

Keys to Understanding Spray-guided Combustion of a Narrow-spacing Gasoline Direct Injection SI Engine with a Centrally Mounted Multi-hole Injector

Shigeo Yamamoto, Dai Tanaka and Kimihiko Sato
Mitsubishi Motors Corp.

Minoru Yokoe
Mitsubishi Automotive Engineering Corp.

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ABSTRACT

Spray-guided gasoline direct injection SI engines attract as one of new generation lean-burn engines to promise CO₂ reduction. These typically adopt "narrow-spacing" concept in which an injector is centrally mounted close to a spark plug. Therefore, geometric targets of the fuel spray and a position of the spark plug have to be exactly limited to maintain a proper mixture in the spark gap. In addition, the stable combustion window is narrow because the spark ignition is limited in a short time during and immediately after the injection. These spatial and temporal restrictions involve some intractable problems concerning the combustion robustness due to the complicate phenomena around the spark plug. The local mixture preparation near the spark plug significantly depends on the spray-induced charge motion. The intense flow induced by the motion blows out and stretches the spark, thereby affecting the spark discharge performance. Moreover, the fuel interaction with the spark plug affects not only the spark discharge performance but also the mixture preparation. These phenomena significantly make impacts on the combustion and cause misfires in the worst case because there is a possibility of changing the stable combustion window. This paper describes a study of the spray-guided combustion using a narrow-spacing gasoline direct injection SI engine with a multi-hole injector. A goal of this study is to understand the factors affecting the local mixture preparation at the spark gap and the spark discharge performance. Additionally, the effects of the phenomena on the combustion robustness were investigated.

INTRODUCTION

To prevent global warming and air pollution, efforts to improve the thermal efficiency and reduce the emissions of internal combustion engines are being continued around the world. From this point of view, clean diesel engines and hybrid electric vehicles are anticipated as promising technologies. However, evolution of gasoline spark ignition engines, which can be recognized as the simplest and most cost-effective automotive power units, has also been desired to contribute to a sustainable society for decades, considering supply and demand balance of energy sources, rise in metal prices and accelerating motorization in populous countries. The gasoline SI engines offer an advantage to reduce the emissions thanks to three-way catalyst technologies. However, the thermal efficiency is quite lower than that of the diesel engines because it involves the pumping loss under partial loads due to flammability limits of gasoline / air mixture and it is refused to increase the compression ratio due to knocking. Moreover, the strong dependency on a three-way catalyst to reduce the emissions requires to maintain the mixture to stoichiometry, which spoils the thermal efficiency due to a decrease in the specific heat ratio and an increase in the heat loss.

To solve these issues, direct injection technologies for the gasoline SI engines have been the focus of the world's attention [1]. These technologies allow to increase the volumetric efficiency and prevent the knocking because the latent heat of fuel injected in the cylinder reduces the gas temperature, thereby enabling

an increase in the compression ratio. The freedom of mixing enables to drastically reduce the HC emissions during cold-start conditions utilizing the combustion control for a rapid catalyst warm-up [2]. In addition, these technologies allow to use the stratified charge lean-burn which improves the thermal efficiency under partial loads due to not only a decrease in both the pumping and heat loss but also an increase in the specific heat ratio. When the stratified mixture is prepared by a late injection of the compression stroke, the local rich mixture concentrated near the spark plug ensures the stable flame propagation during the lean-burn operation. The high EGR tolerance enables to reduce the NO_x emissions due to a temperature reduction in the cylinder. However, a lean-burn engine for passenger car generally requires an aftertreatment for NO_x and sulfur-free gasoline. Although it makes the best use of the gasoline direct injection technologies concerning CO₂ reduction, this issue has hindered the widespread acceptance.

Spray-guided combustion attracts as one of new generation lean-burn technologies. It enables to improve the thermal efficiency due mainly to the less wall-wetting fuel compared with the existing lean-burn systems in production. The mixture preparation strongly depends on the fuel spray dynamics. The local mixture near the spark plug is prepared by the charge motion induced by the movement of spray itself without utilizing the piston movement or the intense tumble / swirl charge motion. It typically adopts "narrow-spacing" concept in which the injector is mounted close to the spark plug on a central part of the cylinder head. Therefore, geometric targets of the fuel spray and a position of the spark plug have to be exactly limited to maintain a proper mixture in the spark gap. In addition, the spark ignition is limited in a narrow range during and immediately after the injection for the stable combustion. The short time interval from the injection to the spark ignition and the short distance from the injector tip location to the spark plug position remains a large number of liquid droplets during the combustion due to a lack of the fuel evaporation time. The droplets might result in carbon fouling of the spark plug. These spatial and temporal restrictions lead to some intractable problems concerning the combustion robustness. The fragile robustness might result in misfires in the worst case because there is a possibility of changing the stable combustion window due to a production tolerance and a time degradation of the engine components.

