

Engine Technologies for Achieving 45% Thermal Efficiency of S.I. Engine

Koichi Nakata, Shinichiro Nogawa, Daishi Takahashi, Yasushi Yoshihara, Atsunori Kumagai, and
Tetsushi Suzuki
Toyota Motor Corporation

ABSTRACT

To correspond to the social requirements such as energy security, and climate change, enhancing engine thermal efficiency is strongly required in these days. As for the specific engine technologies to improve engine thermal efficiency, Atkinson cycle, cooled EGR (Exhaust Gas Recirculation), and low friction technologies have been developed [1, 2, 3, 4]. As a result, the current maximum thermal efficiency comes close to 40%. However, since it is considered that much higher engine thermal efficiency is required in the future to meet more stringent social requirements, a new prototype L4 engine which features a long stroke design with a high tumble is investigated to clarify the future direction in this paper. In regard to combustion, the lean boosted concept with cooled EGR is examined. In consequence, it is shown that more than 45% engine thermal efficiency can be achieved. This paper describes the means to enhance engine thermal efficiency and a future possibility.

CITATION: Nakata, K., Nogawa, S., Takahashi, D., Yoshihara, Y. et al., "Engine Technologies for Achieving 45% Thermal Efficiency of S.I. Engine," *SAE Int. J. Engines* 9(1):2016, doi:10.4271/2015-01-1896.

INTRODUCTION

Countries around the world are introducing more stringent fuel economy standards as part of measures to address issues related to energy security and climate change. To correspond to these requirements, automakers have been making a lot of efforts to develop new vehicles. One comprehensible example is that HVs have been spreading widely throughout the world because the fuel economy of HVs is much better than that of conventional vehicles.

As for the engine development, enhancing the maximum engine thermal efficiency is especially essential for HVs because the engine operating points are mainly on the high engine load area where engine thermal efficiency is close to the maximum engine thermal efficiency. Therefore the maximum engine thermal efficiency for HVs has been enhanced prior to the engines for conventional vehicles. In these days, the technologies which have been developed for HVs are being adopted to the engines for conventional vehicles [2,3]. Figure 1 shows engine thermal efficiency history and the future direction. As described before, the maximum engine thermal efficiency comes close to 40%. Main technologies which have been developed to contribute to enhance engine thermal efficiency are Atkinson cycle, cooled EGR, and low friction technologies. In the short term, it is expected to enhance the maximum engine thermal efficiency more than 40% by modifying the current technologies [5]. However, since it is considered that much higher engine thermal efficiency is required to meet more stringent social requirements in the future, new technologies should be developed. In the following sections, this paper describes the future technologies for enhancing engine thermal efficiency.

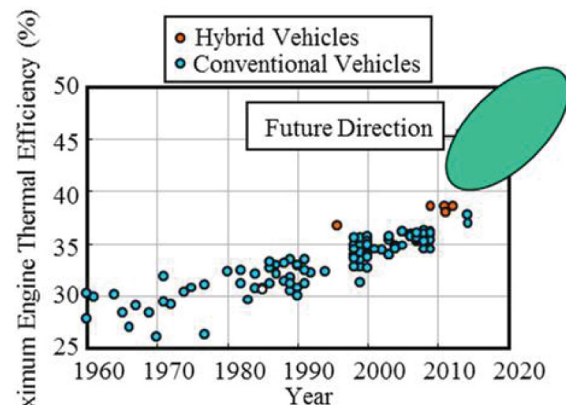


Fig.1 Engine Thermal Efficiency History and Future Direction

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THERMAL EFFICIENCY ENHANCEMENT

Theoretical engine thermal efficiency is well known as the Otto cycle equation. This equation means a higher expansion ratio or a higher specific heat ratio leads to higher engine thermal efficiency. The former one can be achieved by raising the compression ratio [6] or by retarding EVO (Exhaust Valve Open timing) and the latter one can be achieved by adopting lean burn [7]. However raising the compression ratio and lean burn has some issues to be solved such as knocking and the enhancement of combustion.

Actual engine thermal efficiency results from various losses such as mechanical loss, pumping loss, cooling heat loss, exhaust loss, and unburned loss, differing from theoretical engine thermal efficiency.

