

Fuel System Pressure Increase for Enhanced Performance of GDi Multi-Hole Injection Systems

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ABSTRACT

The progressive trend towards the GDi engine downsizing, the focus on better fuel efficiency and performance, and the regulatory requirements with respect to the combustion emissions have brought the focus of attention on strategies for improvement of in-cylinder mixture preparation and identification and elimination of the sources of combustion emissions, in particular the in-cylinder particulate formation.

This paper discusses the fuel system components, injector dynamics, spray characteristics and the single cylinder engine combustion investigation of a 40 [MPa] capable conventional GDi inwardly-opening multi-hole fuel injection system. It provides results of a study of the influence of fuel system pressure increase between 5 [MPa] to 40 [MPa], in conjunction with the injector static flow and spray pattern, on the combustion characteristics, specifically the particulate and gaseous emissions and the fuel economy.

The combustion data shows the marked effect of fuel pressure increase on reduction of the combustion emissions and improvement of fuel consumption. It also illustrates an influence of the injector specifications that is evident at all system pressures.

The data highlights the complex relation of the fuel system pressure, the injector specifications and the combustion characteristics, which must be taken into consideration for GDi homogeneous combustion system optimization.

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INTRODUCTION

Gasoline engines with direct fuel introduction are well established as automotive power source with the overall scope of improved fuel economy and increased specific performance. After the mid-1990s when the first gasoline direct injection engines (GDi) was introduced to the market, the engine operation was focused on stratified part load combustion to gain higher efficiency mainly by reducing the pumping losses, a preferable lean charge composition and a higher compression ratio. The expensive and sophisticated aftertreatment and the required fuel quality limits the global usage of stratified operation. Today the dominating efficiency improvement approach is shifting the load regime of the engine towards higher values. In order to keep or even improve the vehicle dynamics turbo-charging is a widely introduced and accepted technology in the meantime also for gasoline engines. The temporal flexibility of the fuel injection enables very effective scavenging operation at low engine rpm's minimizing the turbo lag compared to conventional port fuel injection (PFI) turbocharged engines and consequently makes longer gear ratios acceptable (downspeeding). The significant

higher power density by turbo-charging enables in addition a reduction of the engine displacement (downsizing) which allows the operation in a more efficient engine load range.

Figure 1 displays the progression of the GDi high pressure fuel system, since its market introduction in the mid-Nineties. These systems supported stratified combustion and operated in the range of 10 [MPa] fuel system pressure. The broader introduction of turbocharging for GDi engines require extended flow ranges which can be accommodated by the variable fuel pressure [1]. The second driver for the higher fuel pressure is the requirement for better atomization and improved mixture formation, primarily effected by introduction of the spray-stratified (second generation) combustion systems in 2006 [2].

Future legislation for the CO₂ / fuel consumption and emission reduction are spurring significant development efforts of the GDi 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]. 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 particulate emissions - mass as well as number - a higher fuel pressure is capable to sustainably reduce the engine emissions [7, 8].

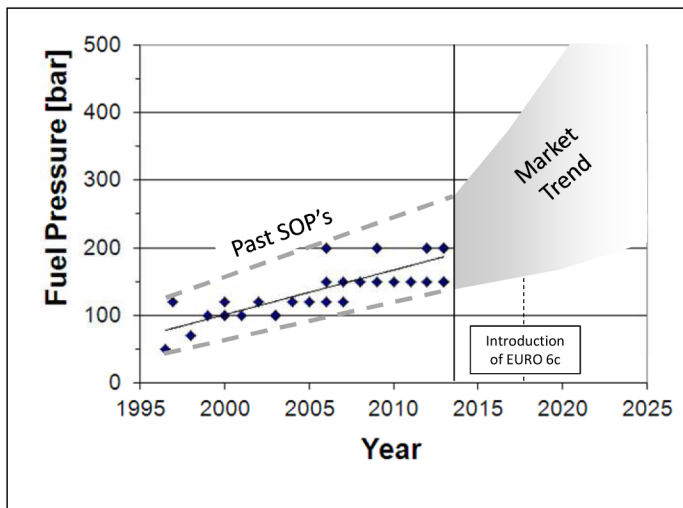


Figure 1. Pressure Evolution for GDI Systems and Future Trend

In the following chapters, the requirements and implications of a system pressure increase to 40 [MPa] for the GDI conventional multi-hole fuel system components are discussed. Then, the influence of fuel injection increase between 5 [MPa] and 40 [MPa] on the injector hydraulic performance and the spray structure, penetration and atomization are illustrated with the aid of experimental data. The effect of fuel system pressure on the combustion characteristics is of primary interest: in this context the single-cylinder engine combustion data for three GDI multi-hole injectors - with different spray patterns and static flows - operating at different fuel pressures are presented and discussed. Finally, a summary of the main findings of this study is provided.

