

A Study of Gasoline Lift-off Combustion in a Spark Ignition Engine

Daisuke Tanaka, Koji Hiraya and Hirofumi Tsuchida
Nissan Motor Co.Ltd.

Hidetoshi Wakasa, Yutaka Murata, Jin Kusaka and Yasuhiro Daisho
Waseda University

Copyright © 2008 SAE International

ABSTRACT

The aim of this study is to demonstrate the concept of gasoline lift-off spray combustion in which the burning velocity is controlled by the rate of mixture supply to the flame zone. With this concept, gasoline fuel is injected under high pressure to promote atomization, evaporation and mixing with the air, thereby quickly forming a homogenous mixture extending to the flame downstream of the spray. As a result, the injected fuel is burned sequentially. In this study, a constant-volume combustion vessel was used to visualize and analyze spray combustion. The experimental results made clear the effects of the initial conditions (e.g., injection pressure and nozzle hole diameter) and the ambient conditions (e.g., temperature and pressure) on the flame lift-off length and soot formation. In addition, the conditions facilitating this combustion concept were examined by conducting combustion simulations with the KIVA-3V code, taking into account the detailed chemical reaction mechanisms. Both the experimental and simulation results showed that the nozzle hole diameter and injection pressure are important factors for enhancing mixture formation rate in the spray and avoiding an over-rich mixture in gasoline lift-off combustion. Based on these findings, experiments were then carried out using a single-cylinder experimental engine. The results obtained under a limited condition of a single-hole nozzle spray confirmed that the combustion period can be controlled by means of the injection duration. It was also confirmed that sootless spray combustion was accomplished with little emission of unburned hydrocarbons.

INTRODUCTION

To improve thermal efficiency through lean combustion, various concepts have been proposed for forming a stratified mixture in spark ignition (SI) internal combustion engines [1-5]. In this connection, vigorous research efforts are being made to find effective ways of expanding the

stable combustion region and improving engine performance. However, with most of these stratified mixture concepts, the engine operating load is adjusted by the size of the stratified mixture, which means that the engine operating point for obtaining the best fuel economy is determined by the piston bowl size or by the fuel injector specifications. In engine operating regions that deviate from the optimum operating point, hydrocarbon (HC) or nitrogen oxide (NOx) emissions may increase markedly owing to excessive diffusion of the mixture or drop in the limit of EGR rate, respectively. For that reason, an exhaust gas aftertreatment system is an indispensable technology at the present time. In order to meet more stringent exhaust emission regulations in the coming years, it will be increasingly more important to reduce the formation of emissions in the combustion process as much as possible.

Research has been under way for more than 20 years on premixed compression ignition (PCI) combustion aimed at reducing NOx and particulate matter (PM) emissions from diesel engines simultaneously [6,7]. However, this approach still has several unresolved issues, including the difficulty of applying this combustion process to the high load region and the increase in HC and carbon monoxide (CO) emissions. As a combustion concept for resolving the principal issues in PCI combustion, Sibers and Higgins have proposed an approach that might be called "diesel lift-off combustion" [8-10]. The flame lift-off length in spray combustion is defined as the distance from the nozzle tip to the flame zone. The load can easily be controlled by the injection duration because the mixture is the rate-limiting factor in spray combustion. Sootless spray combustion is accomplished by completing atomization and evaporation of the mixture through enhancement of the air entrainment within the lift-off length. The reduction of the ambient temperature also substantially reduces NOx formation. Because the boundaries of the mixture are relatively distinct in a diesel fuel spray [11], it is estimated that diesel lift-off combustion can be accomplished with minimal unburned hydrocarbons.

Based the foregoing studies, we reasoned that if the advantages mentioned above could be incorporated into a

gasoline direct-injection engine, fuel economy could be further improved. Compared with conventional flame-propagated combustion of a premixed mixture, it is posited that burning the mixture sequentially and instantly can reduce the area of contact of hot combustion gas on the cylinder wall, thereby reducing cooling losses. Furthermore, as suggested in earlier studies of gasoline spray combustion[12,13], because an unburned mixture does not form in the end gas zone, it should be possible to achieve knock-free combustion even at higher compression ratios that leads to improvement of thermal efficiency [14].

This paper presents the results of a study concerning the feasibility of gasoline lift-off combustion with spark ignition, based on the hypothesis that this is the ideal form of stratified combustion and that it may achieve knock-free operation. First, the conditions facilitating such combustion in a quasi-quietest field were investigated by conducting fundamental experiments with a constant-volume combustion vessel and combustion simulations using the KIVA-3V code and taking into account the detailed chemical reaction mechanisms. Then, a single-cylinder engine was used to conduct performance and visualization experiments to study the feasibility of this combustion concept under non-steady-state conditions.