Therefore it is essential to decrease various losses to enhance engine thermal efficiency. Figure 2 shows the ways to enhance the maximum engine thermal efficiency. In this figure, a word of “HV” means Prius. In the first generation engine which has an engine displacement of 1.5L and the compression ratio of 13:1, main technologies are Atkinson cycle and low friction technology. The maximum engine thermal efficiency is raised to 37%. In the third generation engine for current Prius which has the engine displacement of 1.8L and the compression ratio of 13:1, newly adopted technologies are cooled EGR, an electric water pump, and low friction technologies. As a result, the maximum engine thermal efficiency is raised to 38.5%. Cooled EGR technology contributes to enhance the engine thermal efficiency extremely because cooled EGR mitigates engine knocking and reduces cooling heat loss due to low temperature combustion. Since the effect of cooled EGR on enhancing engine thermal efficiency is demonstrated, cooled EGR has just started becoming a popular technology at the present day.

In the future, much higher engine thermal efficiency is required to meet the social requirements. Although it is considered that cooled EGR is a mainstream technology for NA engines, new challenges are needed to enhance engine thermal efficiency much more than 40%.

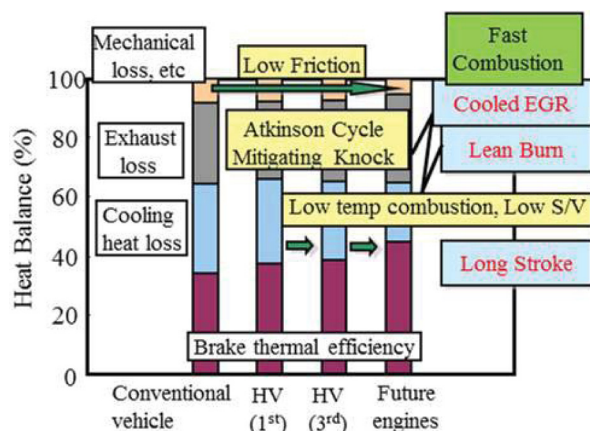


Fig.2. Engine technologies for enhancing the engine thermal efficiency

To enhance the maximum engine thermal efficiency much more than 40%, decreasing cooling heat loss and mitigating knocking are essential in addition to the theoretical approach such as the higher specific heat ratio with lean burn. As for the decrease in cooling heat loss, two approaches are investigated in this study. One approach is a long stroke design, because it is known that the long stroke design leads to decrease in S/V ratio. Here, S and V mean the surface area and volume of the combustion chamber when the piston is at TDC (Top Dead Center). Another approach is low temperature combustion with lean burn. As the effect of lean burn on the decrease in cooling heat loss is larger than that of EGR, it is expected that higher engine thermal efficiency can be achieved with lean burn compared to excess air ratio of 1 condition with cooled EGR. The reason is that the amount of fuel air mixture when the engine is run at lean limit condition is larger than the amount of fuel air mixture when the

engine is run at excess air ratio of 1 with EGR limit condition.

Therefore lean burn is focused on in this paper. Moreover, since fast combustion leads to expand the lean limit, combustion technologies such as the high-tumble and the high energy ignition system are also focused on. In regard to mitigating knocking, cooled EGR is applied to lean burn because it is confirmed that cooled EGR has an effect of mitigating knocking not only the condition where the engine is run at excess air ratio of 1 but also the condition where the engine is run under lean condition.

TEST ENGINE

It is known that the low S/V ratio leads to enhance engine thermal efficiency [8], the long stroke engine design is investigated in this paper. To confirm the effect of the long stroke design on the decrease in cooling heat loss, studies with single cylinder engines which have a different stroke length and a different bore diameter and engines which have already sold in the market are conducted. The compression ratio of all engines is unified to 13:1. Black dots in figure 3 show the stroke length and the bore diameter of the single cylinder engines and white dots shows the engines which have been sold in the market. The maximum stroke bore ratio is restricted to around 1.5 because the engine output power decreases over 1.5 due to the limitation of an engine speed and a valve size.

