Research on the Ignition-Chamber GDI Engine Combustion System*

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Abstract
The ignition-chamber GDI engine combustion system and its fuel injection strategy were presented and studied by multi-dimensional fluid dynamic (CFD) code and experiment. The CFD research result shows that the ignition-chamber combustion system and its fuel injection strategy can ensure that there is flammable mixture with appropriate concentration distribution near the spark plug to enhance the ignition reliability. The performance of the GDI engine with the ignition-chamber combustion system was investigated basing on the existing experiment condition. The result shows that the ignition-chamber combustion system has the potential of decreasing emissions and enhancing the combustion speed and stability.

Key words: GDI, Ignition-Chamber, Equivalence Ratio, Combustion System

1. Introduction
Gasoline direct injection (GDI) engines have many advantages(1)(2), such as high fuel economy, fast response and low HC emission during cold starting. With the increasing of petroleum costing and stringent emission legislation requirement, automotive engineers have been setting the research emphasis on GDI engines. Because the engine with lean burn can obtain better performance, a lot of study has been put out on(3)-(5). Ignition reliability and combustion stability are the two important factors of developing lean burn system.

It is necessary to form stratified charge for lean burn. Many approaches were used to produce the stratified charge in conventional gasoline engines, such as the pre-chamber stratified charge flame-jet ignition system with special fuel supplying system for the pre-chamber, the famous successful example of which is the Honda CVCC combustion system(6). GDI engines have the potential to expand the lean stably operation limit. With the development of fuel injection and control technology, GDI engines obtain more chances to improve the performance by lean burn and stratified charge. There are many combustion systems in GDI engine products, which can be divided into three categories according to the ways of forming stratified charge(7)(8) as shown in Fig.1: (1) the wall-guided combustion system, which uses the momentum of the fuel spray and the chamber wall to form stratified charge, like the Toyota D-4 engine(9), the Honda K20B engine(10) and the Mitsubishi GDI engine(11); (2) the spray-guided combustion system, which uses the momentum of the fuel spray to form stratified charge directly; (3) the air-guided combustion system, in which the in-cylinder flow is the most important factor for stratified charge forming, such as the Volkswagen FSI GDI engine(12). Most of the GDI engines impose a very strong additional requirement on the mixture forming. A suitable temporal progress of the evaporation and mixing process, well controlled spatial evolution of mixture distribution and reproducibility are all necessary. Depending on the engine operating condition, injection timing window

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and available cylinder volume for the injected fuel are often constrained and the ignition timing window is very narrow (13)(14).

In order to enhance ignition reliability and combustion speed of GDI engines, extend the stably lean operation limit and form more suitable mixture for ignition and combustion, the ignition-chamber combustion system was brought forward by Dalian University of Technology (DUT) of China: The system has an ignition-chamber in the cylinder, in which is a spark plug; a multi-hole fuel injector is out of the ignition-chamber; one of the injector’s holes points to the inlet of the ignition-chamber (one hole of the ignition-chamber). Further, the fuel injection strategy matching with the ignition-chamber combustion system was designed: According to operating conditions, one or more injections were adopted in one cycle. The injections can be divided into two kinds in conformity to their functions: (a) the main injection, which is mainly used to adjust the engine power output; (b) the controlled injection, which is mainly used to control the fuel equivalence ratio in the ignition-chamber. The main injection takes out in intake stroke while the charge flow velocity is large between the fuel injector and the ignition-chamber, so the fuel from the injector’s hole that points to the inlet of the ignition-chamber cannot enter the ignition-chamber and all the fuel remains in the main combustion chamber as shown in Fig.2. The controlled injection takes out in compression stroke, while the charge flow velocity is small between the injector and the ignition-chamber due to the collapse of large scale flow structures, then most of the fuel from the injector’s hole can enter the ignition-chamber through the inlet of the ignition-chamber but the fuel from other holes remains in the main chamber as shown in Fig.3. In Fig.2 and Fig.3, only the sprays on the symmetrical plane are showed. That is the way to control the fuel equivalence ratio near the spark plug through controlling the quantity of the fuel entering the ignition-chamber.

This paper presents the new GDI engine concept and its fuel injection strategy. The 3D-CFD research was carried out by the AVL Fire. In order to study and validate the ignition reliability and the basic performance of this kind of combustion system with an ignition-chamber, some experiment were carried out, and the experiment will be introduced
in the end of this paper. Although the configuration of the combustion system and operating condition using in the experiment are different from the simulation’s, the basic performance can be presented.

