Influence of Flow Field Structure after the Distortion of Tumble on Lean-Burn Flame Structure

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ABSTRACT

By the multi-color laser sheet method with high spatial-resolution and by LDV method with high temporal-resolution, in-cylinder flow field structure after the distortion of tumble was analyzed. In place of the usual treatment to classify the instantaneous local-fluid-velocity components into bulk flow and turbulence, a new treatment to classify them into bulk flow, turbulence and eddy is proposed. By the two-dimensional measurement of the lean-burn flame chemiluminescence, reaction field structures were analyzed. It was clarified that a lean-burn flame is composed of the unburned gas, reacting gas, quenched gas and burned gas regions. An optimized combustion chamber configuration was proposed to control the tumble distortion timing and the structure of the flow field after its distortion. By the optimization, the bulk flow remaining after the distortion of tumble and its cycle-by-cycle variation are attenuated and eddies are distributed uniformly in the combustion chamber, resulting in a significant lean-limit extension.

INTRODUCTION

The authors have been performing the studies of the lean combustion enhanced by tumble (1)~(3) and have proposed new lean-combustion concepts named "Barrel Stratification (4)" and "Three-layers Barrel Stratification (5)". In these studies, it has been clarified that the flow field in which the combustion proceeds have a complicated structure and a new model should be introduced to describe the combustion phenomena in such a field.

This paper is a brief review of the authors' own works on the flow field and the reaction zone structure observed in the lean combustion enhanced by tumble. In the first section, results of the analysis of the flow field structure after the distortion of tumble by multi-color laser sheet method and high-resolution LDV measurement will be described. In the following section, the results of the analysis of the reaction zone structure by two-dimensional chemiluminescence measurements will be described. In the last section, an example of the method to optimize the combustion chamber configuration will be proposed. Influences of the optimized configuration on the flow field structure, discharge arc and flame kernel behavior and eddy burning in the reacting zone will be described.

FLOW FIELD STRUCTURE

In the case of two-intake-valve engines with pent-roof combustion chamber, intense tumble can be generated by the optimization of the intake-port configuration (1). In such engines, although a distinctive barrel-like vortex structure is observed during the early and middle stages of compression stroke, it is distorted and converted into turbulence at the latest stage of compression stroke. In order to clarify the flow field structure, the authors developed a high-resolution two-color PIV method, and found that tumble is converted into horizontal twin vortices with a relatively long lifetime before converted into turbulence (2). However, the significant cycle-by-cycle variation of the structure of the flow field controlled by twin vortices makes it difficult to estimate the instantaneous three-dimensional flow field structure by the two-dimensional PIV measurement.

The authors developed a method to measure the three-dimensional velocity components from a single two-dimensional PIV photography (6). The principle of this method is illustrated in Fig. 1. A two-color light beam from an Ar-ion laser is separated into green and blue beams and pulsated by two AOM's and converted into sheets. A pulse laser beam from a YAG laser is also converted into sheets and superimposed on green and blue sheets. Thin blue sheet of Ar-ion laser and YAG laser sheet are involved in thick green sheet of Ar-ion laser. The radiation timings of these three sheets are scheduled as illustrated in the figure, that is, instantaneous YAG laser radiation timing is involved in short blue-light radiation duration, which is involved in long green-light radiation duration. The photographic records of the tracer particles (polymer micro balloon) passing through the sheets are composed of green and cyan (green + blue) images and

