

Evaluation of Engine Performance and Combustion in Natural Gas Engine with Pre-Chamber Plug under Lean Burn Conditions

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ABSTRACT

Engines using natural gas as their main fuel are attracting attention for their environmental protection and energy-saving potential. There is demand for improvement in the thermal efficiency of engines as an energy-saving measure, and research in this area is being actively pursued on spark ignition engines and HCCI engines. In spark ignition gas engines, improving combustion under lean condition and EGR (exhaust gas recirculation) condition is an issue, and many large gas engines use a pre-chamber. The use of the pre-chamber approach allows stable combustion of lean gas mixtures at high charging pressure, and the reduction of NOx emissions. In small gas engines, engine structure prevents the installation of pre-chambers with adequate volume, and it is therefore unlikely that the full benefits of the pre-chamber approach will be derived. However, recent research on pre-chamber plugs suggests that the pre-chamber combustion approach extends the lean limit even when fuel is not supplied to the pre-chamber, and that this limit is not particularly dependent on the large volume of the pre-chamber. This study, therefore, focused on specifications such as pre-chamber orifice diameter and number of orifices, with a view to reducing NOx emissions and improving efficiency in small engines with this type of pre-chamber structure and examined the reasons why the lean limit is extended in pre-chamber systems with no fuel-supply mechanism.

Even in a combustion chamber with a small diameter, it is possible to shorten the combustion period using the jets of a pre-chamber plug. Placing the sparking position in the pre-chamber close to the orifices extends the lean limit. This is likely to be due to the way residual gas in the pre-chamber and new gas mixed. Residual gas, flow, atmospheric temperature and other factors influence ignition in the pre-chamber, but it was thought likely that ambient temperature in side of the pre-chamber in particular contributed to ignition and had an effect on combustion stability under lean condition. It was therefore decided to evaluate this factor using pre-chamber plugs made of three materials with different thermal conductivity: stainless steel, steel, and aluminum. Also the temperature in the pre-chamber of the pre-chamber plug was measured. Reducing the thermal conductivity of the material of which the pre-chamber is made increases the temperature in side of the pre-chamber and stabilizes the jets, shortening early-phase combustion and extending the lean limit. Furthermore one of the lowest thermal conductivity materials which are ceramic was tried to evaluate.

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INTRODUCTION

There is renewed interest in the potential of natural gas, owing to its low CO₂ emissions per heat value, and by the development of techniques for the exploitation of shale gas, etc. It is also important that the thermal efficiency and performance of gas engines that run on natural gas be enhanced. The generating efficiency of large stationary gas engines is more than 50%, and progress is being made in the reduction of emissions through the attachment of exhaust after-treatment devices. However, the generating efficiency of small

gas engines with an output of 100kW or less is around 34%, and the scope for improving their performance is considerable. The Japan Gas Association aims to raise the efficiency of this class of engine to 40% or more. This will involve extending the lean limit and supercharging. A variety of research is under way with a view to enhancing combustion stability under lean conditions. For example, supercharging has been combined with HCCI combustion to achieve more than 43% efficiency. Dual-fuel combustion, which involves direct injection of a small pilot oil for total calorific value, is also expected to achieve high

thermal efficiency. However, controlling ignition timing is an issue in HCCI, while NO_x emissions under high loads and unburned hydrocarbon emissions under low loads are issues in dual-fuel combustion. The authors found that the configuration of the pre-chamber in large pre-chamber type gas engines can result in a significant improvement in combustion. A pre-chamber can be fitted to small gas engines, but constraints on the dimensions of the pre-chamber and the need to supply fuel to the pre-chamber make this difficult.

This study, therefore, focused on pre-chamber plug which achieve results close to those obtained with the pre-chamber system by a relatively simple method. It was also likely to be possible to adopt existing gas engines.

TEST ENGINE AND METHODOLOGY

Table 1 shows the specifications of the test engine used in this study. The engine was a 4-cycle diesel engine of which the cylinder head was modified to convert it to spark ignition.

Figure 1 is a schematic diagram of the experimental setup. The fuel used was 13A natural gas supplied as city gas (45MJ/m³, typical composition: CH₄ 88.9%, C₂H₆ 6.8%, C₃H₈ 3.1%, C₄H₁₀ 1.2%) and a constant supply was ensured by installing a venture mixer upstream from the intake port.

Table 1. Engine specifications.

