

Knocking Mitigation of Gasoline Engine by Reduction of Unburned Area Using Pre-chamber Jet Combustion

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ABSTRACT

Analysis was conducted of knocking mitigation when using passive pre-chamber jet combustion as compared to a gasoline engine with stoichiometric spark ignition combustion. Jets emitting from the pre-chamber enabled the propagation flame to rapidly reach the bore end, shortening the combustion duration. This reduced the unburned area of end-gas in the latter half of combustion and mitigated knocking. It was also shown that by creating more nozzles and thus increasing the number of jets, the unburned field is partitioned and made smaller, which suppresses auto-ignition and mitigates knocking. It was confirmed that setting specifications to maximize the knocking mitigation effect and thermal efficiency can raise the compression ratio by 1.8 and increase thermal efficiency by 1.1 pts.

1. Introduction

Countries around the world are stepping up their efforts to become carbon neutral. Under the scenario where an increase in temperature caused by climate change is kept below 1.5°C, it will be necessary to reduce emissions of the greenhouse gas CO₂ by at least 45% in 2030 as compared to 2010⁽¹⁾. To that end, increasing the thermal efficiency of internal combustion engines is an effective way of reducing CO₂ emissions.

In gasoline spark ignition (SI) combustion, the ignition timing needs to be retarded more than the minimum advanced for best torque (MBT) in order to help avoid knocking. This increases time loss and is an issue in the effort to increase thermal efficiency. The retarding of ignition timing leads to lower thermal efficiency in the normal load zone, and because it is necessary to suppress increases in exhaust gas temperature at the output point, it leads to lower output. For the sake of maintaining output, fuel enrichment has been used to date to protect the exhaust system, however this increases CO emissions. Because nations are adopting Real Driving Emissions (RDE) legislation, regulations on CO emissions are being strengthened. Moreover, RDE legislation going forward is likely to ban the use of fuel enrichment itself. Therefore, it will not be easy to maintain output as in the past. As the above indicates, knocking mitigation is key to increasing

thermal efficiency and output, lowering CO emissions, and conforming to RDE legislation.

As countermeasures, methods are being attempted that use pre-chamber jet combustion and, with the discharging jets, increase turbulence kinetic energy on the flame propagation side and shorten combustion duration to mitigate knocking⁽²⁾⁻⁽⁴⁾. Many case studies have been reported of using pre-chamber jet combustion in order to stabilize lean-burn SI combustion, which has a tendency to be sluggish⁽⁵⁾⁻⁽⁷⁾. As for gasoline stoichiometric SI combustion, there are case studies that analyzed the knocking mitigation effect when trying to increase the compression ratio⁽²⁾⁻⁽⁴⁾, but those studies do not have any detailed pre-chamber jet combustion status analysis. Because the jets of combustion gas ejected from the many nozzles exhibit complex combustion forms, there are many unknowns about the effect pre-chamber jet combustion has on knocking and its auto-ignition behavior inside the cylinder. To establish the specifications of pre-chamber jet combustion, it is necessary to elucidate these phenomena.

This research clarified phenomena relating to pre-chamber jet combustion knocking mitigation in gasoline stoichiometric SI combustion. It also used the knocking mitigation effect of pre-chamber jet combustion to study the effect of increasing the compression ratio to increase thermal efficiency.

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2. Principle of Pre-chamber Jet Combustion

This research used pre-chamber jet combustion with a passive pre-chamber⁽²⁾⁻⁽⁴⁾. A passive pre-chamber is a pre-chamber with no interior fuel injection nozzles. Rather, the air-fuel mixture is ingested from the main-chamber side. An illustration of the passive pre-chamber jet combustion chamber used in this study is provided in Fig. 1.

In the passive pre-chamber, the pressure differential between the main chamber and pre-chamber during engine compression stroke is used to bring the air-fuel mixture of the main chamber into the pre-chamber. A spark plug in the pre-chamber then ignites the air-fuel mixture and the subsequent rise in pre-chamber pressure causes hot burned gas and unburned gas to be ejected from the pre-chamber nozzle holes⁽⁴⁾. This increases the ignition surface area of the main chamber air-fuel mixture and the turbulence kinetic energy on the main chamber flame surface, enabling rapid combustion.

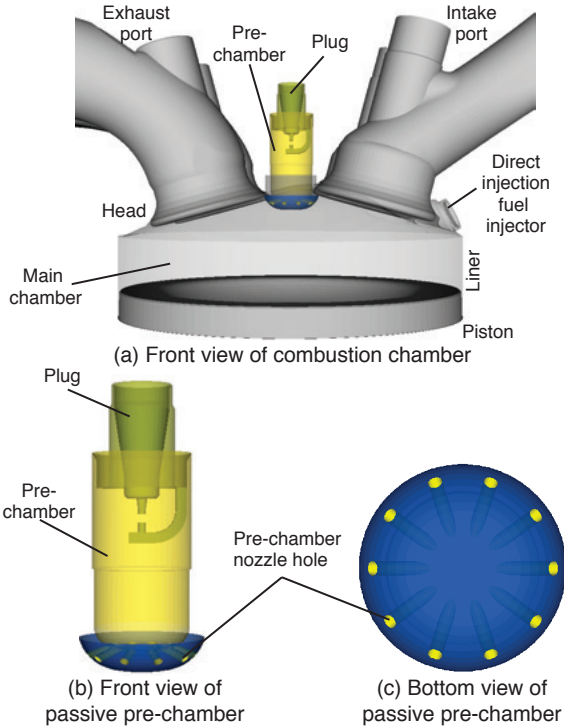


Fig. 1 Schematic diagram of combustion chamber and passive pre-chamber

3. Knocking Analysis Method

3.1. Test Engine and Evaluation Load

For the analysis, a pre-chamber was added to a single-cylinder engine that was developed based on mass-production 1.5 L direct injection turbo inline four-cylinder specifications. Specifications of the engine used for the analysis are provided in Table 1.

Table 1 Test engine specifications

Number of cylinders	1
Displacement volume [cm ³]	374.5
Bore [mm]	73
Stroke [mm]	89.4
Compression ratio	10.6 (base), 12.4
Valve system	DOHC 4-valve
Intake port tumble ratio	1.8
Fuel injection system	Direct injection (Injection pressure: 10 [MPa])
Fuel	Japanese regular gasoline (Research octane number: 91)
Ignition system	Direct ignition (Ignition energy: 60 [mJ])
Plug heat value	#8
Pre-chamber specifications	Hole number: 4, 6, 8, 10, 12
	Hole diameter [mm]: 0.3, 0.4, 0.5, 0.65, 0.8, 0.95
	Volume [cm ³]: 0.42, 0.52, 0.83, 1.12, 1.36, 1.92
Boost device	Super charger

In pre-chamber jet combustion, nozzle hole (hereinafter, hole) diameter and pre-chamber volume are involved in jet penetration (hereinafter, penetration)⁽⁴⁾ and it is believed that the number of holes is involved with the partition state of unburned area inside the cylinder. Analysis was therefore conducted as below using these as design variables for the pre-chamber specifications, as shown in Table 1.