The spray-guided combustion requires a fuel spray with fine atomization utilizing the high-pressure fuel injection. Moreover, the spray crowd has to be always maintained on a position near the spark plug independent of the cylinder pressure to supply enough amount of the fuel vapor in the spark gap. These characteristics can be successfully realized by either an outward-opening injector or a multi-hole injector [3, 4]. The former is directly actuated by a piezo actuator [5, 6]. It forms an axisymmetrical hollow cone spray near a right angle and

generates the fuel vapor cloud on the outer edge of the spray, which is suitable for the mixture preparation of the narrow-spacing concept. In addition, it has a high response, a high dynamic flow range and a high-precision minimal injection due to the variable needle stroke thanks to the piezo actuation. Although it has been already in production for luxury cars, the high-cost prohibits the progress for popular cars. The latter can utilize diesel nozzle technologies. It is cost-efficient due to a direct actuation employing a solenoid and allows to flexibly adjust the spray arrangement with demands of the combustion chamber design. There are many studies applying the injector to the spray-guided combustion [7, 8, 9].

It should be noted that a few studies reported some findings relating to the fuel interaction with a spark plug employing a spray-guided engine based on the narrow-spacing concept in which a multi-hole injector is centrally mounted close to the spark plug with a single ground electrode [10, 11, 12]. They observed the spark discharge behavior experimentally. The spray-induced charge motion leads to the intense flow with high velocity near the spark gap. The flow results in the dramatic spark stretching and frequent restriking, which shortens the spark discharge duration. An increase in the spark discharge duration is favorable for the stable ignition. The fuel interaction with the ground electrode occurs the fuel wetting. Differences in the electrode's orientation affect the interaction and the spark ignition stability.

In this study, the spray-guided combustion was investigated using a gasoline direct injection SI engine based on the narrow-spacing concept in which a multi-hole injector is centrally mounted close to a spark plug. A goal of this study is to understand the factors affecting the local mixture preparation at the spark gap and the spark discharge. Keys to solve the puzzles are to pursue the effects of not only the fuel interaction but also the spray-induced charge motion on the complicate phenomena near the spark plug. Additionally, The effects of the phenomena on the combustion robustness were investigated by means of combination of spark discharge measurements and a free spray CFD simulation in a constant-volume vessel with a detailed geometry of the spark plug.

ENGINE AND OPERATING CONDITIONS

A prototype gasoline direct injection engine based on the Mitsubishi 4B11 IL-4 DOHC 4-valve 2.0 L PFI natural aspirated production engine was used in this study. The engine specifications and operating conditions are shown in **Table 1**. The combustion chamber of the cylinder head and the intake port are basically the same as the production engine. The in-cylinder charge motion induced by the intake air is relatively weak. The compression ratio is higher than that of the production engine for Japan's regular gasoline (RON 91). A multi-hole injector with a 6-hole nozzle

Table 1 Engine specifications and operating conditions

Bore / stroke	86 / 86 mm
Number of cylinders	4
Displacement	1997 cc
Compression ratio	10.5
Gasoline	Japan's Regular (RON 91)
Coolant temp.	85 °C
Engine speed	1500 rpm
Fuel injection quantity	9 mm ³ / stroke
Air-fuel ratio	40 with EGR
Fuel rail pressure	20 MPa

spark plug on a central part of the cylinder head based on the narrow-spacing concept as shown in **Figure 1**. The neighboring two sprays from the injector are arranged in straddling sprays which pass through both sides close to the spark gap on the bottom view. The spark plug with a single ground electrode is used in this study. If not otherwise specified, a 1.0 mm spark gap and a 100 mJ inductive ignition coil are used and the ground electrode was set in an orientation where the spark gap faces to the injector. The orientation involves the least fuel impingement as described later. The fuel spray characteristics, a position of the spark plug, a shallow-dish piston cavity were optimized for the spray-guided lean-burn. This engine system enabled to use the spray-guided combustion mode at a wide speed and load range. However, the orientation of the spark plug had to be fixed to demonstrate the performance for a reason as described later. Using this engine, all experiments in this paper took place under a specified light load at 1500 rpm engine speed with a hot coolant conditions as shown in **Table 1**. The spray-guided air-fuel ratio was 40 with an EGR ratio and the fuel rail pressure was 20 MPa.