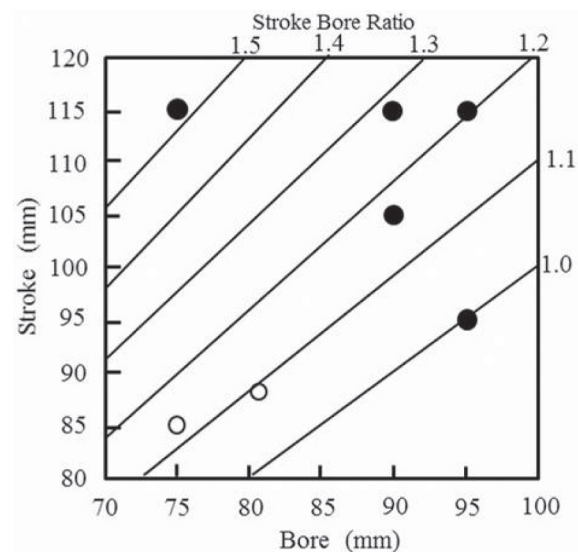


Fig.3. Bore and Stroke of single cylinder engines

Since it is confirmed that the long stroke design has two major factors to enhance engine thermal efficiency, a prototype engine which has the stroke bore ratio of around 1.5 is used. One factor is that the long stroke engine leads to low S/V ratio which has an effect of decreasing cooling heat loss and another factor is the enhancement of combustion. In addition to the long stroke design, a high tumble port is adopted to enhance combustion. Table 1 shows the engine specification and figure 4 shows the outline view of the prototype engine.

Table 1. Engine specifications

Cylinder	L4
Bore x Stroke	75 x 113 (St/B=1.51)
Displacement	1997cc
Compression ratio	13.0: 1
Tumble number	3.6
Fuel supply	Direct Injection + PFI
Piston	Cylindrical surface shape

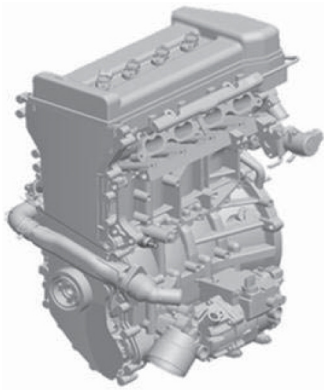


Fig.4. Outline View of Prototype Engine

TEST RESULTS AND DISCUSSION

Effect of Long Stroke Design

It is considered that the long stroke design has two effects on enhancing engine thermal efficiency. One effect is to decrease the S/V ratio and the other is to increase an air flow and an air turbulence in the combustion chamber. In regard to the S/V ratio, the S/V ratio is calculated by utilizing the CAD. Figure 5 shows the calculated points of the S/V ratio and the contour figure of the S/V ratio in the case of the compression ratio 13:1 against the different bore diameter and the different stroke length. Since the contour figure is calculated by using a small number of data, the accuracy of the line which shows the S/V ratio of 4.5/cm may be lower compared to another two lines. As a whole it can be seen in figure 5, the S/V ratio approximately depends on the stroke length.

Figure 6 shows the test results conducted with single cylinder engines and production engines as shown in figure 3. Vertical axis shows the improving rate of IMEP (Indicated Engine Thermal Efficiency) against the S/V ratio where the basing point is the engine which has the bore diameter of 75mm and the stroke length of 84.7mm. It is confirmed that the low S/V ratio when the stroke length is changed leads to enhance engine thermal efficiency. Since it is confirmed that the long stroke engine design has potential to decrease cooling heat loss, the long stroke concept is applied to the prototype engine as shown in table 1.