FUEL SYSTEM ASPECTS

One reason for introduction of GDI systems is to improve the fuel economy of gasoline powered vehicles. Therefore it is necessary to carefully assess all required measures, with respect to the fuel system, and implications for total engine outputs in order to meet this overall objective. A fuel system pressure increase can be expected to elevate the parasitic losses and, on this ground alone, will be counterproductive for engine CO₂ reduction. A comprehensive review and optimization of the entire fuel system - from the fuel tank to the injector - needs to be performed. This must include all pertinent aspect of a fuel system pressure increase, for instance the structural, hydraulic as well as the system component interactions, in order to guarantee a safe and efficient operation in engine applications.

Fig. 2 shows schematically the entire GDI fuel system, from the fuel tank through to the injector.

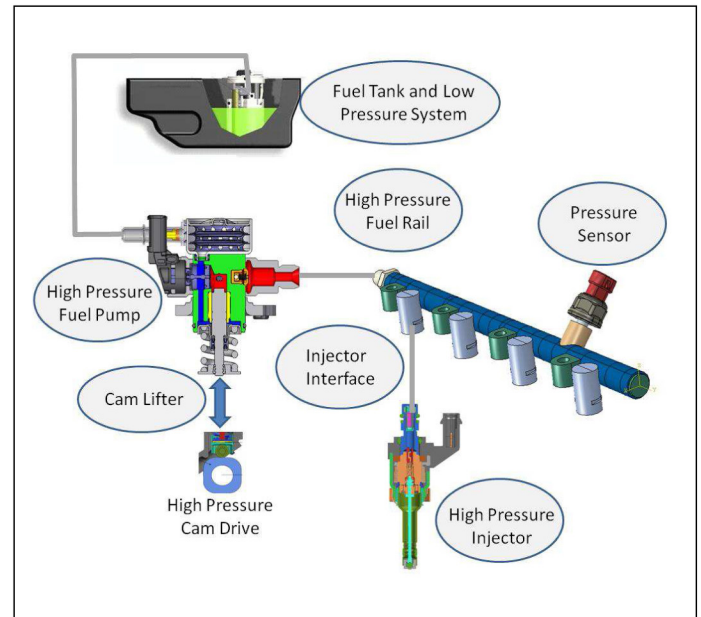


Figure 2. GDI Fuel System and Components

The fuel is delivered from the fuel tank by the fuel pump to the inlet the GDI high pressure pump. The fuel enters the high pressure pump through the damper body, passes the inlet metering valve, and is then pressurized by the plunger and exits via the outlet check valve into the high pressure side of the fuel system. A fuel pipe connects the pump outlet fitting with the high pressure (common) rail which distributes the fuel to the individual injectors. The fuel pressure sensor is also typically mounted on the fuel rail to enable an accurate measurement and control. In the following chapters the implications of a fuel system increase from the current 20 [MPa] to 40 [MPa] are reviewed.

Low Pressure System

Today's high pressure pumps with an "on demand" fuel delivery generate pressure pulsations that are reflected into the low pressure fuel supply system. The amplitude and frequency of these pressure waves are determined by the pump swept volume and the maximum cam-shaft rotational speed. As long as this key fuel pump characteristic is not altered, no high pressure system excitation is expected and no specific measures need to be considered for the fuel system pressure increase.

High Pressure Pump

The high fuel pressure is produced by the high pressure pump. Consequently, an increase of the fuel system pressure requires sufficient structural integrity of the high pressure pump. The components of the pump that are responsible for the fuel pressurization - or in the high pressure circuit - need special

attention. In particular, interfaces on the high pressure side that are normally welded must be rigorously design optimized in order to withstand a significant higher fatigue stress levels.

The pumping force is determined by the plunger diameter and the pressure in the pumping chamber. By simply increasing the fuel pressure a nearly linear increase of the pumping force is observed. This higher force needs to be provided by the cam shaft via the cam lift and the cam lifter. In Fig. 3 the simulated pump cam load as function of fuel pressure and plunger diameter is shown for a given specific cam lift profile. It is very obvious that the force is a strong function of the plunger diameter. Depending on the camshaft drive situation, a fuel pressure increase may result in a reduced plunger diameter in order to limit the contact stress between cam and cam lifter and the maxima in the pump driving torque.