FUNDAMENTAL STUDY OF GASOLINE LIFT-OFF COMBUSTION

EXPERIMENTAL SETUP

Figure 1 shows a schematic diagram of the experimental setup used to visualize the fuel spray. The method used here was to form a high-temperature and high-pressure field by spark igniting a lean premixed mixture of ethylene, oxygen and nitrogen that had been precharged in the constant-volume combustion vessel.

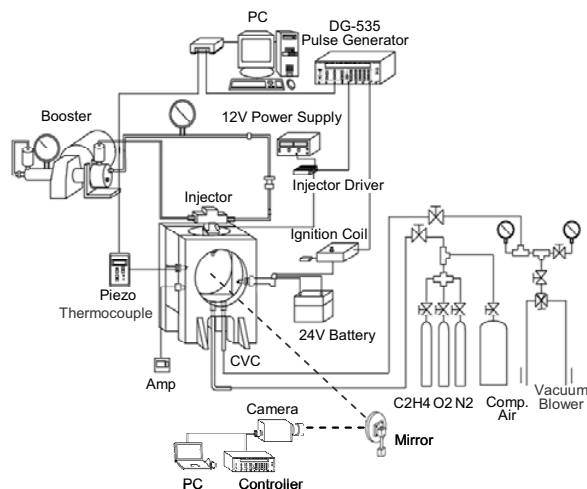


Fig. 1 Experimental setup

By adjusting the charging pressure of the premixed ethylene mixture and the interval from spark ignition to the onset of fuel injection, fuel spray and combustion measurements were obtained under ambient conditions approximately equal to those of actual engine operation. Fuel temperature was kept at 293 K for all experimental conditions. The shadowgraph method using a strobe light was applied to photograph the liquid phase of the evaporated spray, while combustion was photographed directly with a high-speed video camera (Phantom V6.0, Vision Research).

SIMULATION METHOD

Spray Model

The Taylor analogy breakup (TAB) model is generally used in performing numerical analyses of a gasoline spray[15]. However, since a high-pressure spray discharged from a single-hole diesel nozzle was the object of analysis in this study, it was thought that the fuel droplet breakup process would show tendencies similar to those of a conventional diesel spray. Accordingly, the Kelvin-Helmholtz instability and Rayleigh-Taylor instability (KH-RT) model was used as the fuel droplet breakup model [16]. In calculating the relative velocity needed to describe the droplet breakup process, the dependence on the calculation cell was reduced by estimating the ambient gas velocity using a weighting technique based on the reciprocal of the distance from the eight vertices of the cell. Similarly, the dependence on the calculation cell was also eliminated from the fuel droplet collision model. [17]

Validation of Spray Model Accuracy

Since spray properties are strongly dependent on the fuel injector specifications, the spray model was optimized on the basis of experimental results. Because the breakup model used here is mainly applied to diesel sprays, the model coefficients concerning the droplet diameter following breakup and the breakup length were adjusted in order to apply the model to gasoline sprays.

Figure 2 shows calculation results of the liquid-phase fuel penetration length of the evaporated spray as a function of time after the start of injection, in comparison with the experimental results. The injection pressure was 40 MPa and the nozzle hole diameter was 0.08 mm. The results in the upper row are for an ambient pressure of 1.0 MPa and an ambient temperature of 640 K; the results in the lower row are for an ambient pressure of 2.5 MPa and an ambient temperature of 820 K. Shown on the right side are calculated images of the fuel parcel at 1.0 ms after the start of injection for each set of conditions and the images visualized with the shadowgraph method. To avoid uncertainty of the calculation (such as parcel numbers), liquid penetration length in the calculation is defined by following; Total mass of fuel parcels is obtained. The distance is equal to the liquid length obtains 95 % of the mass calculated above.