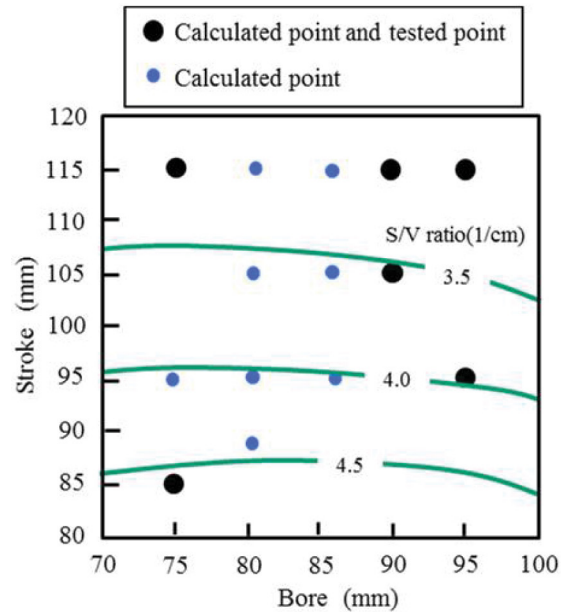


Fig.5. S/V Ratio

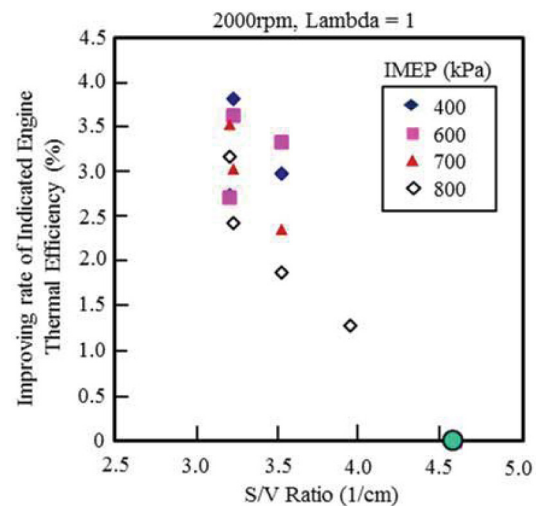


Fig.6. Effect of S/V Ratio on Thermal Efficiency

Combustion Concept for High Engine Thermal Efficiency

Since it is confirmed that the long stroke engine has a potential to enhance engine thermal efficiency, the prototype engine which has the long stroke length is used to realize more than 45% engine thermal efficiency. As described in the previous part, one effective combustion system to enhance engine thermal efficiency is lean burn. However, an issue of lean burn is NOx emission. As for the enhancement of combustion, low temperature combustion to decrease cooling heat loss and reduce NOx should be considered. In this study, homogeneous lean burn is adopted from the viewpoint of NOx emission.

Homogeneous Lean burn

In regard to the lean burn concept, NO_x emission is an important factor for meeting the emission regulations. Figure 7 shows the estimation of NO_x emission [9] against the air-fuel ratio. It can be seen that homogeneous lean burn is the most effective way to reduce NO_x emission.

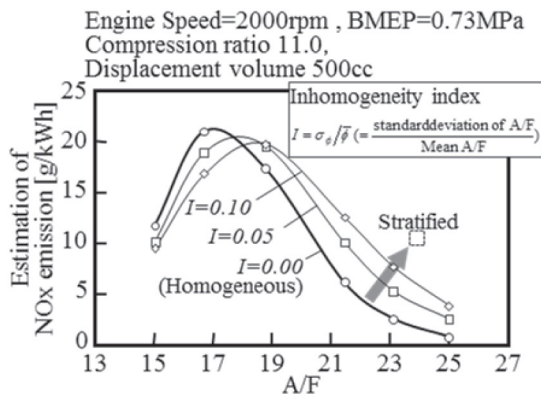


Fig.7. Tendency of engine exhaust NO_x emission

Figure 8 shows the NO_x emission of past production engines and an in-house experimental engine. In this figure, results of three different combustion systems are illustrated and it can be found that weakly stratified lean burn gives the lowest NO_x emission. These results support the analysis in figure 8. Therefore the homogeneous lean burn concept is adopted in this study.

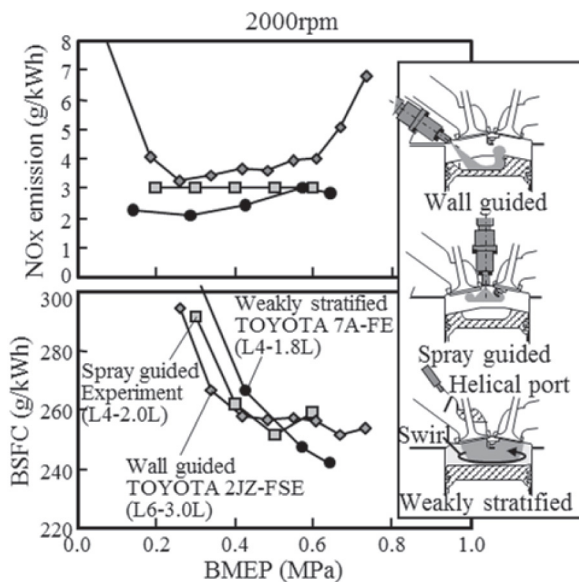


Fig.8. Relationship between BSFC and NO_x emission

Air Flow and Air Turbulence in Combustion Chamber

As for combustion, a lot of fundamental studies have been reported [10, 11]. Some studies indicate that the higher air turbulence promotes combustion. It is also proven that the air turbulence is essential to enhance homogeneous lean burn from past engine tests [9]. In addition to the high tumble port which helps enhance the air

flow and the air turbulence in the combustion chamber, the effect of the long stroke design is also focused on. In this section, the results of the calculated air flow and air turbulence are described. Then the measured results are also described.