Engine type	Single cylinder
Displacement (cm ³)	550
Stroke (mm)	96.9
Bore (mm)	85.0
Compression ratio	12.0:1
Number of Valves	4
Engine speed (rpm)	1200

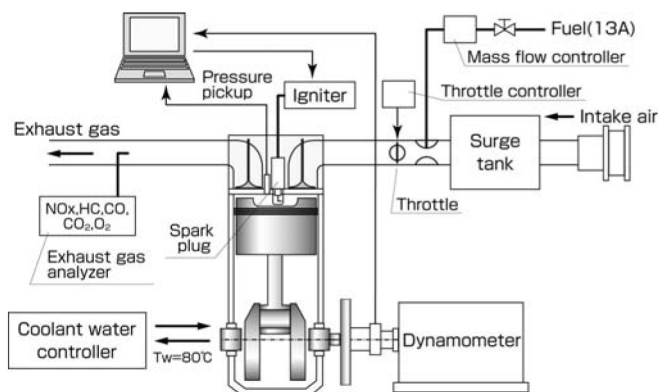


Figure 1. Schematic diagram of experimental setup.

Figure 2 is a schematic diagram of the pre-chamber plug. A spark plug (NGK ER9EH) with a thread diameter of M8 and a plug socket with a thread diameter of M12 was fitted. The electrode of the spark plug was longer than that of a

conventional plug, so that it protruded beyond the surface of the cylinder head. Table 2 shows the specifications of the pre-chamber plug. The operating conditions were 1200 rpm and a constant fuel flow rate (0.64 Nm³/h: equivalent to an indicated mean effective pressure of around 500 kPa). The variance of air excess ratio λ was controlled by adjusting the airflow rate using a throttle valve. Operating conditions were defined as a coefficient of variance of indicated mean effective pressure ($COV_{(IMEP)}$) of 5% or less and zero misfires per 1,200 cycles (indicated mean effective pressure of 100 kPa or lower).

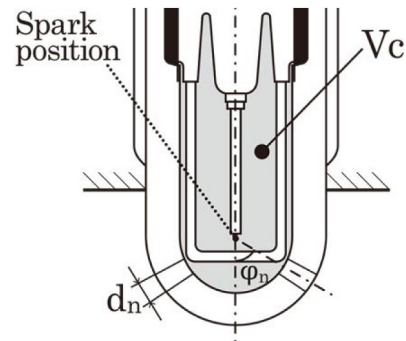


Figure 2. Schematic diagram of pre-chamber plug.

Table 2. T Pre-chamber specifications.

Number of orifices (n)	5
Diameter of orifice s(dn)[mm]	1.2
Angle of orifice axis (ϕ n)[°]	60
Pre-chamber volume (Vc)[mm ³]	400

Experiment Results and Discussion

Determining the Basic Characteristics of the Pre-Chamber Plug

The basic characteristics of a pre-chamber plug were determined using a standard spark plug, as shown in the left-hand drawing of Figure 3, and a pre-chamber plug as shown in the right-hand drawing. Figure 4 shows the cumulative heat release rate (Q_t) at the same air excess ratio and ignition timing for the pre-chamber plug and conventional plug. With the pre-chamber plug, the increase in heat release rate begins earlier and combustion duration, defined as the period between the time when heat release reaches 10% of total heat release for 200 cycles and the time when it reaches 90% (θ_{10-90}), is shorter. Figure 5 shows the relationship between air excess ratio and coefficient of variance of indicated mean effective pressure ($COV_{(IMEP)}$). At the same λ , the pre-chamber plug showed a smaller $COV_{(IMEP)}$ than the conventional plug, and the lean limit was extended. It was therefore decided, with a view to reducing combustion fluctuation and misfires under even leaner conditions, to examine the effect of pre-chamber plug specifications and in-cylinder flow on combustion and engine performance.

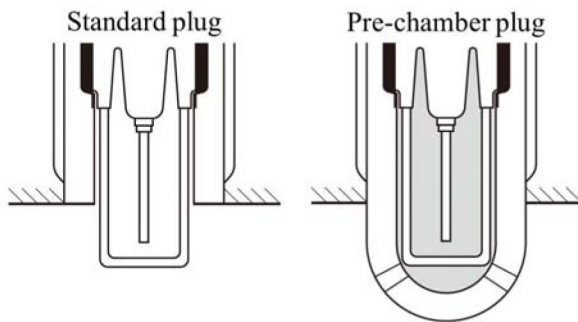


Figure 3. Schematic diagrams of standard plug and pre-chamber plug.