Table 2 Conditions of free spray CFD simulation in a constant-volume vessel with detailed geometry of a spark plug

CFD code	STAR-CD
Number of cells	140,000 cell
Size of vessel	φ100 X 69 mm
Time step	10 μs
Turbulence model	Standard k-ε
Spray model	DDM
Primary atomization model	Reitz's WAVE
Secondary atomization model	Enhanced TAB
Wall impingement model	Naber & Reitz
Fuel	n-heptane
Fuel injection quantity	9 mm ³ / stroke
Fuel injection pressure	20 MPa
Pressure in vessel	1.3 MPa
Temperature in vessel	700 K

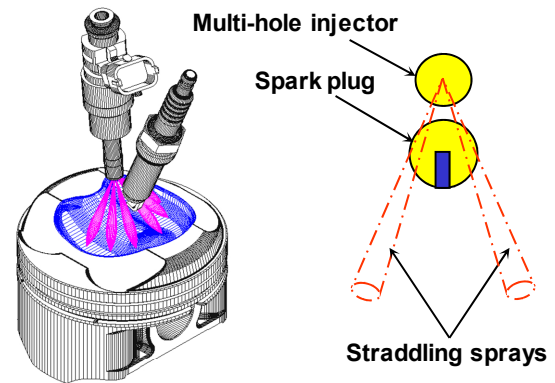


Fig. 1 Geometric relationship between fuel spray of multi-hole injector and spark plug

MEASUREMENTS AND CFD SIMULATION

Measurements - In addition to the standard measurements such as torque, engine speed, cylinder pressure, fuel consumption, airflow rate, temperature and pressure of each part, the spark discharge voltage and current were simultaneously recorded with 1 microsecond resolution. The voltage and current waveforms of one cycle look-alike for the average of 50 cycles (4 megawords record length) were selected to investigate various spark discharge phenomena of the spray-guided combustion.

3-D CFD simulation - In the case of the spray-guided combustion, it is likely that not only the fuel interaction with the spark plug but also the spray-induced charge motion significantly affect both the local mixture preparation at the spark gap and the spark discharge performance. Therefore, it is important to understand the complicate phenomena near the spark plug in detail. A conventional in-cylinder flow simulation using a 3-D CFD code with dynamic moving mesh helps to understand these phenomena. However, it is difficult to apply an engine model including a detailed geometry of the spark plug because it requires a large number of cells and the

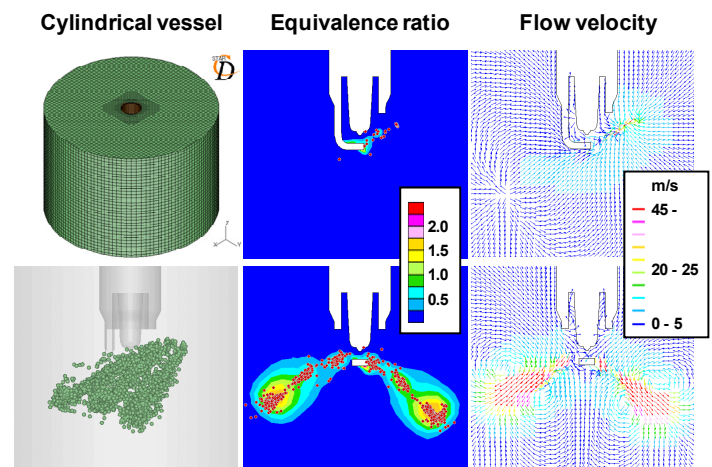


Fig. 2 Free spray CFD simulation in a constant-volume vessel with detailed geometry of spark plug

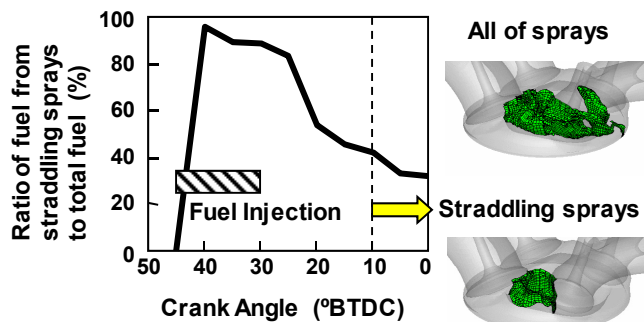


Fig. 3 Ratio of fuel from straddling sprays to total fuel at a position of spark gap using CFD simulation