2. Research on the ignition-chamber GDI engine combustion system by CFD

In order to research the capability of the ignition-chamber combustion system forming stratified charge, a simulation model based on a common 4-valve gasoline engine was designed as shown in Fig. 4. The intake port and chamber can be known from Fig. 4(a); and the detailed location and direction of the sprays are as shown in Fig. 4(b). Table 1 gives out the parameters of the model. The ignition-chamber was set in the center of the cylinder head, a part of which was extended into the cylinder. The fuel injector was arranged under the intake ports. To match with the spray angle and injection timing, the head of the piston was changed into the triangle shape; the shape and the ignition-chamber are as shown in Fig.5.

![Fig. 4 Structure of the simulation model: (a) is the intake port and chamber; (b) is the location and direction of the sprays](image)

![Fig. 5 Structure of the piston head and the ignition-chamber](image)

<table>
<thead>
<tr>
<th>Table 1 The basic parameters of the simulation model</th>
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<tbody>
<tr>
<td>No. of valves</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Bore/Stroke</td>
</tr>
<tr>
<td>Ignition-chamber</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Intake valve timing</td>
</tr>
<tr>
<td>Injector holes: No./ Diameter</td>
</tr>
<tr>
<td>Injection pressure</td>
</tr>
<tr>
<td>Quantity of injected fuel in one cycle</td>
</tr>
<tr>
<td>Quantity of fuel injected as the controlled injection</td>
</tr>
</tbody>
</table>

The focus of the fuel injection strategy is that the fuel from the injector’s hole that points to the inlet of the ignition-chamber can not enter the ignition-chamber in intake stroke but can enter in compression stroke. In order to inject the fuel into the ignition-chamber in compression stroke, besides the flow is not too strong, the performance of the fuel injector is very important. The detailed demands to the fuel injector are as
follows: (a) the spray angle is small enough, which is the precondition that most of the fuel can enter into the ignition-chamber; (b) the penetration and the speed of the spray are large enough for the fuel entering the ignition-chamber. From the existing research\(^{(15)}\), it is believed that all the demands to the injector can be achieved through suitable designing. The paper\(^{(15)}\) shows that the penetration of the spray can achieve 30mm downstream of the injector tip with high speed and the spray angle can be reduced to about 8 degree by enhancing the l/d ratio of the hole of the injector to 6.3. Thus, it is sure that the fuel can be injected into the ignition-chamber if the influence from the in-cylinder flow is not too large; for injecting the fuel into the ignition-chamber, charge flow of low velocity is necessary. As the in-cylinder flow has very large effect on the fuel injection strategy, the CFD work of which was carried out firstly.

![In-cylinder velocity of intake stroke](image)

Figure 6 shows the in-cylinder flow velocity on the symmetrical plane of the valves from 20 °CA ATDC to 90 °CA ATDC of intake stroke. Because all the air entered the cylinder from the two intake valves, the velocity was very large, especially near the intake valves. Most of the velocity (between the injector and the ignition-chamber) was above 100m/s and the largest exceeded 150m/s.
Figure 7 shows that the in-cylinder flow velocity from 100 °CA BTDC to 30 °CA BTDC of compression stroke (The color bar for referring has been changed). As a result of the collapse of large scale flow structures, the velocity was much smaller than in intake stroke and most of the velocity was below 10m/s. Low velocity between the fuel injector and the ignition-chamber was very beneficial to the fuel entering the ignition-chamber.

The above is the research on the in-cylinder flow. From the result, it is believed that there is suitable flow velocity for the injection strategy: The main injection can take out in intake stroke as the flow velocity is large and the controlled injection can take out in compression stroke.

In order to research the fuel equivalence ratio in the ignition-chamber, the fuel spray simulation was carried out. The most crucial research object was the fuel from the injector’s
hole that points to the inlet of the ignition-chamber. To obtain the distinct result without the influence from other injector’s holes, only the hole that points to the ignition-chamber was set. The main injection started at 20 ºCA ATDC and ended at 35 ºCA ATDC in intake stroke as shown in Fig.8; the controlled injection started at 100ºCA BTDC and ended at 93ºCA BTDC in compression stroke as shown in Fig. 9.

From the process of the fuel injections, it can be observed that the strategy using the in-cylinder flow to control the spray is doable. In order to enhance the ignition stability and enlarge the ignition timing window, stable mixture and suitable fuel equivalence in ignition-chamber are necessary, and then the fuel equivalence ratio in the ignition-chamber was investigated.