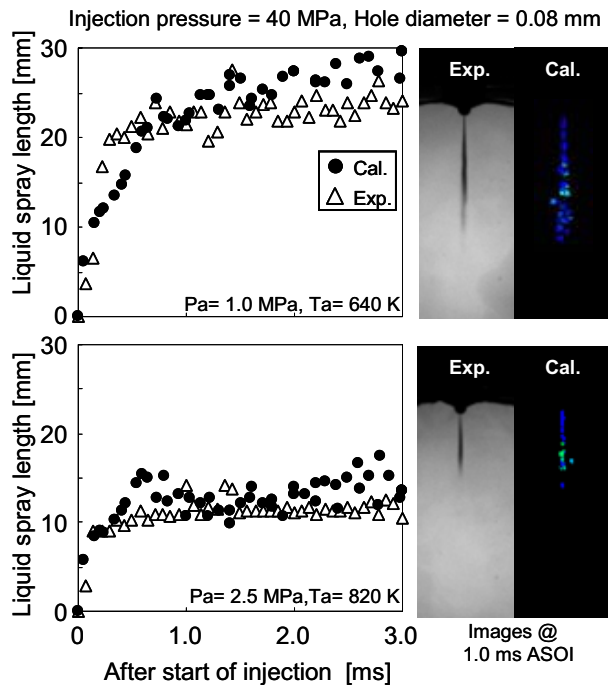


Fig. 2 Comparison of evaporated spray calculation results with experimental data

The results indicate that the liquid-phase fuel penetration length was the greatest at around 0.5 ms after the start of injection, after which it showed virtually a constant value. Under an ambient temperature condition of 640 K, the shape of liquid phase was narrow and the fuel spray was completely evaporated within a distance of less than roughly 30 mm from the nozzle tip. That is attributed to the good atomization characteristic of gasoline owing to its low viscosity and low surface tension and to its quick evaporation because of a low boiling point. Such characteristics are thought to be desirable tendencies to accomplish sootless combustion under the condition of the shorter lift-off length. The calculated penetration lengths show some scatter, but they generally reproduce the spray shape and liquid-phase fuel penetration length under the two sets of conditions with different ambient temperatures and pressures. These results confirm that the KH-RT breakup model is applicable to gasoline sprays.

Combustion Model

The KIVA-3V code does not include thermal-physical values for chemical species at the elemental reaction level, including the intermediate products of combustion. Therefore, elemental reaction schemata described in the CHEMKIN[18] format and thermal-physical values described in the NASA polynomial format for each chemical species were incorporated into the KIVA-3V code to facilitate chemical reaction calculations that took into account elemental reaction processes. The partially stirred reactor (PaSR) model was adopted as the combustion model and the multi-step method adopted in the KIVA-3V code was used.

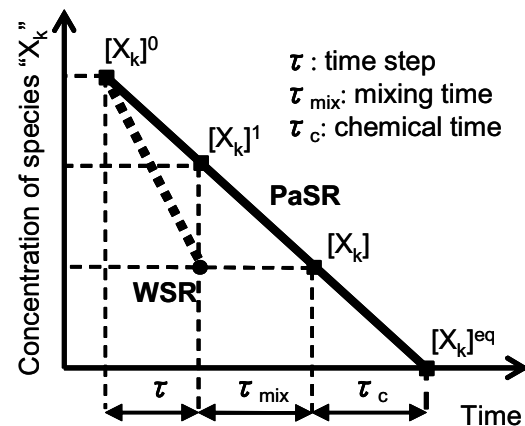
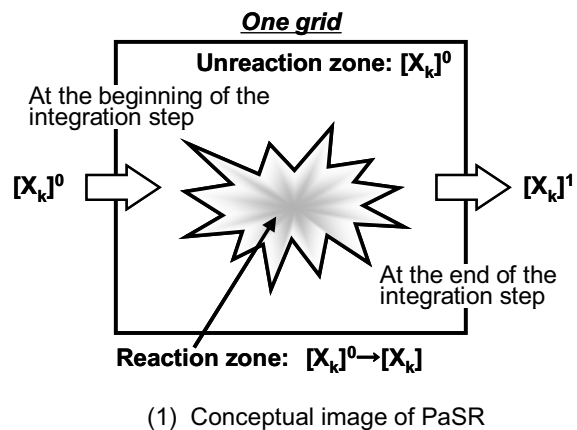


Fig. 3 Concept of Partially Stirred Reactor model

The PaSR model takes into account the effect of turbulent mixing on the burning velocity, i.e., the so-called micro-mixing effect. A conceptual image of the PaSR model is shown in Fig. 3 and further details about the model can be found in reference. [17,19] The reduced scheme of iso-octane proposed by Golovitchev and containing 83 chemical species and 406 elemental reactions was used as the elemental reaction mechanism. [20]

STUDY OF CONDITIONS FACILITATING LIFT-OFF COMBUSTION

Previous findings concerning diesel lift-off combustion show that sootless spray combustion can be accomplished by ensuring the lift-off length. The lift-off length can be increased by reducing the ambient temperature or by reducing the oxygen concentration under a condition where a small nozzle hole diameter is used in conjunction with high-pressure fuel injection. As is well known, gasoline and diesel fuel differ in both their chemical and physical processes. Gasoline is a more difficult fuel to ignite than diesel fuel, making spark ignition

of the spray necessary. Additionally, gasoline has low viscosity and low surface tension and a quick evaporation characteristic due to its low boiling point. Because of these differences, the effects of the injection pressure, nozzle hole diameter and other initial injection conditions and the ambient temperature and pressure conditions on the lift-off length and soot formation were investigated first of all by conducting spray tests and performing numerical simulations with the KIVA-3V code. The experimental and simulation conditions are given in Table 1, and the computational mesh used in the simulations is shown in Fig. 4.