The evaluation load point was set at an engine speed of 2,000 rpm and indicated mean effective pressure (IMEP) of 1,300 kPa (fuel injection of 30 mg/st per cycle per cylinder), conditions under which the time loss caused by the knocking limit becomes an issue.

3.2. Computational Technique

To analyze both the knocking mitigation effect of pre-chamber jet combustion and the phenomenon, testing was done on actual equipment, and phenomenon analysis was also conducted of the combustion by computational fluid dynamics (CFD). Combustion CFD was performed using Convergent Science's 3D-CFD software CONVERGE 3.0.14. An overview of the computational model is given in Table 2.

Here, the Extended Coherent Flame Model (ECFM)⁽⁸⁾ was used as the combustion model. In this model, flame propagation combustion is calculated using a flame surface density equation. Also included in this approach are the Tabulated Kinetics of Ignition (TKI) model, which uses various parameters to express auto-ignition in a table, as the auto-ignition model⁽⁹⁾ and the Imposed Stretch Spark Ignition model (ISSIM), which models the ignition circuit and ignition part combustion

Table 2 Calculation software and model

CFD software	CONVERGE v3.0.14
Turbulence model	RNG k- ζ -f
Spray model	Kelvin-Helmholtz and Rayleigh-Taylor
Combustion model	Extended Coherent Flame Model
Ignition model	Imposed Stretch Spark Ignition
Auto-ignition model	Tabulated Kinetics of Ignition
Fuel	Regular gasoline

gas, as the ignition model⁽⁹⁾. This model makes it easy to analyze combustion parameters of flame propagation combustion and can also isolate auto-ignition combustion for analysis. This makes it a good model for analyzing SI combustion, which consists of both flame propagation combustion and auto-ignition combustion. The reproducibility of conventional SI combustion and pre-chamber jet combustion with this model has been confirmed⁽⁹⁾.

Details of the combustion model are shown in Fig. 2. The propagation flame combustion rate (OMEGA_CFM) indicates the unburned fuel chemical reaction speed on the flame propagation reaction surface, while the auto-ignition combustion rate (OMEGA_TKI) indicates the unburned area's auto-ignition reaction speed. In this research, the effect that changing the various pre-chamber jet parameters has on flame propagation is evaluated by OMEGA_CFM and the effect it has on auto-ignition is evaluated by OMEGA_TKI.

3.3. Knocking Judgment Method

The conventional method of judging knocking is to calculate a Fourier transform of the pressure as measured

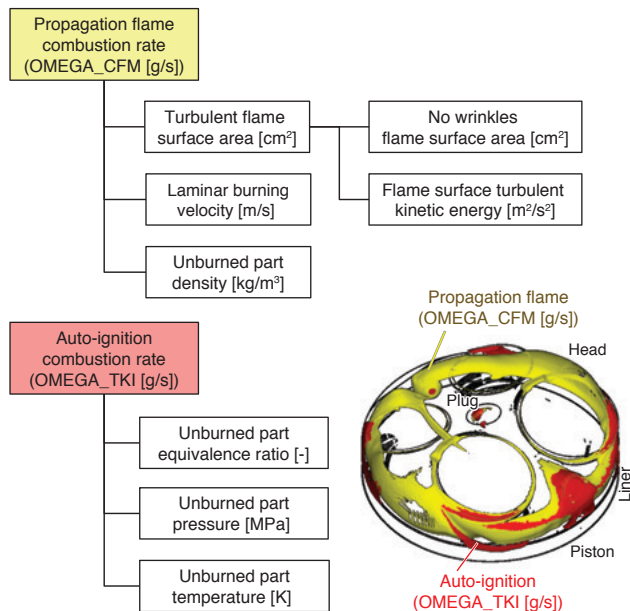


Fig. 2 Factor analysis of flame propagation combustion and auto-ignition combustion

inside the cylinder and then use band-pass filtering, after which knock intensity (KI), the difference between the maximum and minimum values of pressure amplitude, is calculated⁽¹⁰⁾. Then, after ignition timing characteristics are measured, the combustion timing at which KI suddenly changes is found and the knocking limit combustion timing is judged.

For analyzing pre-chamber jet combustion by CFD, this research devised a new knocking judgment method using CFD calculation results. Because knocking is so closely related to auto-ignition of unburned area of end-gas in the latter half of combustion⁽¹¹⁾, the research team believed it could judge knocking based on the auto-ignition combustion rate calculated by CFD. An overview is given in Fig. 3. Figure 3(a) shows combustion over time and how the auto-ignition combustion rate approaches the peak. This peak value is defined as the maximum auto-ignition combustion rate (OMEGA_TKI_max). The results for OMEGA_TKI_max at the time when the ignition timing shown in Fig. 3(b) is changed confirm the behavior such that the combustion center of gravity timing (Mass Fraction Burned 50%: MFB 50%) is advanced and OMEGA_TKI_max is increased. Therefore, it seems possible to estimate knocking limit MFB 50% by setting a fixed threshold for OMEGA_TKI_max. When actual equipment with the various combustion specifications used as parameters was compared to the CFD knocking limit in pre-chamber jet combustion, OMEGA_TKI_max 1.5 g/s was used as the knocking threshold for the

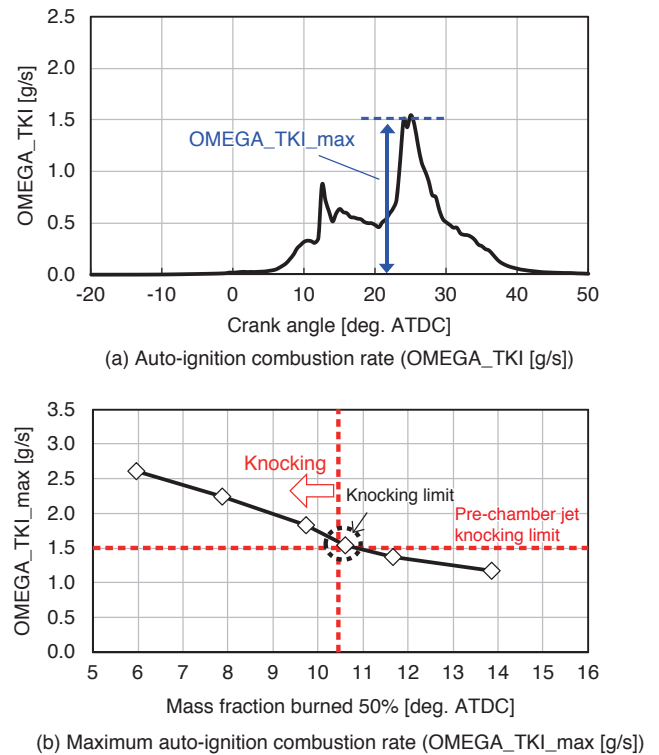


Fig. 3 Knocking judgment method by CFD auto-ignition observation in pre-chamber jet combustion

test engine's evaluation load, which confirmed that there is a correlation between the actual equipment and CFD at knocking limit MFB 50%.