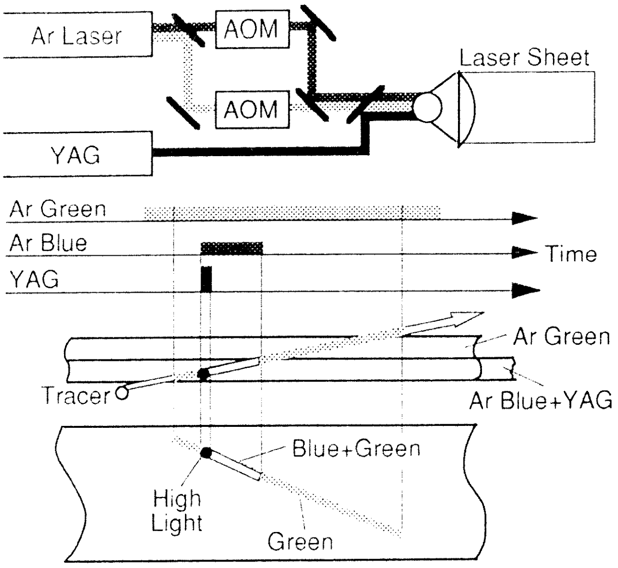


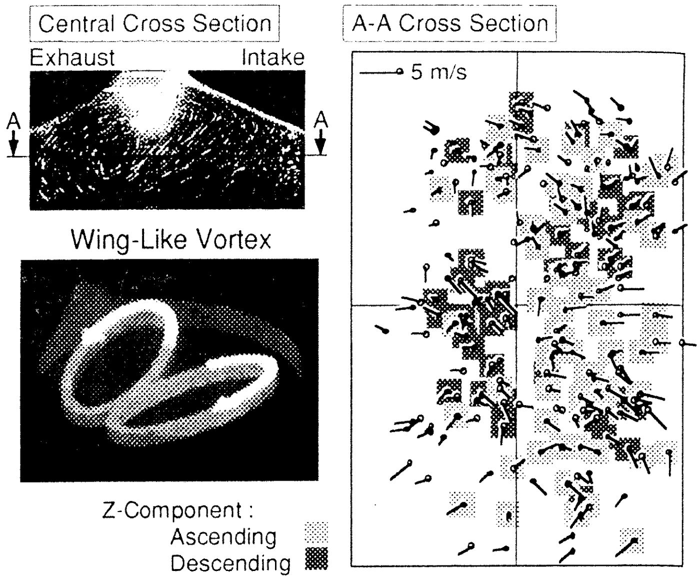
Fig.1 Instrumentation for the instantaneous 3D velocity measurement

highlights by YAG laser. Two-dimensional velocity components on the horizontal plane can be derived from the blue image. The YAG laser highlight is used to identify the starting point. Time required for a particle to pass through the green sheet can be obtained by dividing the green image length by blue image length. By comparing the length of green images before and after the highlights, vertical direction of the tracer movement can be estimated.

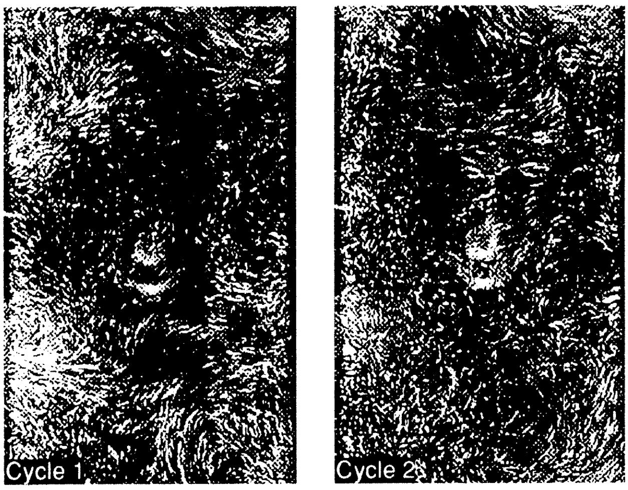
Applying this method, flow field structure during the distortion process of tumble was analyzed. An example of the results is shown in Fig. 2. It was clarified that the tumble distortion process is initiated from the conversion of barrel-like vortex to wing-like twin vortices starting about 30 degrees before TDC. The lifetime of the wing-like vortices is about 20 degrees crank angle, therefore the flow field during the early flame propagation is controlled by this wing-like bulk flow. At TDC, these vortices are converted into many small eddies with the scales of 5 to 10 mm. Cycle-by-cycle and spatial variation of the distribution of eddies are significant.

In order for the qualitative analysis of the local velocity components, high-temporal-resolution LDV measurements were performed. Figure 3 shows a typical cycle-resolved data obtained in the vicinity of the spark plug. In the figure, bulk flow is defined by phase averaging with the range of 10 degrees crank angle. Auto correlation of high-frequency components as a function of crank angle is shown in the same figure. It is shown that the high-frequency components are composed of a component with a scale of 5 to 10 degrees crank angle and a turbulence with scale equilibrium. The authors propose to call the non-equilibrium components with the scale of 5 to 10 mm as eddies.

