

Development of Ignition Technology for Dilute Combustion Engines

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ABSTRACT

In recent years, from a viewpoint of global warming and energy issues, the need to improve vehicle fuel economy to reduce CO₂ emission has become apparent. One of the ways to improve this is to enhance engine thermal efficiency, and for that, automakers have been developing the technologies of high compression ratio and dilute combustion such as exhaust gas recirculation (EGR), and lean combustion. Since excessive dilute combustion causes the failure of flame propagation, combustion promotion by intensifying in-cylinder turbulence has been indispensable. However, instability of flame kernel formation by gas flow fluctuation between combustion cycles is becoming an issue. Therefore, achieving stable flame kernel formation and propagation under a high dilute condition is important technology.

This paper discusses the most suitable discharge specification for stable high dilute combustion based on the mechanism of flame kernel formation in various gas flow conditions, and then shows the expanding effects of dilute combustion limit compared with conventional ignition technology. Engine tests were conducted in various engine conditions. In the high gas flow condition, keeping high discharge current achieved stable flame kernel formation because of the suppressed discharge blow-off, and in low gas flow conditions, expanding discharge duration improved dilute combustion limit because of heat loss reduction. As a result, controlling discharge current to optimal values under each engine conditions could achieve superior engine thermal efficiency. In addition, it achieved ignition system energy savings.

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INTRODUCTION

Improving vehicle fuel economy to achieve CO₂ emissions reduction for the global warming and energy issues is essential. Automakers have been developing technologies (e.g. direct injection, turbo charged downsizing and high compression ratio) to improve vehicle fuel economy through engine thermal efficiency enhancement. In recent years, dilute combustion such as cooled EGR and lean burn combustion are regarded as key technologies to achieve engine thermal efficiency enhancement [1, 2]. However, excessive dilute combustion leads to combustion speed reduction because of lower fuel density, and limits the engine thermal efficiency improvement effect. Generally, intensifying in-cylinder turbulence is known to be an effective way to improve combustion speed [3, 4, 5], as it can stabilize dilute combustion by promoting flame propagation. However, specifically focusing on ignition and initial process of combustion, stabilization of ignitability and initial combustion under high gas flow velocity and dilute air-fuel mixture conditions is a major issue. Therefore, development of ignition technology for achieving stable dilute combustion has been proposed by many researchers. For

example, there is radio frequency ignition, corona ignition, micro wave ignition, laser ignition, multiple spark plug and so on [6, 7, 8, 9, 10]. However, these technologies have not been put to practical use due to many issues such as energy consumption and packaging, etc. In recent years, technical approach by conventional spark ignition systems has also been actively proposed because conventional spark ignition has high energy density and high versatility [11, 12]. Although they have investigated the effect of dilute combustion limit by enhancing discharge current / energy, they have not yet been quantified sufficiently to optimize discharge specification based on the discharge principle under various engine conditions.

This paper focuses on the difference of flame kernel formation and growth by the discharge phenomenon such as discharge stretching, blow-off and short-circuiting under various discharge environments and discusses the optimal discharge specification for dilute combustion based on the discharge principle. Furthermore, the effect of ignitability improvement is evaluated by using a dilute combustion engine followed test result analysis.

THE AIM AND ISSUE OF DILUTE COMBUSTION

Enhancing engine thermal efficiency leads to improvement of vehicle fuel economy. The theoretical thermal efficiency is shown in Equation (1).

$$\eta_{th} = 1 - \left(\frac{1}{\epsilon}\right)^{\kappa-1} \quad (1)$$

Where, ϵ is compression ratio, and κ is specific heat ratio. Increasing these parameters enhances thermal efficiency. Dilute combustion is an effective way to achieve this. For example, cooled EGR combustion is a technology to enhance thermal efficiency by achieving suppression of knocking caused by high compression ratio and reduction of engine cooling heat loss. Lean burn combustion can also enhance thermal efficiency by increasing specific heat ratio. For these reasons, dilute combustion has been adopted widely in recent years.