The correlation between actual equipment and CFD at knocking limit MFB 50% in pre-chamber jet combustion when the pre-chamber hole diameter, volume, and number of holes were changed is shown in Fig. 4. Using CFD, this judgment method can estimate the actual equipment's knocking limit MFB 50% with a precision within 0.5 deg., confirming that a judgment method using the auto-ignition combustion rate is valid.

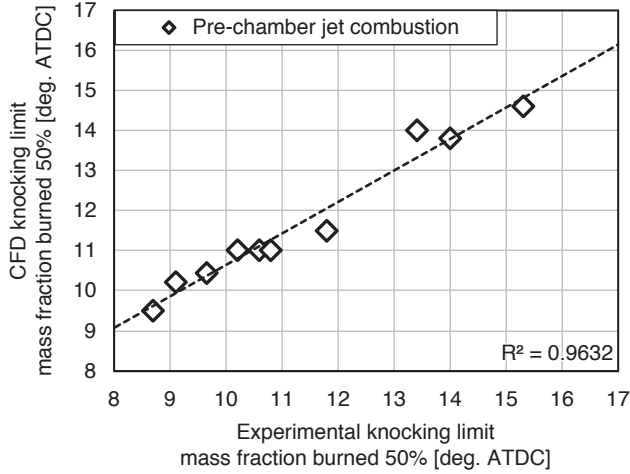


Fig. 4 Knocking limit between experiment and CFD on pre-chamber jet combustion

4. Analysis of Knocking Mitigation Effect

4.1. Pre-chamber Hole Diameter and Knocking

CFD was used to analyze the relationship between pre-chamber hole diameter and knocking. Here, the CFD auto-ignition combustion rate was used to judge knocking and comparisons were made under knocking limit conditions. This comparison makes it possible to observe the auto-ignition phenomenon when knocking is occurring so that the knocking mitigation effect can be quantitatively evaluated. Penetration, as used below, is defined as the distance reached from pre-chamber holes to flame propagation reaction surface, whereas end-gas auto-ignition volume is defined as the value in the range within 10 mm inside the liner wall. Pre-chamber specifications analyzed by CFD are given in Table 3.

The MFB 50% and combustion duration at the knocking limit are shown in Fig. 5. For 1 deg. of shortening of combustion duration, MFB 50% at the knocking limit advances approximately 1 deg. Combustion duration is shortest at hole diameter $\Phi 0.5$ mm, at which time the knocking mitigation effect is greatest. This presumably means that maximizing penetration at $\Phi 0.5$ mm maximizes turbulent flame surface area and minimizes combustion duration, as shown in Fig. 6. Moreover, at $\Phi 0.4$ mm and

Table 3 Pre-chamber jet specifications on CFD

	Pre-chamber jet combustion $\epsilon 10.6$					
Excess air ratio	Stoichiometric					
Pre-chamber hole specification	10 holes, 0.3 mm diameter	10 holes, 0.4 mm diameter	10 holes, 0.5 mm diameter	10 holes, 0.65 mm diameter	10 holes, 0.8 mm diameter	10 holes, 0.95 mm diameter
Pre-chamber volume [cm ³]	0.83	0.83	0.83	0.83	0.83	0.83

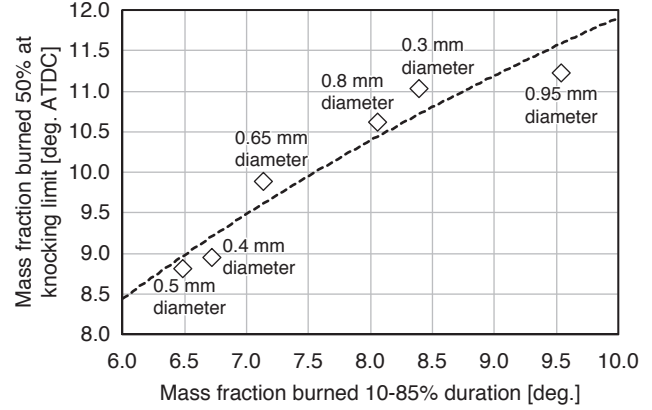
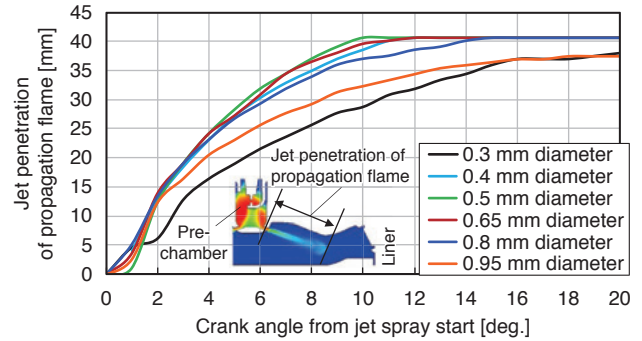
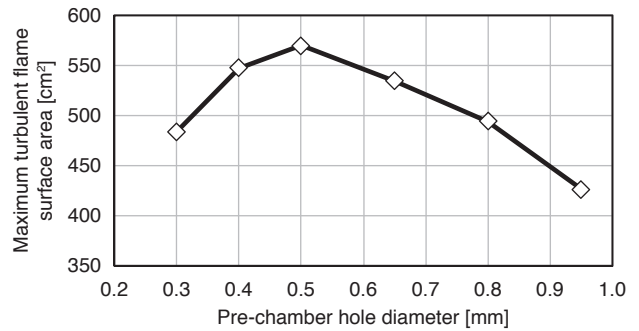


Fig. 5 Effect of pre-chamber hole diameter on knocking by CFD



(a) Relationship between pre-chamber hole diameter and jet penetration of propagation flame



(b) Relationship between pre-chamber hole diameter and maximum turbulent flame surface area

Fig. 6 Effect of pre-chamber hole diameter on jet penetration of propagation flame and maximum turbulent flame surface area by CFD

below, the jet flow volume from the apertures declined, whereas at $\Phi 0.65$ mm and greater, the jet flow velocity from the apertures also declined, presumably indicating that in each case penetration declined and combustion duration increased.