meshing process takes a long time. To solve this problem, a free spray CFD simulation in a constant-volume vessel with a detailed geometry of the spark plug was applied using the STAR-CD code based on an assumption that the flow near the spark plug primarily depends on the fuel spray dynamics. The calculation conditions are summarized in **Table 2**. The detailed geometry of the spark plug was accurately duplicated as shown in **Figure 2**. The spark plug was equipped on a top center of the cylindrical vessel with 140,000 cells. The fuel spray from a 6-hole nozzle was injected in the vessel. The relative arrangement between the sprays and the spark plug was the same as the engine. To simulate the real fuel spray, several modeling techniques, standard $k-\varepsilon$ for turbulent flow, DDM (discrete droplet model) for spray dynamics [13], Reitz's WAVE for primary atomization [14], Enhanced TAB (Taylor Analogy Break-up) for secondary atomization [15] and Naber & Reitz for wall impingement [16] were applied here. The nozzle hole diameter, flow rate and spray arrangement were given and the droplet size and spray tip penetration were calibrated based on the actual measurements. The pressure and temperature in the vessel were given as a constant value which was equal to the in-cylinder condition at a spark timing. n-heptane was used as the fuel, which evaporates slower than the lighter components and faster than the heavier components of gasoline. It should be noticed that these differences affect the mixture preparation during the injection [17], although an equivalence ratio is represented here as a mass ratio of the fuel vapor to the air in the mixture. This method is not quantitatively accurate. However, it is anticipated that the simple and cost-effective method is useful for a qualitative and comparative evaluation. In this research, not only this method but also a conventional method with dynamic moving mesh was used in accordance with the intended use.

FACTORS AFFECTING MIXTURE PREPARATION AND SPARK DISCHARGE

It is important to find some factors affecting the local mixture preparation at a spark gap and the spark discharge behavior of the spray-guided combustion. The

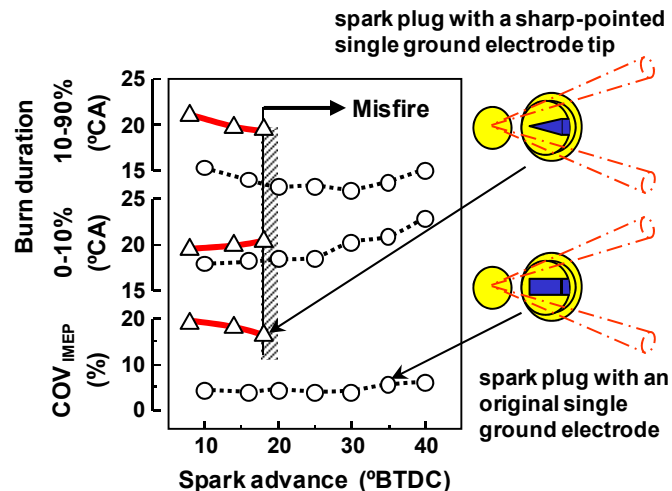


Fig. 4 Effect of impinging fuel on spray-guided combustion using a spark plug modified ground electrode to sharp-pointed tip

factors were investigated by analyzing complicate phenomena around the spark plug.

Origin of spray-guided fuel - In Each fuel injected from the multi-hole injector with the straddling sprays were chased using the CFD simulation with the dynamic moving mesh as shown in **Figure 3**. When the spray-guided combustion takes place at a spark timing during or immediately after the injection, the fuel at a position of the spark gap mostly comes from the straddling sprays. The other fuel increases together with the piston moving closer to TDC (top dead center) as time advances after the injection. It is mostly the wall-guided fuel which is transported toward the spark plug after impinging on the piston cavity. As the fuel supply quantity increases with an rise in the engine load, this engine can utilize the wall-guided-like combustion with the injection earlier than the spark timing.

Role of plug-guided fuel - One of purposes to apply the straddling sprays is to avoid the fuel wetting on the spark plug due to the fuel impingement. The Effects of the fuel

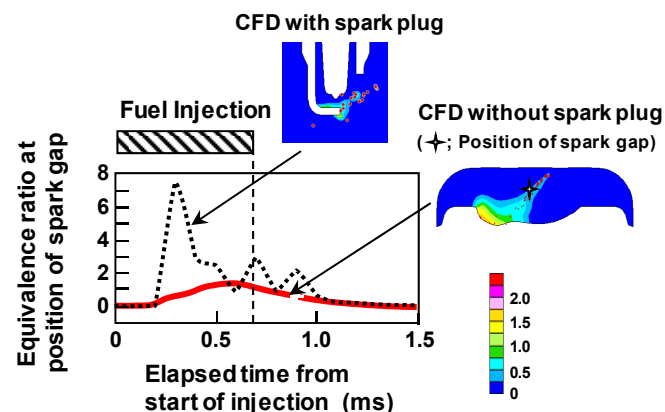


Fig. 5 Temporal change of local equivalence ratio at a position of spark gap using CFD with and without spark plug model