Flow field during the combustion is composed of wing-like bulk flow, eddies and turbulence. Bulk flow will contribute to control the flame propagation. Eddies will control the mixing

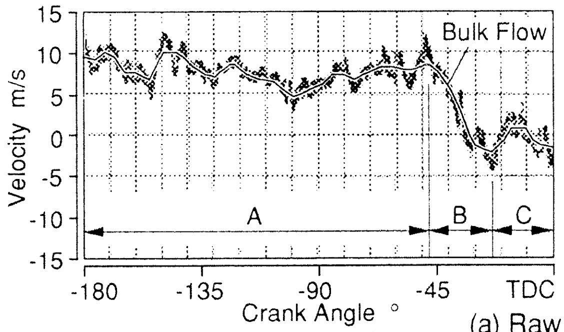


(a) Flow field structure at 15°BTDC

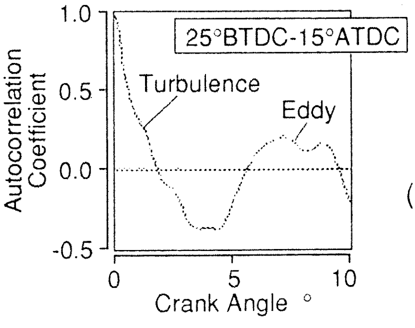


(b) Flow field structure at TDC

Fig.2 Flow field structure after the distortion of tumble (1000 min^{-1}, WOT, motoring)



(a) Raw data



(b) Auto-correlation of high-passed data (10°CA gate)

Fig.3 Definition of bulk flow, eddy and turbulence (velocity at spark plug, horizontal direction from intake to exhaust side, 1000 min^{-1}, WOT, motoring)

Table 1 Typical combustion parameters

Engine Speed	: 1000 min^{-1}
Equivalence Ratio	: 0.6
Laminar Burning Speed	: 10 cm/s
Turbulence Intensity	: 250 cm/s
Integral Scale	: 0.5 cm
Taylor Micro Scale	: 0.04 cm
Turbulent Reynolds Number	: 2500
Damköhler Number	: 3
Karlovitz Number	: 4

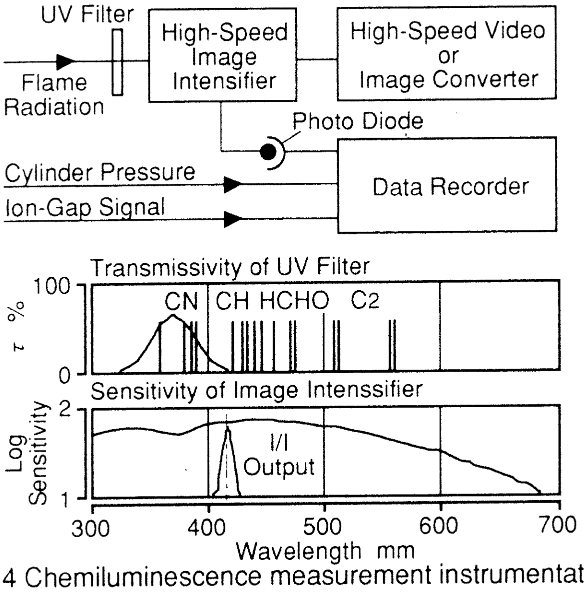
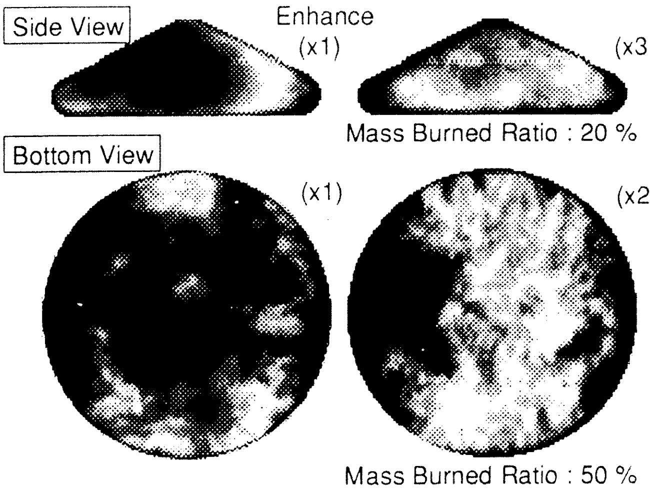


Fig.4 Chemiluminescence measurement instrumentation

of unburned gas, reacting gas and burned gas. Turbulence will be a factor determining a microscopic turbulent-flame structure.