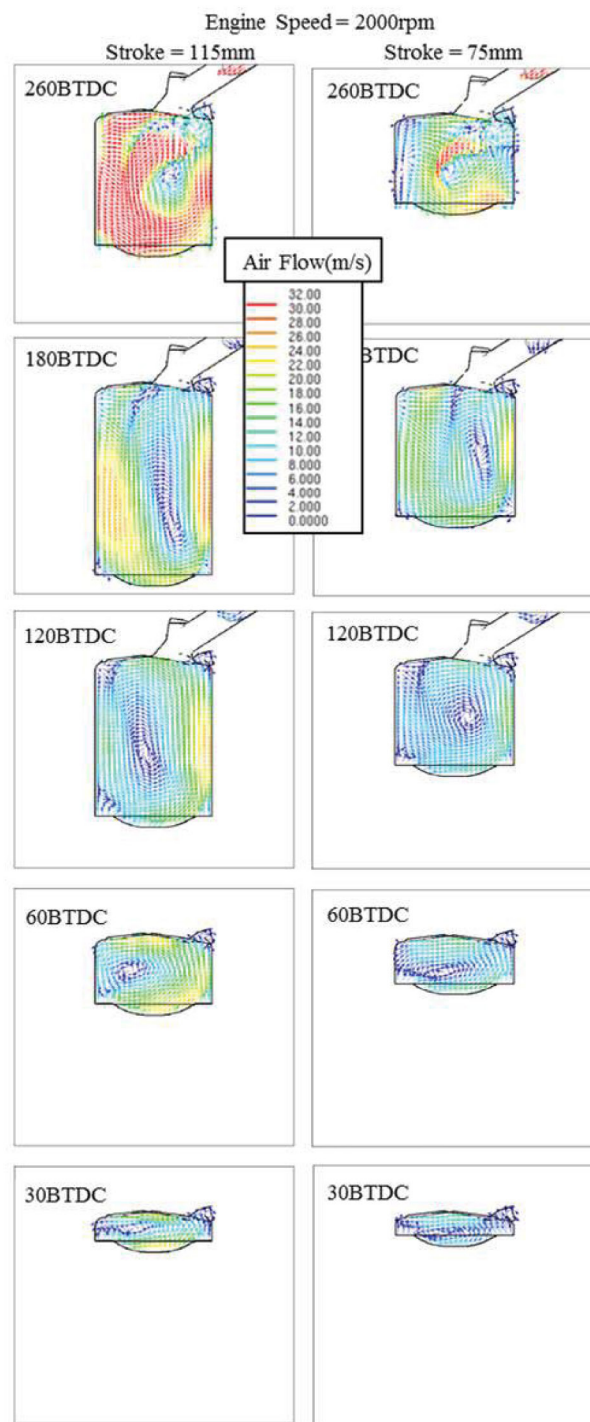


Fig.9. Effect of Stroke Length on Air Flow

Figure 9 shows one example of the effect of the stroke length on the calculated air flow at 2000rpm by using STAR-CD. In these calculations, the bore diameter is 75mm and the shape of intake port

is same for both cases. The tumble number is 3.6. It can be seen that the longer stroke length gives higher air flow. This is because the longer stroke length gives faster piston speed which generates higher air flow. The air flow is around 20m/s at 30 deg BTDC in the case of the stroke length of 113mm. The result indicates that the air flow is around 20m/s at the ignition timing when the prototype engine is run under the lean burn condition.

Figure 10 shows the effect of the stroke length on the air turbulence at 30 deg BTDC. This result is also calculated by using STAR-CD. Figure 11 shows the comparison of the maximum value of the averaged air turbulence during the intake stroke. The calculated results show that the longer stroke engine design has the higher air turbulence. To confirm the calculated results, the air turbulence is measured by using a hot-wire anemometer made by KANOMAX.