![Fig. 8 Process of the main injection](image)

![Fig. 9 Process of the controlled injection](image)

Figure 10(a) gives out the fuel equivalence ratio of one kind of injection timing of the controlled injection. Figure 10(b) shows the fuel equivalence ratio at 20ºCA BTDC of different injection timings. Because the fuel from the injector's hole points to the inlet of the ignition-chamber of the controlled injection has the absolute impact on the fuel equivalence ratio in the ignition-chamber and the influence of others can be compensated by adjusting the fuel quantity of the controlled injection if necessary, only the injector's hole points to the inlet of the ignition-chamber and the controlled injection was set, which is the reason that the fuel equivalence ratio out of the ignition-chamber is very low. Some advantages of this kind of combustion system can be known: the ignition-chamber has the ability of keeping the stable mixture near the TDC and the same injection timing can be used to different ignition timings.
(a) Injecting between 100ºCA BTDC and 93ºCA BTDC

(b) The fuel equivalence ratio at 20ºCA BTDC of different injection timings

Fig. 10 Distribution of the fuel equivalence ratio
The ideal results have been received from the simulation. The ignition-chamber combustion system using the injection strategy can produce suitable mixture for ignition in the ignition-chamber.

3. Experiment of the ignition-chamber GDI engine combustion system

The experiment of ignition-chamber GDI combustion system was carried out. For experiment, an ignition-chamber with a spark plug was installed and the fuel system was also modified for gasoline. The parameters of the test engine are as shown in Table 2. The sketch of the ignition-chamber combustion system for the experiment is as shown in Fig.11.

<table>
<thead>
<tr>
<th>Type</th>
<th>Ignition–chamber GDI engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Style</td>
<td>one cylinders</td>
</tr>
<tr>
<td></td>
<td>four-stroke, water-cooling</td>
</tr>
<tr>
<td></td>
<td>natural aspirate</td>
</tr>
<tr>
<td>Bore/Stroke</td>
<td>100mm/120mm</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>12</td>
</tr>
<tr>
<td>Injector hole: No./ Diameter</td>
<td>3/0.24mm</td>
</tr>
</tbody>
</table>

The purpose of the experiment was to research the ignition reliability and the basic performance of this kind of combustion system on condition that the fuel equivalence ratio in the ignition-chamber was suitable to ignite, thus the distance between the injector and the ignition-chamber was short to make sure that there was enough fuel to enter the ignition-chamber. The fuel injection system can carry out only one injection during one circle, so the engine combustion system was designed for idling operating condition only. The compression ratio of the engine with the shallow bowl was 12. The injector had three holes, one pointed to the inlet of the ignition-chamber and the others pointed to the piston; the diameter of the injector’s holes was 0.24mm. The structure of the ignition-chamber was as shown in Fig.12, the diameter of the ignition-chamber hole is 1.5mm; the fuel from the injector’s hole that pointed to the ignition-chamber was injected into the ignition-chamber through the inlet, and then moved to the vicinity of the spark plug while diffusing and atomizing on the effect of charge flow. The flame with unburned mixture was ejected into the main combustion chamber after ignition from the ignition-chamber, and then the mixture in the main combustion chamber was ignited and combusted.

The combustion experiment of idling operating condition was completed. The experiment result shows that:
(a) With this combustion system, the engine can work stably under the overall air-fuel ratio is 48.
(b) The lowest idling rotate speed can be reduced to 400 r/min.
(c) Figure 13 gives out the contrast of CO and HC emission of different ignition timing with Euro 3 without any after treatment equipments, it can be found that the HC and CO emission are less than Euro 3 requirement.

From the experiment results, it is believed that the ignition-chamber combustion system has the potential to enhance the performance of GDI engine on emission, stability and lean combustion.

4. Conclusions

The ignition-chamber combustion system was researched by CFD; the ignition reliability and the basic performance of this kind of combustion system were investigated through the simple combustion experiment. The results from this research can be summarized as follows.

1. The fuel injection strategy is doable and there is suitable and stably mixture in the ignition-chamber and the ignition timing window can be enlarged.
2. The ignition-chamber GDI combustion system has the potential of enhancing the ignition and combustion stability and decreasing the emissions.

This paper presents the research on the feasibility of the ignition-chamber GDI engine combustion system, and there is a lot of research work to do in future, such as the further optimization of the ignition-chamber, the combustion chamber and the fuel injection strategy for all the operating conditions, and also more experiment study is necessary. With the development of fuel injection technology, multi-stage injection with alterable injection rate may be helpful to this kind of combustion system.

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