REACTION ZONE STRUCTURE

Typical experimental conditions and turbulent combustion parameters and summarized in Table 1. In the typical lean-combustion condition, Karlovitz number exceeds 1. In such a condition, characteristic lifetime of chemical reaction is shorter than that of turbulent heat transfer. Therefore, in the diagram expressing the turbulent flame structures (7), it is located in the "Distributed Reaction Regimes".

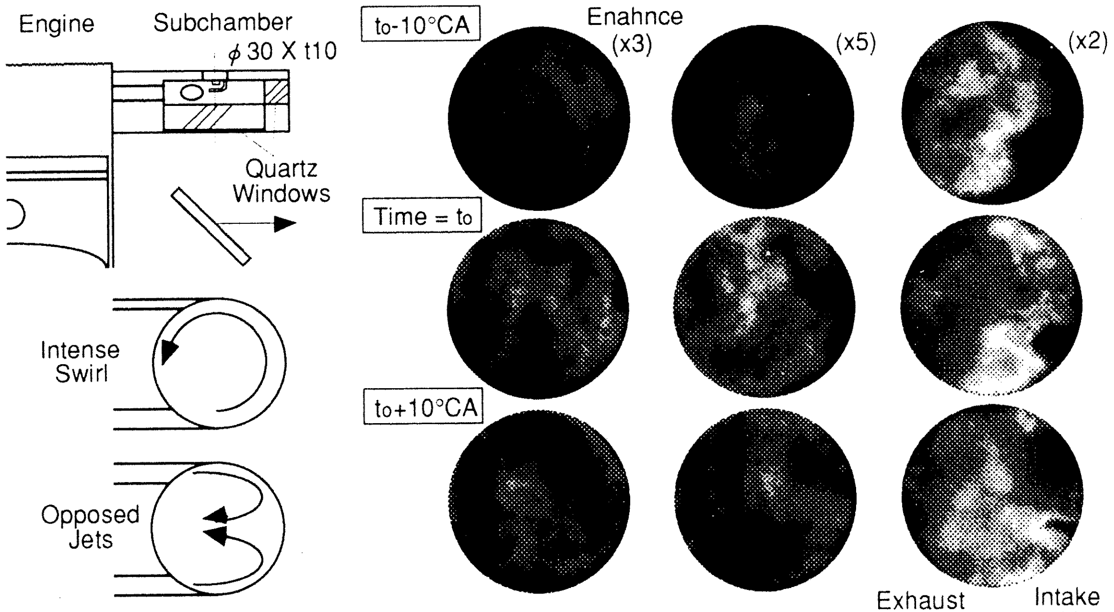


(a) A/F: 16 (b) A/F:24

Fig.5 CN band chemiluminescence distribution ($1500\ min^{-1}$, IMEP: 0.3 MPa)

Reaction zone structure was analyzed by chemiluminescnence (8). The experimental scheme is illustrated in Fig. 4. A weak chemiluminescence in the wavelength range of 350 to 390 nm including the CN band was amplified using an image intensifier with a short-decay phosphor having a high sensitivity in the ultraviolet and visible short wavelength range. It has been confirmed that the flame luminosity corresponds to a local heat release rate. Images were recorded in the D-RAM of a high-speed video system with the framing speed of 4500 and 13500 FPS.

Examples of the results are shown in Fig. 5. When the air to fuel ratio of the mixture is low, reaction zone can be observed