However, unstable combustion fluctuation and speed due to lower fuel density inhibits expansion of dilute ratio. This has become an obstacle to enhancing thermal efficiency. Figure 1 shows relationship between excess air ratio and combustion duration, as well as combustion fluctuation and fuel consumption in lean burn combustion. Both 0-10 % and 10-90 % combustion duration are extended by increasing excess air ratio, and these deteriorate combustion fluctuation and fuel consumption. These extensions of combustion duration have each factor. The factor of 0-10 % combustion duration is unstable flame kernel formation and poor flame growth. The factor of 10-90 % combustion duration is flame propagation velocity reduction. These have become major issues to achieve thermal efficiency enhancement in dilute combustion.

The following images show flame kernel formation, flame growth and flame propagation. Figure 2 shows the process from flame kernel formation to flame propagation.

$$E_{IN} = E_{IG} - Q_{SP} \quad (2)$$

$$E_{IG} = \int_0^{T_2} V_2 \times I_2 \, dt \quad (3)$$

Each parameter is defined as the following. E_{IN} is energy supplied to the air-fuel mixture by the discharge, and is represented by the simple expression of Equation (2). E_{IG} is ignition energy to be supplied from the ignition system, it is shown as Equation (3). V_2 is discharge voltage between the electrodes of the spark plug, I_2 is discharge current, and T_2 is discharge duration. Q_{SP} is cooling loss energy in the spark plug.

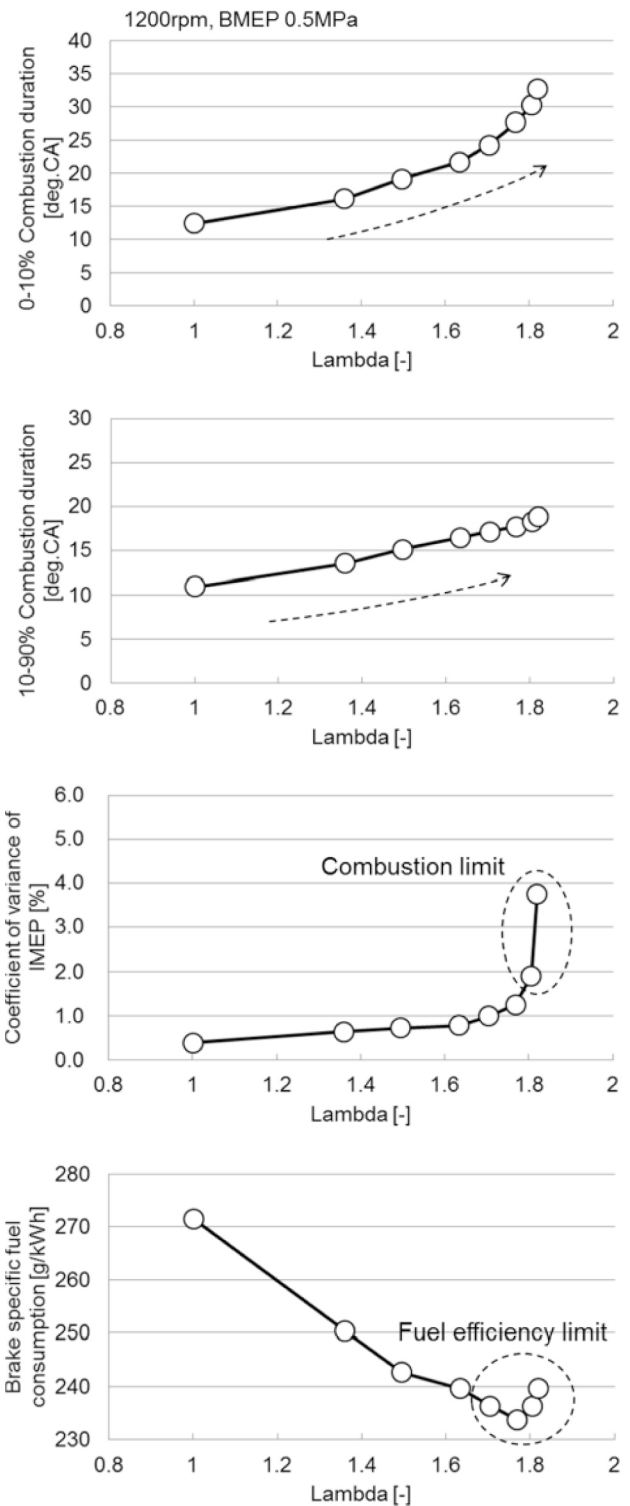


Figure 1. Relationship between excess air ratio and combustion duration, combustion fluctuation, fuel consumption in lean burn combustion