OMEGA_CFM and OMEGA_TKI are shown in Fig. 7. In specifications where knocking was mitigated, ignition timing could be advanced and combustion happened earlier. As Fig. 7(a) shows, the timing at which propagation combustion moved from the peak to the latter half was advanced to 8 deg. ATDC at hole diameter $\Phi 0.5$ mm, in contrast to the 11 deg. ATDC at hole diameter $\Phi 0.95$ mm. Moreover, as Fig. 7(b) shows, auto-ignition combustion started rising in the latter half of propagation combustion and was advanced to 11 deg. ATDC at hole diameter $\Phi 0.5$ mm in contrast to the 14 deg. ATDC at hole diameter $\Phi 0.95$ mm. The subsequent auto-ignition combustion peak was synchronous with the end of propagation combustion and was advanced to 22 deg. ATDC at hole diameter $\Phi 0.5$ mm in contrast to the 27 deg. ATDC at hole diameter $\Phi 0.95$ mm.

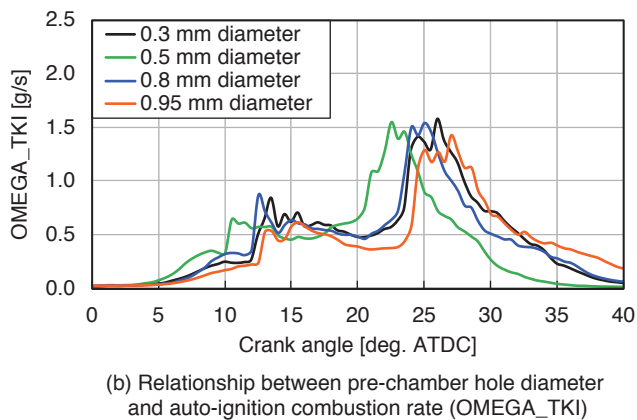
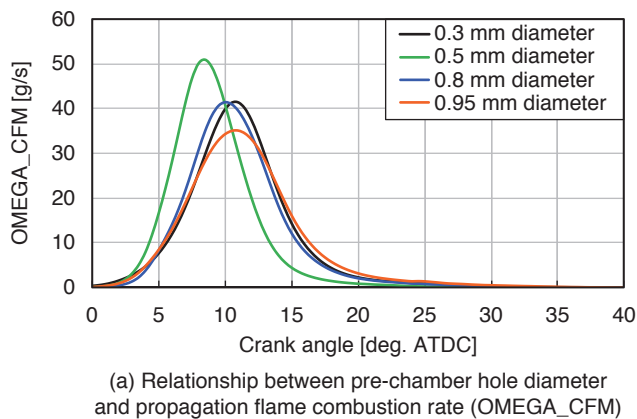


Fig. 7 Effect of pre-chamber hole diameter on relationship between OMEGA_CFM and OMEGA_TKI by CFD

Figure 8 shows an image of the flame while Fig. 9 shows the end-gas auto-ignition volume when OMEGA_TKI rises. Here, at hole diameter $\Phi 0.5$ mm, the time at which OMEGA_TKI rose was the most advanced and the end-gas auto-ignition volume was at its minimum.

These results indicate that extending penetration to produce rapid flame propagation reduces end-gas unburned air-fuel mixture and suppresses auto-ignition.

4.2. Pre-chamber Volume and Knocking

CFD was used to analyze the relationship between pre-chamber volume and knocking. The CFD auto-ignition combustion rate was used to judge knocking and comparisons were made under knocking limit conditions. Pre-chamber specifications analyzed by CFD are given in Fig. 10.

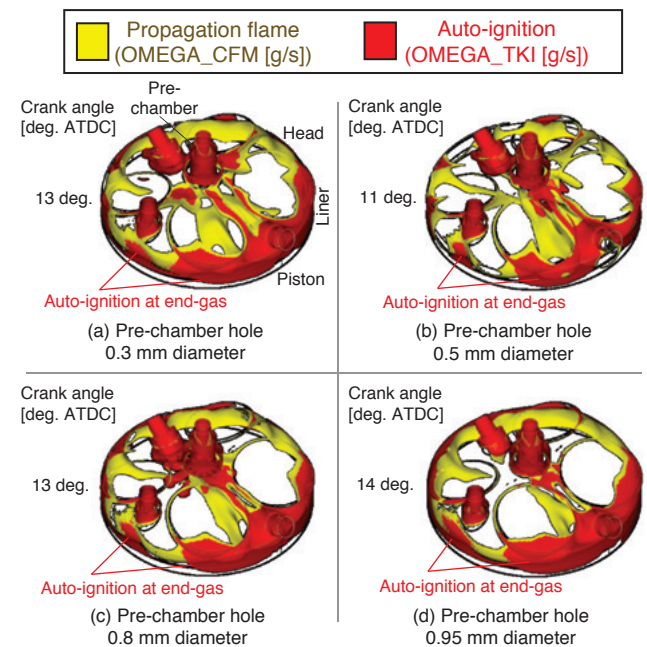


Fig. 8 CFD image analysis of pre-chamber hole diameter

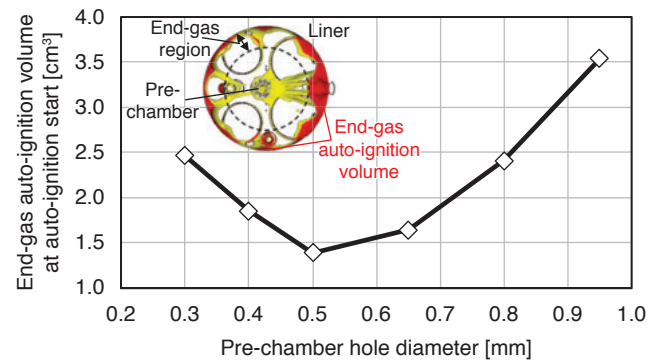


Fig. 9 Effect of pre-chamber hole diameter on end-gas auto-ignition volume by CFD

The combustion duration and MFB 50% at the knocking limit are shown in Fig. 11. For 1 deg. of shortening of combustion duration, MFB 50% at the knocking limit advances approximately 2 deg. Enlarging the pre-chamber volume shortened the combustion duration and increased the knocking mitigation effect. Penetration and maximum turbulent flame surface area are shown in Fig. 12. Enlarging the pre-chamber volume extended penetration and increased turbulent flame surface area. These appear to be factors in shortening combustion duration.