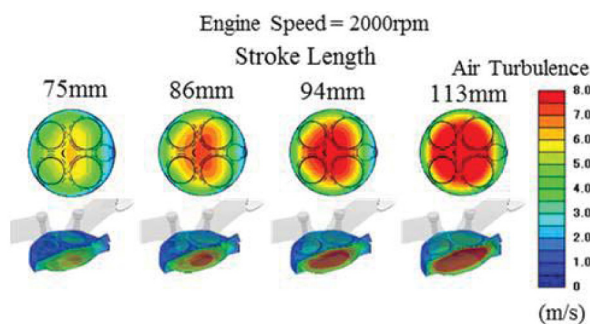


Fig.10. Effect of Stroke Length on Air Turbulence at 30 deg BTDC

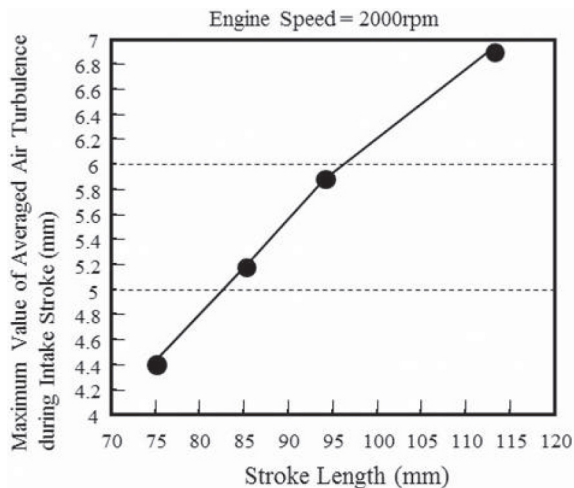


Fig.11. Effect of Stroke Length on Air Turbulence during Intake Stroke

Figure 12 shows the result of the measured air turbulence. For measuring the air turbulence, the prototype engine and modified production engines are used which are dotted as points in figure 12. The tumble number of each engine is from 3.5 to 3.6. It is confirmed that the long stroke engine enhances the air turbulence in the combustion chamber and the order of the air turbulence is similar to the calculated results.

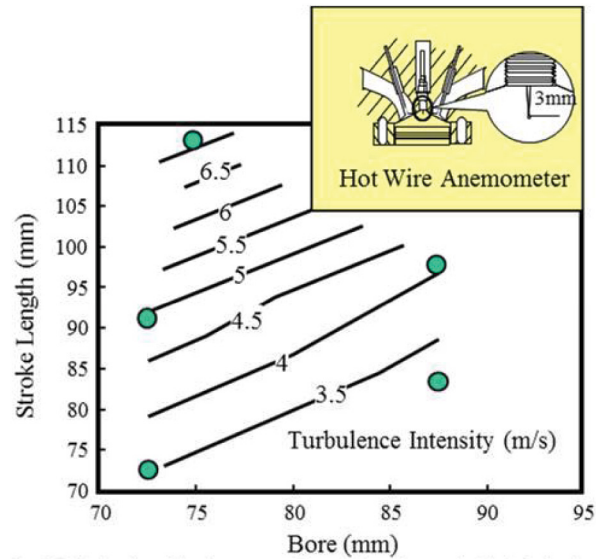


Fig.12. Relationship between Bore, Stroke and Air Turbulence

Effect of Discharge Current

As described in the previous part, the strong air flow and the strong air turbulence are essential to enhance combustion, especially for lean burn. In this study, the methods to strengthen the air flow and the air turbulence are the long stroke concept and the high tumble port.

When the air flow is enhanced in the combustion chamber, the specification of ignition system should be considered [9]. In this paper, preliminary studies are conducted to confirm the relationship between the air flow, the discharge current, the discharge duration, and the flame growth. Figure 13 shows the outline drawing of the experimental apparatus for the preliminary studies. A rotary controls the air flow speed in the combustion chamber and the pressure of the air-fuel mixture is kept 0.6MPa until the spark timing. Propane is used as a test fuel. To confirm the effect of the discharge characteristics, the discharge current and the discharge duration are changed by changing the air flow in the combustion chamber.

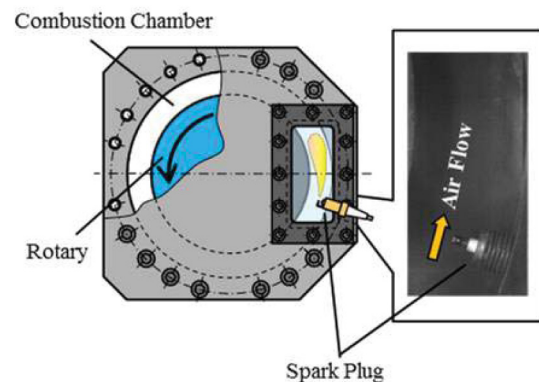


Fig.13. Experimental Apparatus

Figure 14 shows the relationship between the discharge characteristics and the flame area when the air flow is 10m/s. The flame area is measured after 1.5ms after the spark timing. As it can be