Figure 2. The process from flame kernel forming to flame propagation

After discharge initiation, the flame kernel begins to be formed by supplying energy to the air-fuel mixture while the discharge is stretched by the gas flow. Although some ignition energy is lost due to cooling of the spark plug, the flame kernel continues to grow as long as ignition energy is continuously supplied. When the flame kernel is sufficiently grown, it can propagate by chemical reaction. In general, minimum ignition energy for 50 % successful ignitability is significantly increased when excess air ratio increases [13]. For that reason, ignition energy intensification and spark plug cooling loss reduction are required as ignition technology for promotion of flame formation and growth under dilute combustion is advanced. In addition, promotion of flame propagation is also essential for dilute combustion establishment. Equation (4) shows the flame propagation velocity.

$$Wf = Wb + S_T \quad (4)$$

$$S_T \cong S_L + u' \quad (5)$$

$$S_L = [30.5 - 54.9(\phi - 1.21)^2] \left(\frac{T}{T_0}\right)^a \left(\frac{P}{P_0}\right)^b \quad (6)$$

$$a = 2.18 - 0.8(\phi - 1) \quad (7)$$

$$b = -0.16 - 0.22(\phi - 1) \quad (8)$$

Where, Wf is flame propagation velocity, Wb is gas movement velocity and S_T is turbulent burning velocity. Shown in Equation (5), S_L is the laminar burning velocity and u' is turbulent intensity. In Equation (6), $T_0 = 298K$, and $P_0 = 101.3kPa$ are reference temperature and pressure. a and b are constants for a given fuel equivalent ratio ϕ .

Flame propagation velocity is determined by gas movement velocity and turbulent burning velocity. Since turbulent intensity is almost the same, even when dilute ratio is increased, turbulent burning velocity is decreased by reduction of laminar burning velocity at a high dilute ratio condition as shown in Equation (6). In order to solve it, intensifying in-cylinder turbulence such as tumble and swirl has been used. Increase of the turbulent burning velocity promotes flame propagation. However, the larger the value of u'/S_L shown in Karlovitz number is, the higher minimum ignition energy is [3, 13]. The cause is increase of turbulent burning velocity fluctuation and heat loss to turbulence. Thus, the promotion of flame propagation also requires enhancing ignition energy. Furthermore, focusing on ignition environment, gas flow velocity around the spark plug is faster when turbulence intensity is increased. As shown in Figure 2, discharge is usually stretched by gas flow. This discharge stretch continuously supplies energy to wide air-fuel mixture area and achieves larger flame kernel formation. However, high gas flow velocity causes discharge blow-off and inhibits discharge stretch. As the result, it causes a drastic deterioration of flame kernel formation. For these reasons, ignition technology development is strongly required for dilute combustion.

THE ROLE OF IGNITION SYSTEM UNDER DILUTE COMBUSTION

The role of an ignition system is stable flame kernel formation in various ignition environments such as fuel density and gas flow, and for that, ignition systems must continuously supply necessary and sufficient energy to the air-fuel mixture. However, occurrence of discharge blow-off inhibits continuous energy supply. There, the state of flame kernel formation during a cycle in which discharge blow-off occurred on an engine was observed. Figure 3 shows the observation method and result. Visible window was set up on the rear of engine, and flame kernel formation process of cylinder #4 was observed by a high speed camera (Photoron FASCAM SA5). And also, discharge voltage was measured with a high voltage probe (Tektronix P6015A) from the middle of high tension cable and discharge current was measured with a current probe (Tektronix TCP303) attached directly to a high tension cable.

After initiation, discharge starts to supply energy to the air-fuel mixture while discharge stretches, and then the first blow-off occurred. In this time, a small flame kernel could be confirmed. After that, a second flame kernel was formed by re-discharge. Each flame existed apart from each other, and they were anti-inflammatory without flame propagation due to lack of energy. This flame observation result has revealed that blow-off inhibits stable flame kernel formation by separation of flame and lack of energy. Therefore, suppressing discharge blow-off is considered an important technology to achieve stable dilute combustion.