EFFECT OF NOZZLE HOLE DIAMETER ON MIXTURE FORMATION

3D Mixture Simulation

Prior to the experiments, a 3D mixture simulation was conducted to examine the effect of the nozzle hole diameter on the mixture distribution in the spray. Figure 5 shows the gaseous-phase equivalence ratio distribution in a center-axis cross section of the spray with fuel parcels at 2.5 ms after the start of injection and the equivalence ratio distribution in a horizontal cross section of the spray at distances of 10, 30 and 50 mm from the nozzle. The nozzle hole diameters used in the calculations were 0.065, 0.08 and 0.10 mm. The injection pressure was 40 MPa and the ambient temperature was 600 K. The other simulation conditions were the same as those given in Table 1. In the simulation, only the initial fuel droplet diameter was varied in proportion to the nozzle hole diameter; all of the other spray model constants remained unchanged.

Looking at the calculated results for a nozzle hole diameter of 0.10 mm, an over-rich mixture (indicated in red in the figure) is observed near an equivalence ratio Φ of 2.5 in the center of the spray approximately 40 mm below the nozzle. The results show that the mixture distribution in the spray becomes uniformly lean as the nozzle hole diameter is reduced in size to 0.08 mm and 0.065 mm. With a nozzle hole diameter of 0.065 mm, Φ is less than 1.5 at a distance of 30 mm below the nozzle and its distribution is relatively uniform.

Figure 6 shows the gaseous-phase fuel mass fraction calculated for each nozzle hole diameter at a local equivalence ratio Φ of more than 2.0. This evaluation is for 2.5 ms after the start of injection, the same time condition as in Fig. 5. The results show gaseous-phase fuel mass fractions of 27%, 17% and only 4% for nozzle hole diameters of 0.10, 0.08 and 0.065 mm, respectively. According to reference [21], soot formation increases rapidly on the over-rich fuel side beginning from an equivalence ratio Φ of 2.0. It is inferred from this observation that a soot formation region can be avoided with a nozzle hole diameter of 0.065 mm by means of the mixture concentration. The calculated results also suggest that there is a good possibility of obtaining sootless spray combustion even if the flame lift-off length is shortened by movement of the flame zone upward toward the nozzle.

Table 1 Experimental and simulation conditions

Injector type	Diesel common-rail
Nozzle type	Single hole (located on center axis)
Nozzle diameter	0.065, 0.08, 0.10 mm
Injection duration	8 ms
Injection pressure	40,80,120 MPa
Ignition position	30, 50 mm (from injector orifice)
Ignition timing	1.1 ms ASOI*
Ambient density	12 kg/m ³
Ambient temperature	600 ~ 1000 K
Fuel	Iso-octane
Fuel temperature	293 K

* ASOI : After start of injection

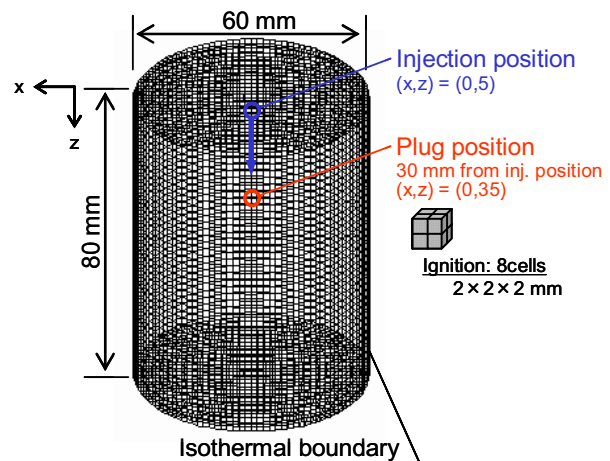


Fig. 4 Computational mesh of constant volume combustion vessel

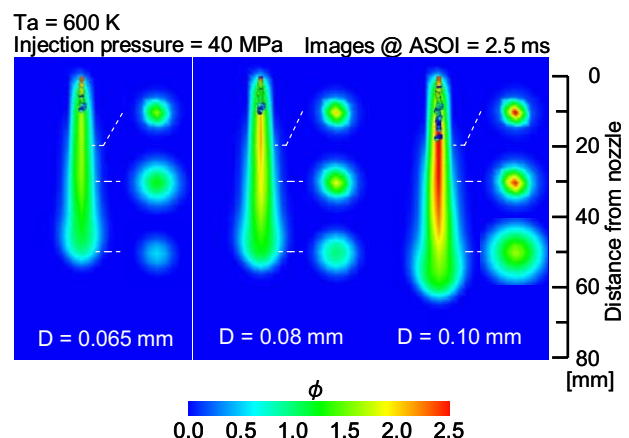


Fig. 5 Effect of nozzle hole diameter on mixture formation