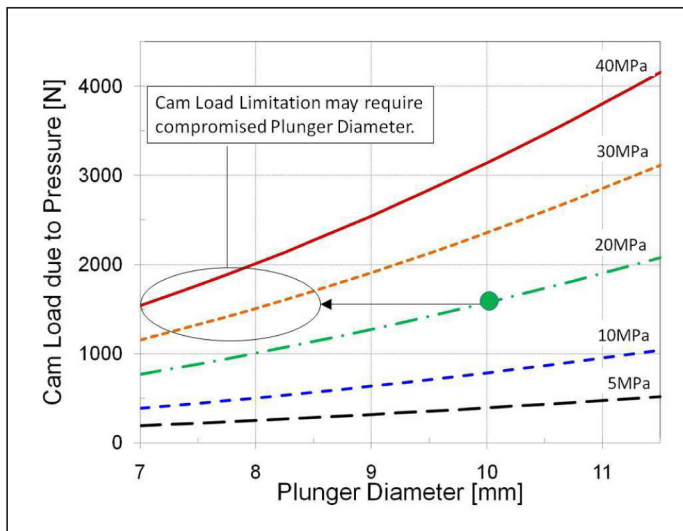


Figure 3. Simulated Pump Cam Load as Function of Fuel Pressure and Plunger Diameter

In order to compensate for the smaller plunger diameter, the cam lift needs to be increased which is to a certain degree possible. The integrated pressure relief valve (PRV) will be adjusted accordingly to provide overpressure protection of the high pressure fuel system.

The additional energy required to provide the fuel mass at a higher pressure as well as the higher friction and bypass losses needs to be considered in the overall efficiency assessment of the combustion engine. A detailed analysis of the fuel pressure impact on high pressure fuel pump efficiency is provided in Reference [9].

High Pressure Fuel Rail

The fuel pipe and the fuel rail are typically connected by metal to metal interfaces which can be carried over for the discussed fuel pressure increase. Also the base architecture of the fuel rail with its typically brazed components like fittings, end plugs or sockets is generally able to withstand the higher stresses. However a careful re-evaluation by finite element analysis

(FEA) needs to be performed to assess the fatigue and overstress situation and provide appropriate guidelines for design improvements.

The fuel pressure sensor requires an extended measurement capability as well as structural strength beyond the fuel system burst limit. Today's 200 [bar] sensor technology can be upgraded to the higher pressure requirements and no new technology needs to be implemented.

The typical connection system between injector and fuel rail consists of a chemically resistive and low temperature capable O-ring in combination with a backup ring. Careful redesign of this critical interface by optimizing the rail socket diameter, the gap between injector upper housing and refining the tolerances is required to withstand a potential extrusion of the backup ring. The O-ring size and material as well as the backup ring dimensions and material are adapted to provide a leak-free function over the engine life. Overpressure tests and extended pressure cycling tests confirm the feasibility of this interface concept and sealing package. The requirement for an expensive screwed interface with an intermediate fuel pipe between the rail and injector, as typically applied in Diesel injection systems, is not deemed necessary for the fuel system pressures up to 40 [MPa].

High Pressure Injector

In general, the injector features that have proven successful for diesel engines can be expected to be pursued for meeting the market and regulatory demands for improvement of the GDI engine fuel economy and emissions. In this context, the fuel injector will be a key component and features such as advanced nozzle design and manufacturing process, high fuel system pressure, controlled fuel injection rate, multiple injections in conjunction with precise minimum injected quantities, will be pursued to improve the fuel economy and reduce pollutant emissions of the future gasoline engines. This renders the injector technology a primary enabler for advancing the GDI engine combustion characteristics.

The focus of the present study is the increase of fuel system pressure of the conventional GDI multi-hole injector from the current 20 [MPa] to 40 [MPa]. Figure 4 displays the Delphi Multec14® GDI multi-hole injector capable of 40 [MPa] fuel system pressure. The increase of fuel system pressure leads to increased product and process specifications in several areas.

The immediate consequence of the higher system pressure is increase of structural stress on the injector pressure vessel. While sufficiently high burst pressure levels can be achieved, meeting lifetime pressure cycling durability is challenging. In particular the structural welds of the injector pressure vessel require careful design and process optimization, as well as a reassessment of material selection. The product validation requires extensive pressure cycling testing and a focus on parts at the limit of specification in terms of