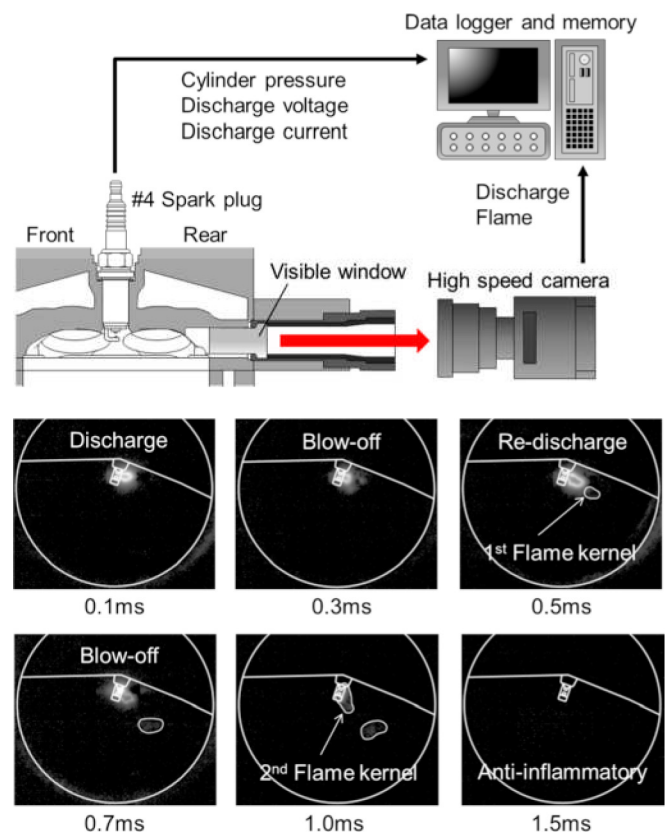


Figure 3. Observing method and result of flame kernel formation at the occurrence cycle of discharge blow-off by using high speed camera

Before examining blow-off suppression method, the blow-off occurrence mechanism should be mentioned. Figure 4 shows the process of discharge blow-off.

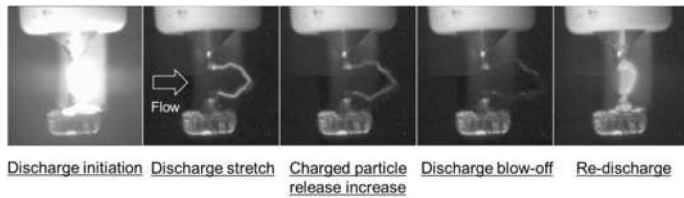


Figure 4. The process of discharge blow-off

Breakdown is caused by repeating ionization of gas molecules (α effect) and secondary electron emission (γ effect) when a voltage difference is generated between spark plug electrodes. After that, discharge changes to the glow / arc discharge known as a continuous discharge. The discharge can be kept if a balance of the amount of charged particles produced and the amount released to the outside is held. Where, the amount of charged particles moved in the discharge space is defined as discharge current. In the gas flow condition, since charged particles are moved by the gas flow, discharge is stretched, and then parts of the charged particles are released outside of the discharge. At this time, the stronger the gas flow is, the more the release amount increases, and discharge blow-off occurs when the balance of the charged particle amount is lost. If any energy remains in the ignition system, re-discharge immediately occurs and the same process described above is repeated. In this way, since keeping the discharge is established by balance of charged particle amount, discharge current is strongly related to blow-off.

For examining blow-off suppression method, the relationship between discharge current and blow-off was confirmed. Figure 5 shows the result. Figure 5-(a) shows the relationship between gas flow velocity around the spark plug and blow-off discharge current. Where, blow-off discharge current is defined as the value of current at the start time that blow-off continuously occurs, an example is shown by dashed line in the discharge current waveform of Figure 5-(b). From this result, we found that blow-off occurs when discharge current is lower than blow-off discharge current, and also blow-off discharge current is higher in accordance with the gas flow velocity increase. This means blow-off occurrence is strongly dependent on the discharge current regardless of discharge channel length. From the above examination results, keeping higher discharge current than blow-off discharge current is considered the most effective way for suppressing discharge blow-off in various gas flow conditions.

