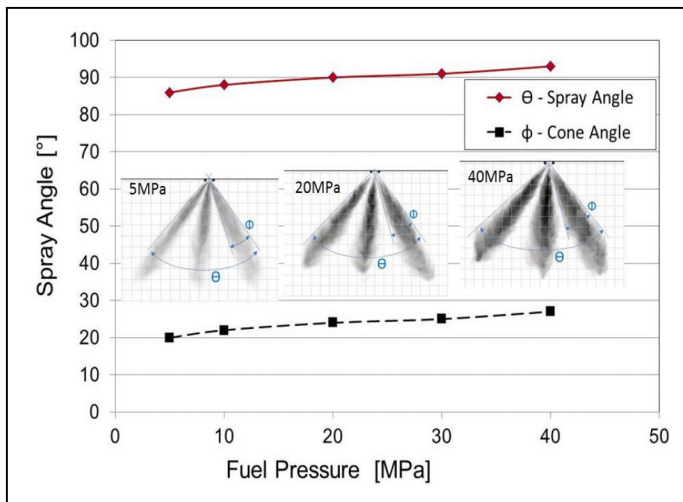


Figure 4. Effect of fuel pressure on the spray and plume cone angles (t = visible end of injection, injected quantity = 11 mg/pulse)

Spray Atomization

Figure 5 shows the effect of fuel system pressure on the spray atomization quality, as illustrated by the time-averaged spray droplet-size histograms for fuel pressures of 5 - 40 [MPa]. In accordance with the SAE J2715 standard [12] guidelines, the laser diffraction measurement is performed at 50 [mm] downstream of the nozzle exit with the n-Heptane fuel. The injection pulse-width is adjusted in order to maintain the same injected quantity (of 7 mg/pulse) for all fuel pressures. This injected quantity is established in accordance with the laser light transmission criterion (avoiding severe laser light obscuration by the spray).

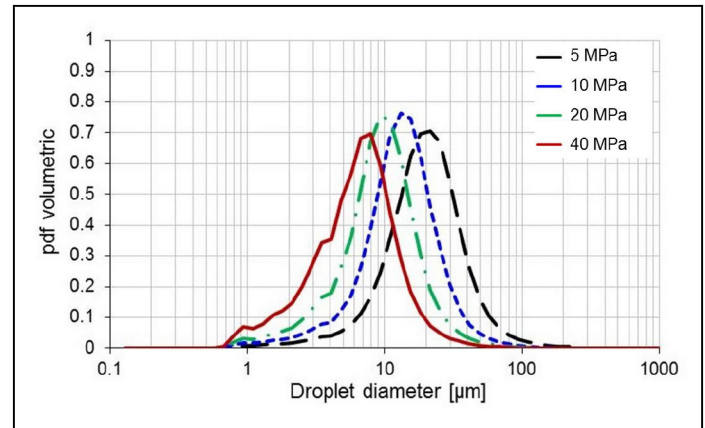


Figure 5. Effect of fuel pressure on the spray droplet-size distribution

Figure 5 shows the marked effect of fuel pressure on the spray atomization, illustrated by the shift of the peak of the probability distribution curve from particle diameter of 20μm to 8μm with the increase of the fuel system pressure from 5MPa to 40MPa.

SINGLE-CYLINDER ENGINE COMBUSTION STUDY

Single-cylinder engine combustion tests were performed in order to assess the effect of fuel pressure system on the combustion characteristics, especially the particulate emissions (both PM and PN) and the injector tip diffusion flame. In this framework, the influence of the injector static flow and spray pattern were investigated through combustion tests of injectors with similar static flow and different plume patterns (labelled as 6H-LF and 5H-LF for low-flow 6 and 5 plume patterns, respectively) and injectors with identical plume pattern and different static flows (labelled as 6H-LF and 6H-HF for 6 plume pattern, low-flow and high-flow, respectively).

The “homogeneous” combustion strategy is adopted for SCE tests. This is the current prevalent GDI combustion strategy that entails fuel injection during the induction process, in order to achieve a “homogeneous” mixture at the time of spark ignition. It is recognized that perfect homogeneity is not achieved due to the time scales of fuel injection, atomization, vaporization and mixing processes. The mixture inhomogeneity is one contributor to the gasoline engine emissions under hot engine operation. Therefore, the effectiveness of tumble charge motion for promotion of mixture homogeneity and reduction of particulate emissions is studied through suitable modifications of the intake port geometry to generate three levels of the intake charge tumble intensity.

Measurement Setup and Equipment

The combustion test-bed is equipped with a single-cylinder GDI engine, whose layout and dimensions are provided in Table 1.