(a) Intense swirl (b) Opposed jets (c) Engine with intense tumble

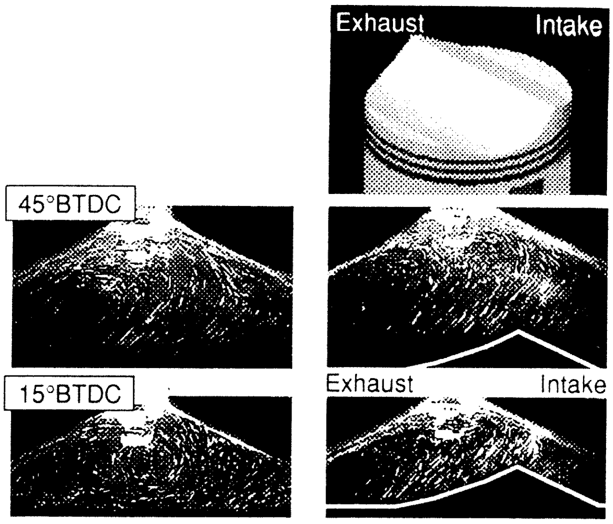
Fig.6 Reaction zone structure in the intense flow field ($1500\ min^{-1}$, A/F:24, IMEP:0.3 MPa) only behind the flame front. When the mixture is significantly lean, however, reaction zone is distributed throughout the combustion chamber. Radiating region, that is, the reacting gas region is composed of many small regions separated by streak-like unburned gas regions and burned gas regions. In the reacting gas region, island-like unburned gas regions or quenched gas regions can be observed. From these results, the authors considered that the distributed reaction zone is composed of unburned gas region, quenched gas region, reacting gas region and burned gas region. Bulk flows control the flame front propagation, turbulence determines the local flame structure and eddies promote the mixing of these regions.

In order to confirm the validity of such a treatment, the authors analyzed the reaction zone structure in more intense flow field with more distinctive structures (8). Experimental procedure and results are shown in Fig. 6. In a subchamber equipped to the side walls of a pent-roof chamber, intense swirl and intense opposed jets were realized. In the case of swirl, where only the bulk flow and turbulence existed in the flow field, reacting zone was distributed only behind the flame contour. In the case of opposed jets where intense eddies filled the chamber, reacting gas zone was distributed throughout the combustion chamber. This reaction zone structure was similar to that of lean-burn flame enhanced by tumble.

OPTIMIZATION OF FLOW FIELD STRUCTURE

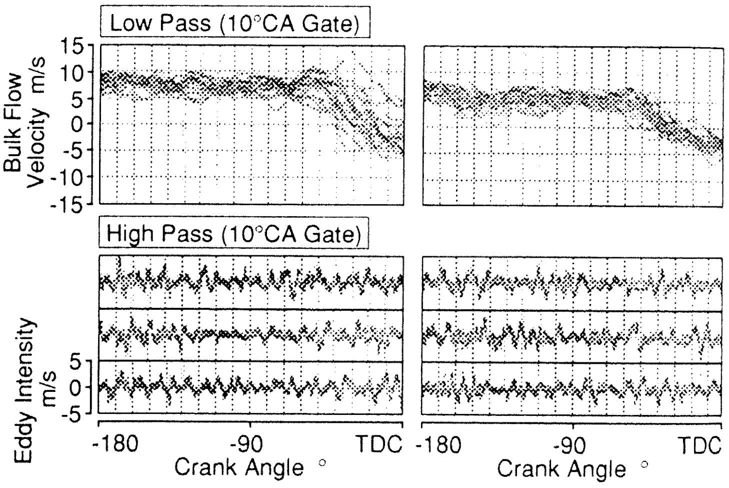
PROMOTION OF TUMBLE DISTORTION BY TUMBLE-CONTROL PISTON - Combustion-chamber configuration optimization was performed (5). The objectives were the attenuation of wing-like bulk flow and the promotion of the eddy generation. It was found that the "Tumble-control Piston" with curved-top surface was one of the solution. Figure 7 shows the configuration and its influence to the flow field structure at 45 and 15 degrees BTDC. Under lean conditions, 45 degrees BTDC corresponds to an ignition timing and the 15 degrees BTDC corresponds to a flame-propagation initiation timing. Figure 8 shows the velocity components in the horizontal plane from the intake to the exhaust side measured in the vicinity of the spark gap. In Fig. 9, the timing of tumble distortion and the bulk flow at TDC are plotted against bulk flow velocities before distortion.