OMEGA_CFM and OMEGA_TKI are shown in Fig. 13. In the same manner as differences in hole diameter, in specifications where knocking was mitigated, ignition timing could be advanced and combustion happened earlier. As Fig. 13(a) shows, expanding pre-chamber volume from 0.52 cm³ to 1.92 cm³ made the timing at which propagation combustion moved from the peak to the latter half advance to 6 deg. ATDC from 11 deg. ATDC. Moreover, as Fig. 13(b) shows, auto-ignition combustion started rising in the latter half of propagation combustion and was advanced to

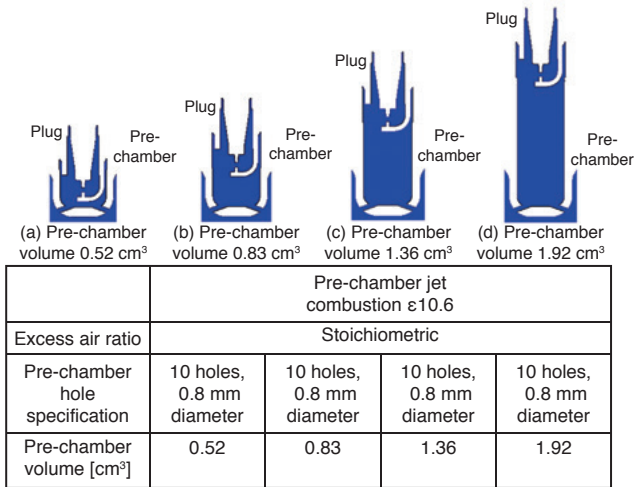


Fig. 10 Pre-chamber jet specifications on CFD

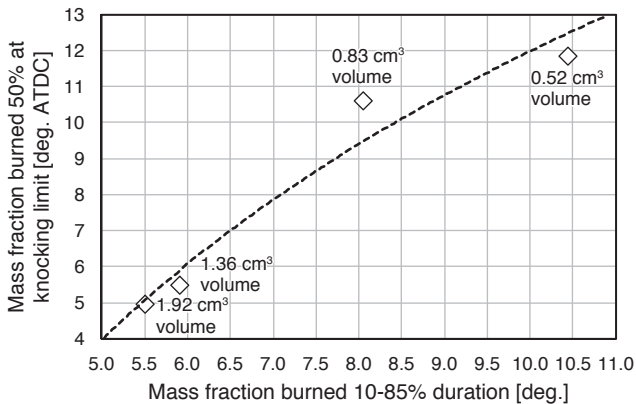
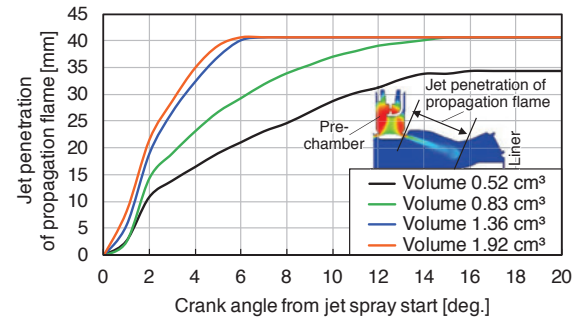
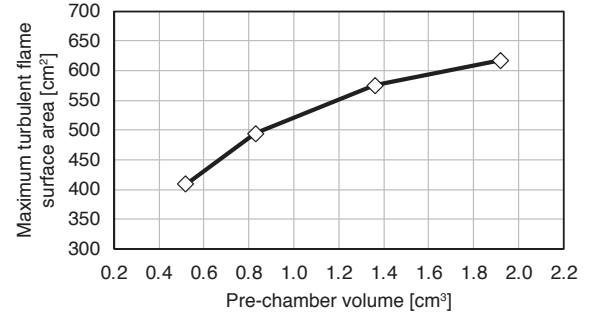


Fig. 11 Effect of pre-chamber volume for knocking by CFD

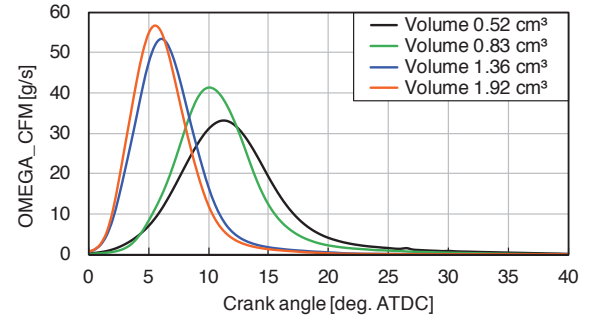


(a) Relationship between pre-chamber volume and jet penetration of propagation flame

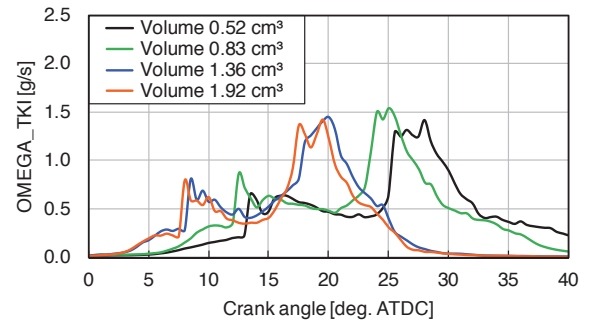


(b) Relationship between pre-chamber volume and maximum turbulent flame surface area

Fig. 12 Effect of pre-chamber volume on jet penetration of propagation flame and maximum turbulent flame surface area by CFD



(a) Relationship between pre-chamber volume and propagation flame combustion rate (OMEGA_CFM)



(b) Relationship between pre-chamber volume and auto-ignition combustion rate (OMEGA_TKI)

Fig. 13 Effect of pre-chamber volume on relationship between OMEGA_CFM and OMEGA_TKI by CFD

8 deg. ATDC from 14 deg. ATDC. The subsequent auto-ignition combustion peak was synchronous with the end of propagation combustion and was similarly advanced to 19 deg. ATDC from 27 deg. ATDC.

Figure 14 shows an image of the flame when OMEGA_TKI rises, while Fig. 15 shows the end-gas auto-ignition volume. It was confirmed that the propagation flame on the high-volume pre-chamber side where combustion duration is short reaches the bore end before auto-ignition of the end-gas and that the auto-ignition area shrinks.

The above indicates that enlarging pre-chamber volume to extend penetration produces rapid flame propagation, reduces end-gas unburned air-fuel mixture, and helps suppress auto-ignition.

However, there will presumably be an increase in pre-chamber heat loss as the surface area inside the pre-chamber grows larger and an increase in main-chamber heat loss as the jet contact surface area on the main-chamber wall increases. Therefore, the effect on heat loss was confirmed in CFD. As Fig. 16 shows, it was confirmed that for a 1 cm³ enlargement of the pre-chamber volume, pre-chamber heat loss increased by approximately 1 pt. and main-chamber heat loss increased by approximately 2 pts. In pre-chamber jet combustion, it is important both to reduce heat loss and shorten combustion duration to mitigate knocking. The results indicate that it is necessary to consider a balance of the two when deciding the volume.