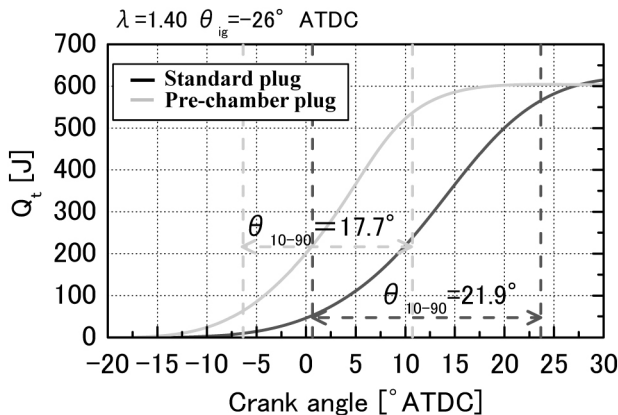
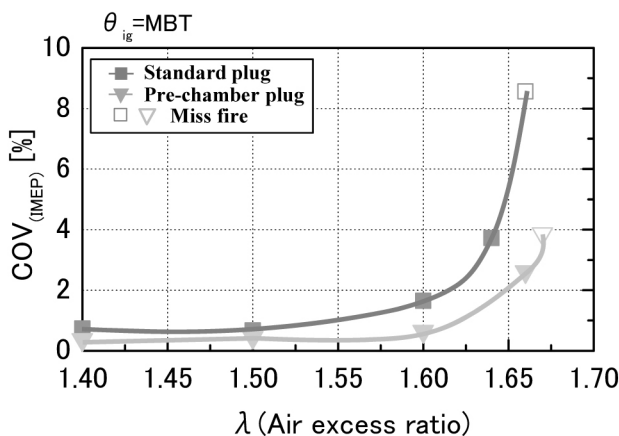


Figure 4. Effect of pre-chamber plug on heat release.

Figure 5. Effect of pre-chamber plug on $COV_{(IMEP)}$.

Improving Sparking Position in the Pre-Chamber

It has been reported that sparking position in the pre-chamber has an effect on combustion [2] [4]. This is likely to be because the residual gas in the pre-chamber and the gas mixture taken into the cylinder that flows into the pre-chamber through the pre-chamber orifice during the compression phase do not mix well and become stratified, and because combustion in the pre-chamber has an effect on combustion fluctuation in the main chamber. In the case of a pre-chamber plug for a small gas engine, it was decided to begin to research about the issue of improving the sparking position in the pre-chamber. The

sparkling position in the pre-chamber plug was altered, as far as possible without changing the volume of the pre-chamber. Figure 6 is a schematic diagram of a pre-chamber plug based on a standard plug of which the central and side electrodes have been extended, and a pre-chamber plug based on a standard plug.

Figure 7 shows the relationship between the coefficient of variance of indicated mean effective pressure and air excess ratio (λ). When the degree of protrusion of the plug electrodes was reduced, misfire cycles occurred at low λ . In this case the lean limit was become low λ . It has been reported that fluctuation during the early phase of combustion affects combustion as a whole, as well as lean limit and combustion stability [5], and it is likely that instability in the early phase of combustion leads to misfires.

Figure 8 shows the distribution of IMEP over 1,200 cycles. The graphs on the left show the results for short electrodes; the graphs on the right show the results when electrodes were extended. The graphs in the top row show the results for air excess ratio $\lambda = 1.4$, at which combustion is stable; the graphs in the middle row show the results at the lean limit (not including misfire cycles); and the graphs in the bottom row show the results for conditions where misfire cycles accounted for 20% or more of the total. Even under lean conditions, when the electrodes were short, the range of IMEP distribution was narrow, and misfire cycles ($IMEP = 0 \text{ kPa}$) occurred. Especially, under conditions where misfire cycles accounted for 20% or more of the total, two peaks in IMEP distribution occurred between 500 kPa and 600 kPa. Misfires under these conditions were accompanied by no heat release whatsoever, and the IMEP during the next cycle was high. It is likely that unburned fuel from the misfire in the main chamber remained in the cylinder, and was burned during the next cycle. When the plug electrodes were long, the range of IMEP distribution was broader, and misfires occurred afterwards. These misfire cycles included many cycles during which heat release occurred ($IMEP \leq 100 \text{ kPa}$). In other words, when the plug electrodes were short, only misfire cycles during which IMEP could not be detected occurred, and the misfire took place in the pre-chamber. By contrast, when the electrodes were long, there were cycles during which IMEP was detected but a misfire occurred. It is likely that combustion occurred in the pre-chamber at least, but that combustion in the main chamber was incomplete. These results suggest that, in the case of the pre-chamber plug of a small gas engine also, residual gas in the pre-chamber and fresh gas mixture flowing into the pre-chamber through the orifice fail do not mix well and become stratified, and that placing the sparking position further inside the pre-chamber will, by ensuring ignition and combustion in an atmosphere where the ratio of fresh gas mixture is higher, reduce combustion fluctuation in the lean zone where the air excess ratio is high.