On the other hand, a sudden change of discharge channel length occurs in spite of high discharge current. This phenomenon is short-circuiting of the discharge channel shown in Figure 6-(a), forming a discharge path in the middle of the discharge channel. This paper will refer to this phenomenon as short-circuiting. This short-circuiting occurs depending on the electric field strength around the discharge channel generated by a voltage difference between discharge channels. This also forms by relatively low voltage differences because there are a lot of charged particles diffused around discharge channel. The generated voltage depends on the environment conditions such as the gas flow, pressure and discharge

characteristics. In addition, as shown in Figure 6-(b), when short-circuiting occurs, discharge voltage decreases by shortening of the discharge channel length. However, discharge current does not become zero unlike blow-off. This means that the short-circuiting does not interrupt discharge. In that respect, it is necessary to distinguish from blow-off. Impact of short-circuiting on flame kernel formation will be mentioned in detail in the next section.

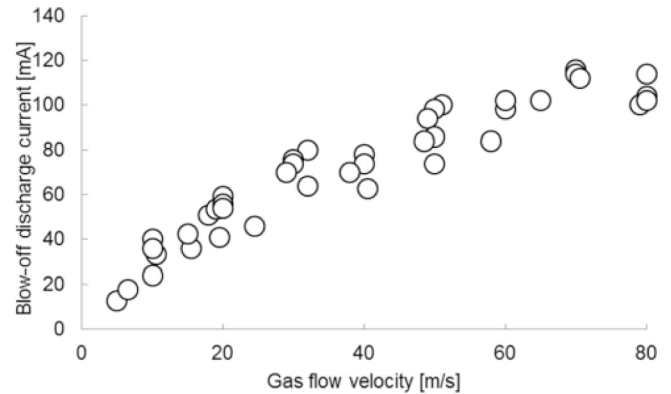


Figure 5-a. Relationship between the gas flow velocity around spark plug and blow-off discharge current

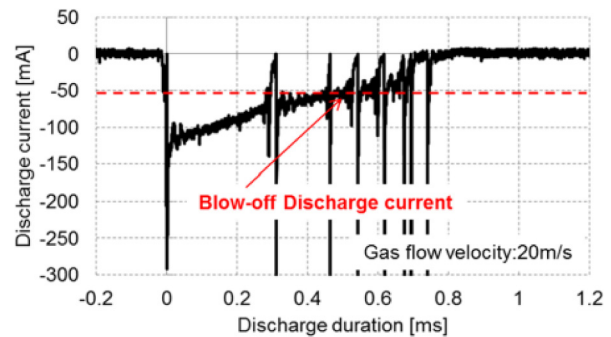


Figure 5-b. Discharge current waveform at blow-off occurrence cycle

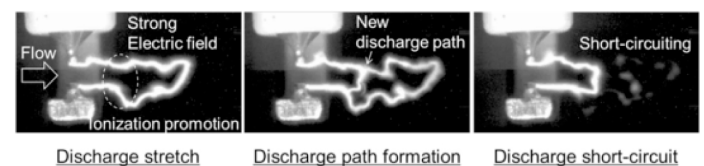


Figure 6-a. The process of discharge short-circuiting

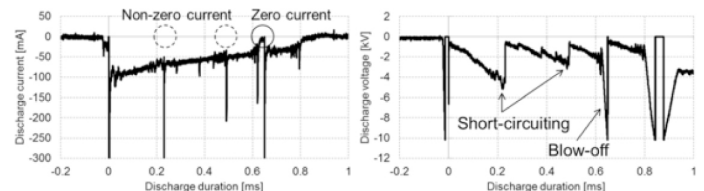


Figure 6-b. Discharge current and voltage waveform during blow-off and short-circuiting occurrence cycle

Next, it makes mention of discharge duration. As noted in Equation (2), supply energy to the air-fuel mixture is energy minus spark plug cooling loss from ignition energy. Although long discharge duration is able to increase ignition supply energy, spark plug cooling loss should be reduced from a viewpoint of power consumption.

Therefore, the relationship between cooling loss and discharge