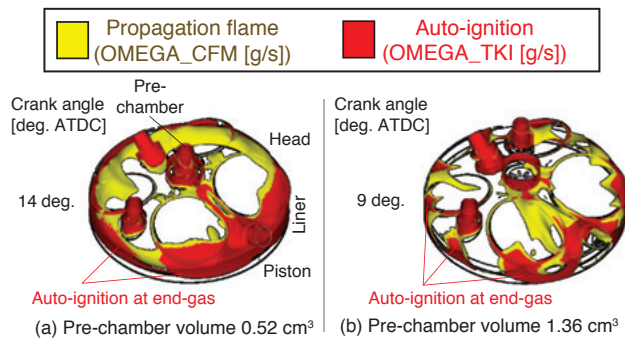


Fig. 14 CFD image analysis of pre-chamber volume

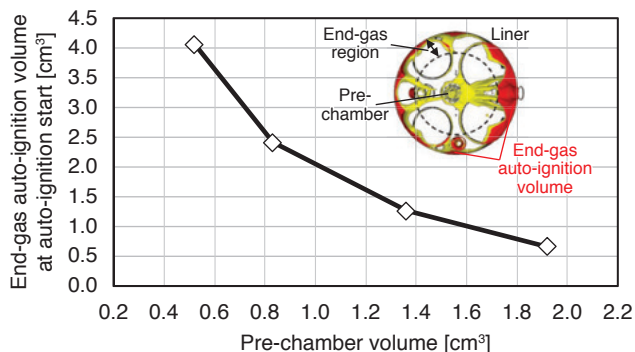


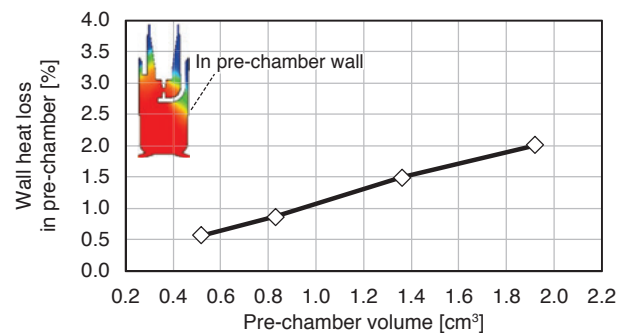
Fig. 15 Effect of pre-chamber volume on end-gas auto-ignition volume by CFD

Table 4 Pre-chamber jet specifications on CFD

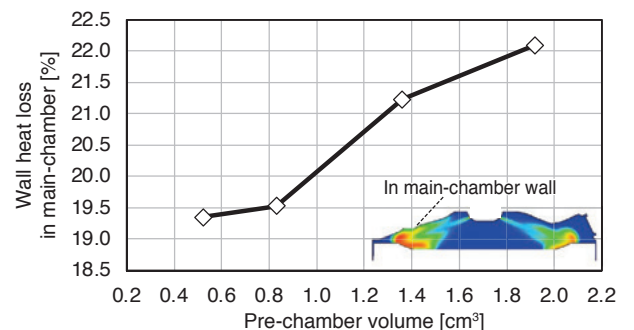
Excess air ratio	Pre-chamber jet combustion $\epsilon 10.6$				
	Stoichiometric				
Pre-chamber hole specification	4 holes, 1.27 mm diameter	6 holes, 1.05 mm diameter	8 holes, 0.9 mm diameter	10 holes, 0.8 mm diameter	12 holes, 0.73 mm diameter
Pre-chamber volume [cm ³]	1.36	1.36	1.36	1.36	1.36

4.3. Pre-chamber Number of Holes and Knocking

In combustion with different numbers of holes in the pre-chamber, as the number of partitions of unburned area by jet will vary, it is anticipated that there will be variations in knocking behavior. Here, CFD was used to analyze the relationship between changes in number of holes in the pre-chamber and knocking behavior. Similarly to what was done before, the CFD auto-ignition combustion rate was used to judge knocking and comparisons were made under knocking limit conditions. To be able to evaluate pre-chamber specifications with different numbers of holes while providing the same amount of jet output, the number of holes and hole diameter were set so that the total surface area of the holes was constant. Table 4 gives the pre-chamber specifications analyzed by CFD, while Fig. 17 gives the combustion duration and MFB 50% at the knocking limit. As the number of holes increases, so does the knocking mitigation effect. Maximum knocking mitigation occurred with 10 holes. When there were more than 10 holes, however,



(a) Wall heat loss in pre-chamber by heat balance analysis



(b) Wall heat loss in main-chamber by heat balance analysis

Fig. 16 Effect of pre-chamber volume on heat loss by CFD

combustion speed declined slightly while knocking limit MFB 50% was largely retarded. Penetration and maximum turbulent flame surface area are shown in Fig. 18. From four to 10 holes, as the number of holes increases, the turbulent flame surface area tends to expand, and the combustion duration tends to shorten. We believe the reason for this is that, although the increase in the number of holes caused penetration itself to decline, the flame surface area expanded with the increasing number of jets.

OMEGA_CFM and OMEGA_TKI are shown in Fig. 19. With 10 holes, at which knocking was mitigated,

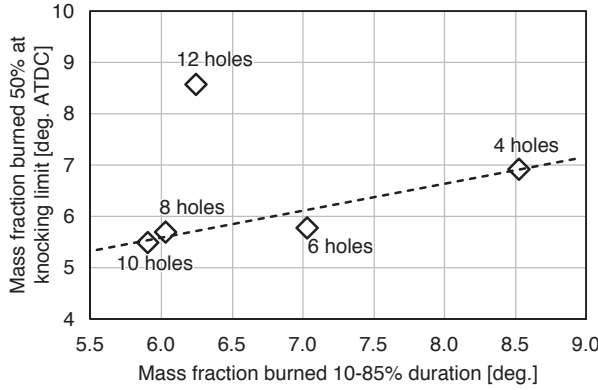
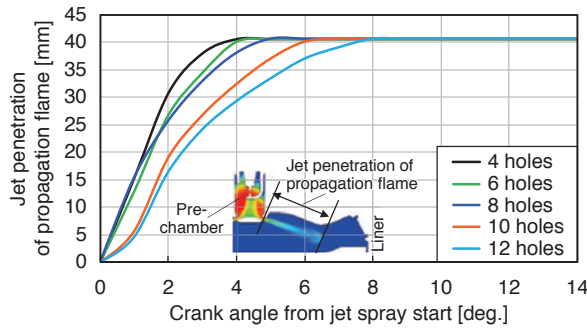
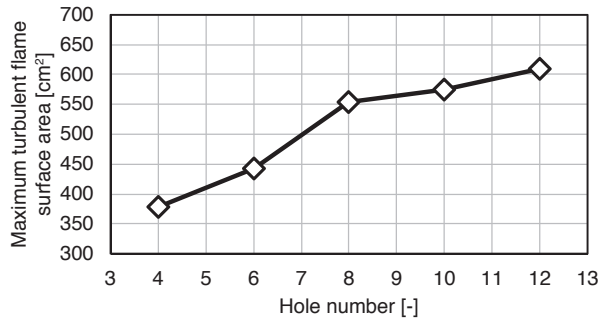