In the case of a flat piston, the distortion of tumble has not started and an intense bulk flow from the intake to the exhaust side exists around the spark plug at 45 degrees BTDC. The wing-like horizontal vortices are formed at 30 degrees BTDC, and rotating bulk flow remains around the spark plug. When the tumble-control piston is used, a distortion of tumble has already started at 45 degrees BTDC and the bulk flow ascends straight from the lower part and collides against the top of the combustion chamber. Similar structure is observed at 15 degrees BTDC. Thus, it is assumed that the bulk flow around the spark plug is substantially attenuated, and small-scale eddies and



(a) Flat-top piston (b) Tumble-control piston

Fig.7 Tumble-control piston and its influence on the tumble distortion process ($1000\ \text{min}^{-1}$, WOT, motoring)



(a) Flat-top piston (b) Tumble-control piston

Fig.8 Velocity component in the direction from intake to exhaust valve at the point of spark plug ($1000\ \text{min}^{-1}$, WOT, motoring)

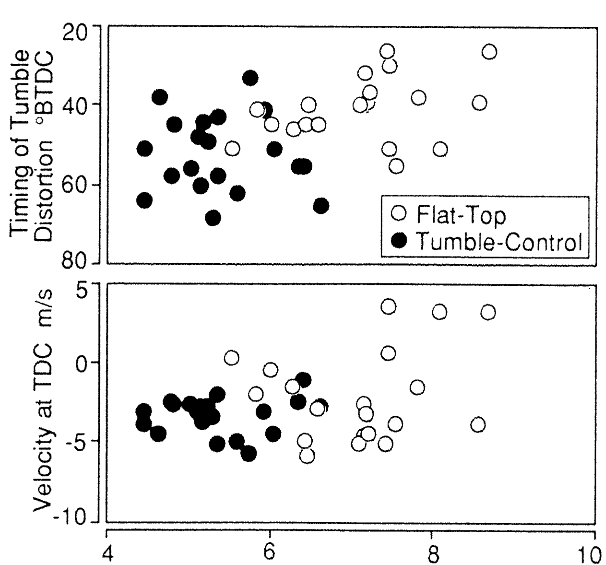
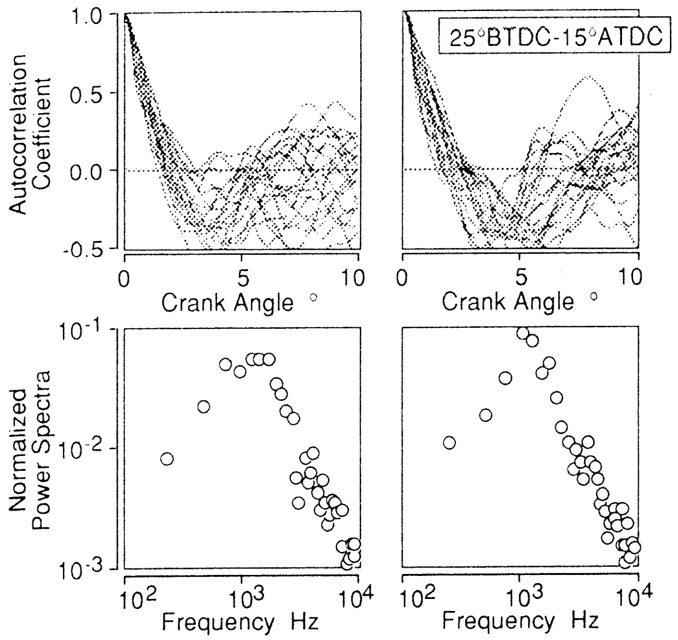


Fig.9 Influence of tumble-control piston on bulk flow



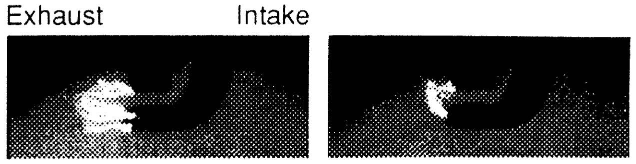
(a) Flat-top piston (b) Tumble-control piston

Fig.10 Influence of tumble-control piston on eddy and turbulence

turbulence is dispersed throughout the combustion chamber. As shown in Figs. 8 and 9, it was confirmed that the cycle-by-cycle variation of bulk flow is reduced significantly by tumble-control piston. Auto-correlation analyses of the high-frequency velocity components was performed. Results are shown in Fig. 10. The influence of the tumble-control piston on the scales of eddies and turbulence could not be observed.