Fig. 17 Effect of pre-chamber hole number on knocking by CFD



(a) Relationship between pre-chamber hole number and jet penetration of propagation flame



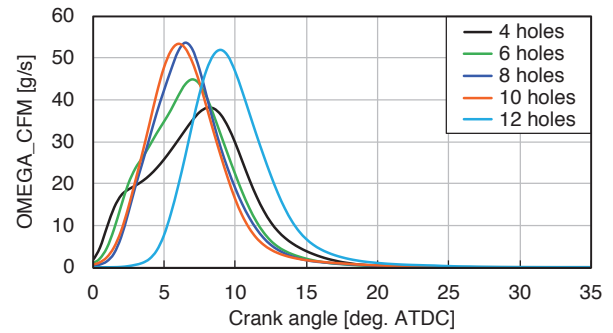
(b) Relationship between pre-chamber hole number and maximum turbulent flame surface area

Fig. 18 Effect of pre-chamber hole number on jet penetration of propagation flame and maximum turbulent flame surface area by CFD

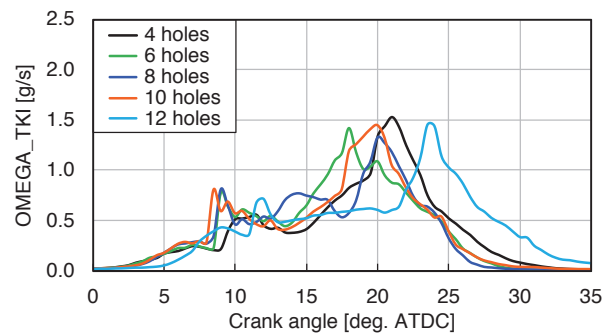
ignition timing could be advanced, and the combustion happened earliest with this number. As Fig. 19(a) shows, the timing at which propagation combustion moved from the peak to the latter half was advanced to 6 deg. ATDC with 10 holes in contrast to the 9 deg. ATDC with 12 holes. Moreover, as Fig. 19(b) shows, auto-ignition combustion began rising in the latter half of propagation combustion and was advanced to 9 deg. ATDC with 10 holes in contrast to the 12 deg. ATDC with 12 holes. The subsequent auto-ignition combustion peak was synchronous with the end of propagation combustion and was advanced to 20 deg. ATDC with 10 holes in contrast to the 24 deg. ATDC with 12 holes.

Here, observation of the flame image when OMEGA_TKI rises in Fig. 20 shows that as the number of holes increases, the increasing number of jets causes flame surface area to expand. Moreover, it was observed that the volume of each auto-ignition part tends to shrink when the unburned field is dispersed, and it was confirmed that the unburned field was most fragmented with 10 holes. With 12 holes, however, the unburned field was not completely dispersed because of interference between adjacent flames. As a result, knocking occurred and ignition timing was not advanced, which presumably retarded knocking limit MFB 50%.

These results indicate that having 10 holes suppresses auto-ignition and offers the best knocking mitigation owing to the effect of avoiding interference between adjacent



(a) Relationship between pre-chamber hole number and propagation flame combustion rate (OMEGA_CFM)



(b) Relationship between pre-chamber hole number and auto-ignition combustion rate (OMEGA_TKI)

Fig. 19 Effect of pre-chamber hole number on relationship between OMEGA_CFM and OMEGA_TKI by CFD

flames and dispersing the unburned field and making it smaller. This analysis found that selecting 10 holes, which is the jet interference limit in this engine, advanced the knocking limit MFB 50% by 1.5 deg. compared to four holes as a benchmark.

4.4. Compression Ratio and Knocking

Generally, an increased compression ratio raises theoretical efficiency but also increases end-gas temperature and pressure, which promotes auto-ignition and becomes a factor in knocking. Here, CFD was used to analyze the effect that compression ratio has on knocking in pre-chamber jet combustion.

Table 5 gives the specifications analyzed by CFD, while Fig. 21 shows the MFB 50% and combustion duration when ignition timing characteristics under each

Table 5 Engine specifications of conventional SI combustion and pre-chamber jet combustion on CFD

	Conventional SI combustion base ϵ 10.6	Pre-chamber jet combustion ϵ 10.6	Pre-chamber jet combustion ϵ 12.4
Excess air ratio	Stoichiometric	Stoichiometric	Stoichiometric
Pre-chamber hole specification	-	10 holes, 0.8 mm diameter	10 holes, 0.5 mm diameter
Pre-chamber volume [cm ³]	-	1.12	0.42

specification were measured. When the knocking mitigation effect under different compression ratios was confirmed, the knocking limit MFB 50% was 5 deg. advanced in pre-chamber jet combustion at compression ratio 10.6 as compared to conventional SI combustion with the same compression ratio. Moreover, even when the pre-chamber jet combustion compression ratio was raised to 12.4, the knocking limit MFB 50% was about the same as conventional SI combustion at compression ratio 10.6. This is presumably because the above-described shortening of combustion duration and the unburned area dispersion effect in pre-chamber jet combustion caused the end-gas's auto-ignition energy to decline.

Also, combustion duration of pre-chamber jet combustion with compression ratio 12.4 was approximately 40% shorter than that of conventional SI combustion with compression ratio 10.6.

5. Results of Tests with Actual Single-cylinder Engine

By using the knowledge gained from analysis up to this point through examination of the specifications of pre-chamber jet combustion, knocking and thermal efficiency of pre-chamber jet combustion in an actual single-cylinder engine were confirmed in order to verify the effectiveness of such combustion. The tested specifications are given in Fig. 22. Moreover, pre-chamber specifications were set based on the results described above.

Figure 23 shows the results of actual single-cylinder engine tests with conventional SI combustion and pre-chamber jet combustion when the ignition timing is varied. The evaluation load for the test was engine speed of 2,000 rpm and IMEP of 1,300 kPa. As Fig. 23(a) shows, combustion duration during pre-chamber jet combustion was approximately 40% shorter than for a conventional SI combustion engine, which is similar to the CFD study results. Moreover, in pre-chamber jet combustion with a compression ratio 1.8 pts. higher than conventional SI combustion, the knocking limit MFB 50% was about the same. These indicate that pre-chamber jet combustion replaced the amount of knocking mitigation with compression ratio, raising the compression ratio by 1.8. Since it is possible to raise the theoretical thermal efficiency with a higher compression ratio, the indicated thermal

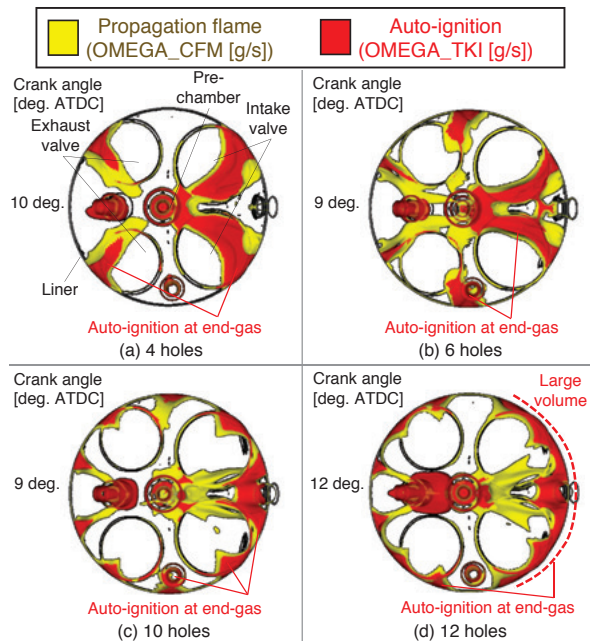


Fig. 20 CFD image analysis of pre-chamber hole number

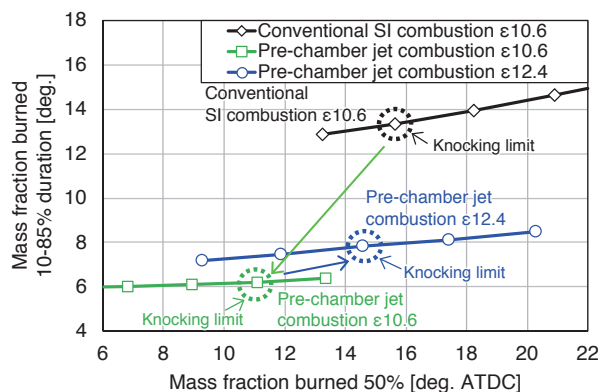


Fig. 21 Relationship between MFB 10-85% duration and MFB 50% in various compression ratios on CFD

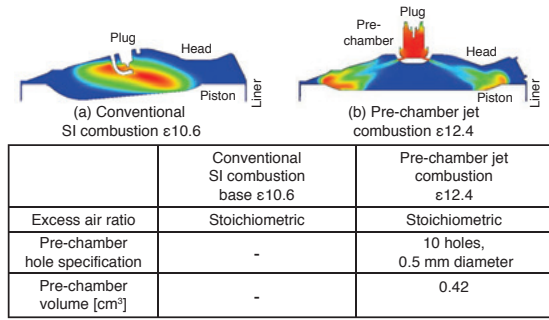
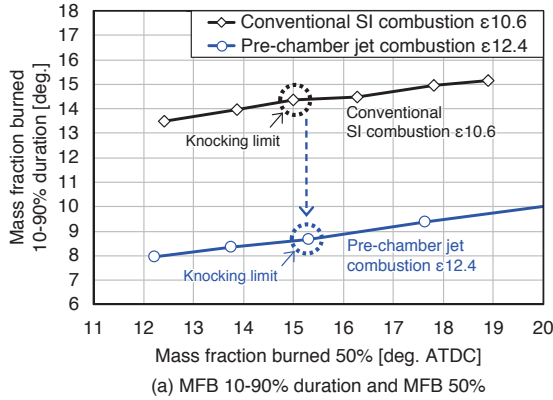
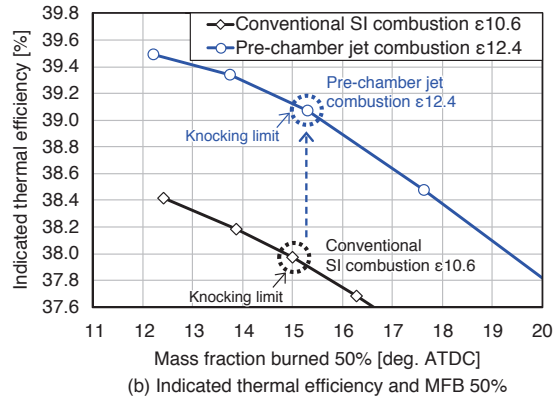


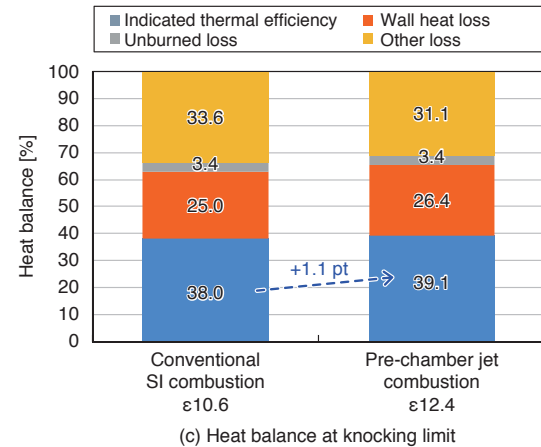
Fig. 22 Engine specifications of conventional SI combustion and pre-chamber jet combustion



(a) MFB 10-90% duration and MFB 50%



(b) Indicated thermal efficiency and MFB 50%



(c) Heat balance at knocking limit

Fig. 23 Experimental results of conventional SI combustion and pre-chamber jet combustion

efficiency of pre-chamber jet combustion with compression ratio of 12.4 was 1.1 pts. higher than conventional SI combustion with compression ratio of 10.6, even after deducting for the increase in heat loss resulting from rapid combustion, as shown in Figs. 23(b) and (c).

6. Conclusion

CFD and an actual engine were used to reveal the following about the knocking mitigation effect and thermal efficiency increasing effect of using pre-chamber jet combustion in comparison to a gasoline stoichiometric SI combustion engine.

- (1) Optimizing pre-chamber hole diameter and enlarging pre-chamber volume advanced the knocking limit MFB 50% from 1 deg. to 2 deg. for each 1 deg. combustion duration that was shortened. This is believed to be because the jets caused the propagation flame to reach the bore-end quickly, which reduced the unburned area of the end-gas and suppressed auto-ignition.
- (2) Selecting 10 holes, which is the jet interference limit in this engine, mitigated knocking by the greatest amount and advanced the knocking limit MFB 50% by 1.5 deg. compared to four holes as a benchmark. This is believed to be because increasing the number of pre-chamber holes and thereby increasing the number of jets partitions the unburned field and makes it smaller, suppressing auto-ignition.
- (3) Pre-chamber jet combustion in an actual single-cylinder engine produced a similar knocking mitigation effect as that found by CFD. By replacing the amount of knocking mitigation with compression ratio and raising the compression ratio by 1.8 pts., this study demonstrated that thermal efficiency increased under the evaluation load by 1.1 pts. compared to a conventional stoichiometric SI combustion engine.

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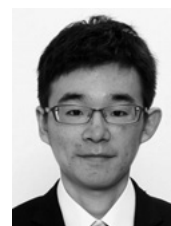
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