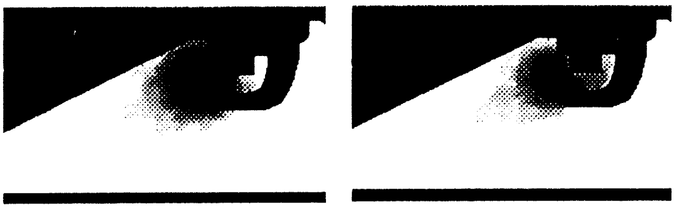
INFLUENCE OF TUMBLE-CONTROL PISTON ON IGNITION - The behavior of the discharge arc and the flame kernel were analyzed. In the case of a flat piston, multi-spark phenomena caused by the arc stretching by the intense bulk flow were observed. When the multiple-spark phenomenon takes place, each arc supplies its discharge energy to different mixture, therefore, the ignition energy is not effectively transferred to a flame kernel. As the intensity of the bulk flow is approximately proportional to engine speed, the misfire problem becomes more significant at higher engine speeds. The most effective means of misfire suppression will be the bulk flow attenuation.

Figure 11 shows the influence of the tumble-control piston on spark ignition phenomena. Images of a discharge arc of 30 consecutive cycles at the timing when the arc is stretched to the longest size are superimposed in the figure. When a tumble-control piston is used, the arc stretching is attenuated and multiple spark phenomena are minimal. The effect of the tumble-control piston on the flame kernel behavior is shown in Fig. 12. In the figure, the probability density of the flame-kernel existing area of 30 consecutive cycles are illustrated. It is shown that flame-kernel holding period were extended by the tumble-control piston. These effects will contribute to the suppression of misfire.



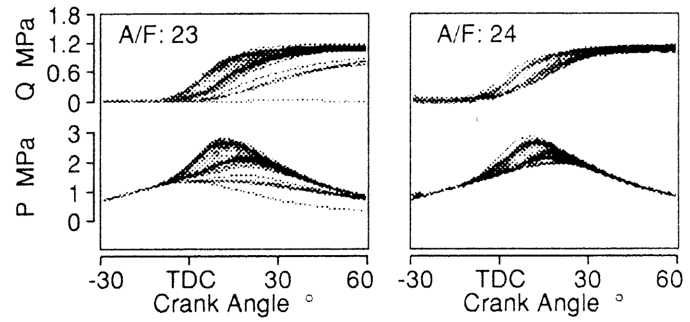
(a) Flat-top piston (b) Tumble-control piston

Fig.11 Influence of tumble-control piston on discharged-arc stretching (1500 min^{-1}, A/F: 24, IMEP:0.3 MPa)



(a) Flat-top piston (b) Tumble-control piston

Fig.12 Influence of tumble-control piston on PDF of Flame Kernel (condition: see Fig.11)



(a) Flat-top piston (b) Tumble-control piston

Fig.13 Influence of tumble-control piston on cylinder pressure (3500 min^{-1}, A/F:24, IMEP:0.6 MPa)

In general, the lean limit is composed of the "misfire limit" where the flame kernel does not show a normal growth and the "combustion stability limit" where the flame does not show a normal propagation. In most cases, it is possible to extend the misfire limit enough to exceed the stable combustion limit with a moderate ignition-energy increase even under high-engine-speed conditions. When tumble is enhanced to extend the stable combustion limit, it is however difficult to extend the misfire limit in the leaner mixture strength than the stable combustion limit. Therefore, it becomes necessary to suppress the misfire by the reduction of the bulk flow intensity around the spark plug.

The effects of the tumble-control piston on the misfire were investigated at an engine speed of 3500 min^{-1}. Results are shown in Fig. 13. Misfire is completely suppressed by tumble-control piston.

INFLUENCE OF TUMBLE-CONTROL PISTON ON EDDY BURNING - One of the essential conditions for stabilizing the combustion in the distributed reaction regime will be to uniformly distribute eddies and turbulence in the combustion chamber. Turbulence is essential to promote the reaction in the elementary turbulent reaction zone, and relatively large-scale eddies promote the mixing of unburned, reacting,

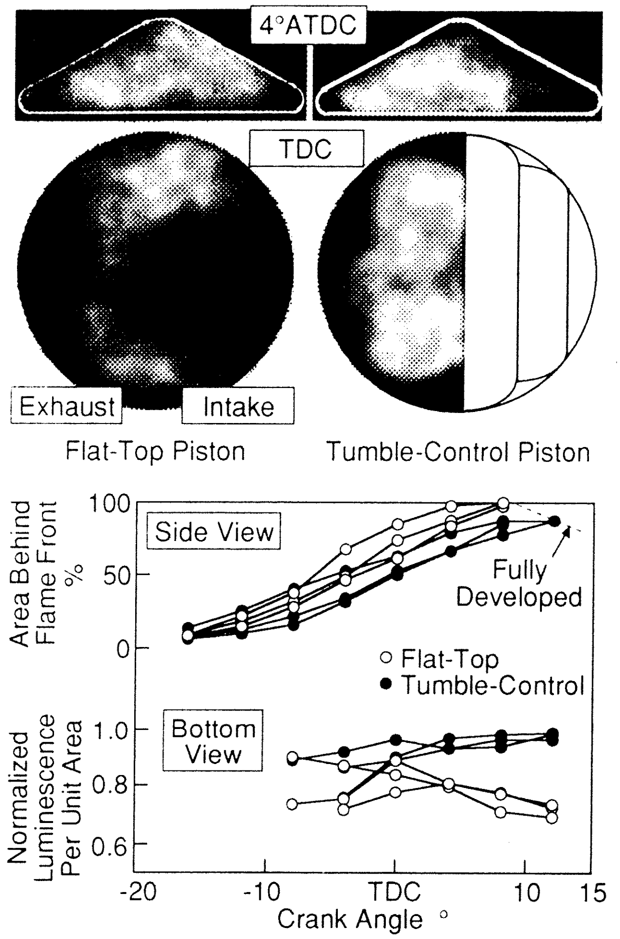
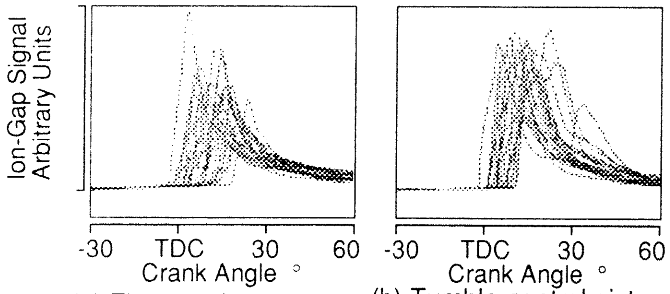


Fig.14 Influence of tumble-control piston on CN band chemiluminescence (condition:see Fig.11)



(a) Flat-top piston (b) Tumble-control piston

Fig.15 Influence of tumble-control piston on ion-gap signal (location: side wall of pent-roof chamber, projection: 8 mm, condition: see Fig.11)

quenched and burned gas regions. Therefore, an effective way to stabilize the lean combustion is to promote tumble distortion, suppress the formation of a large-scale horizontal bulk flow and to accelerate the conversion to eddies and turbulence.

The flame front propagation and the reaction zone structure were investigated using a chemiluminescence. Figure 14 shows the influence of the piston surface configuration on side-view and bottom-view flame images. In the case of a tumble-control piston, although the flame front propagation speed is decreased by the attenuation of the bulk flow, flame luminosity per unit flame area, that is, the local heat release rate in the reaction zone is increased. Figure 15 shows the ion gap signal of consecutive 30 cycles. It is shown that the near-wall heat release rate is increased and its cycle-by-cycle variation is reduced by tumble-control piston. Judging from these results, it is concluded that eddies and turbulence effective in enhancing eddy burning are uniformly dispersed in the combustion chamber by the tumble-control piston.

SUMMARY

In-cylinder flow field structure after the distortion of tumble was analyzed by multi-color laser sheet method and LDV measurements with high spatial and temporal resolution. A new treatment to classify them into bulk flow, turbulence and eddy is proposed. Lean-burn flame reaction field structures was analyzed by the chemiluminescence measurement. It was clarified that a lean-burn flame is composed of the unburned gas, reacting gas, quenched gas and burned gas regions. A combustion chamber configuration was proposed to optimize the structure of the flow field. Because the bulk flow remaining after the distortion of tumble and its cycle-by-cycle variation are attenuated and eddies are distributed uniformly in the combustion chamber, optimized configuration revealed a significant lean-combustion stabilizing effects.

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