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# 33 Experimental Study of Relationship between Gas Flow and Flame Structure for Premixed Turbulent Combustion using a Combustion Bomb

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As premixture combustion, there would be a close correlation between turbulence of gas flow and combustibility. So the precise correlation is needed. The purpose of this study is quantitative evaluation of relationships between flame structure and turbulence characteristics under premixture combustion. Constant volume combustion bomb which is equipped fans to generate turbulence of desired conditions was used. Turbulence intensity was measured by LDV and turbulence intensity was obtained from output of hot-wire anemometer. Flame image was taken by the TV camera with memory and image processing was carried out to get complexity of flame front structure. Complexity of flame was mainly evaluated by fractal dimension. As results, flame complexity was mainly depend on turbulence intensity and the effect of turbulence scale was not made clear.

***Keywords*: Engine Combustion, Engine, Performance / Premixture Combustion, Combustion Analysis, Flame Structure, Turbulence Intensity, Fractal Dimension, Constant Volume Combustion Bomb**

## 1. INTRODUCTION

Premixture combustion has been researched from the view point of improving thermal efficiency and exhaust gas air pollution of internal combustion engines.

Many papers have been described about unsteady combustion in the engine, but they are so difficult to clarify the relationships between combustibility and flow characteristics in detail. Then it is needed to show the relationships more clearly especially from the view point of physical data.

In this paper, a constant volume combustion bomb was used that is able to measure mean flow velocity, turbulence and its scale also to get combustion pressure and combustion flame shapes. This paper aimed to clarify the combustion mechanism especially about the effect of flow characteristics to flame structure of premixture combustion by flow measurement and analysis of flame structure.

## 2. EXPERIMENTAL APPARATUS

To research the relationships between combustibility and flow characteristics, a constant volume combustion bomb which can be generate various flow velocity and turbulence intensity and can be measure flame propagation was used. This apparatus is designed to generate various conditions of flow field and to measure the generated gas velocity by LDV system or hot wire anemometer and to measure combustion pressure by pressure indicator and to take flame images by TV camera.

### 2.1 Combustion Bomb

Constant volume combustion bomb is the size of 120 mm in width and 120 mm in height and 240 mm in horizontal length as shown in Fig. 1. It is equipped to generate gas flow in the bomb by rotating fans that can be change gas

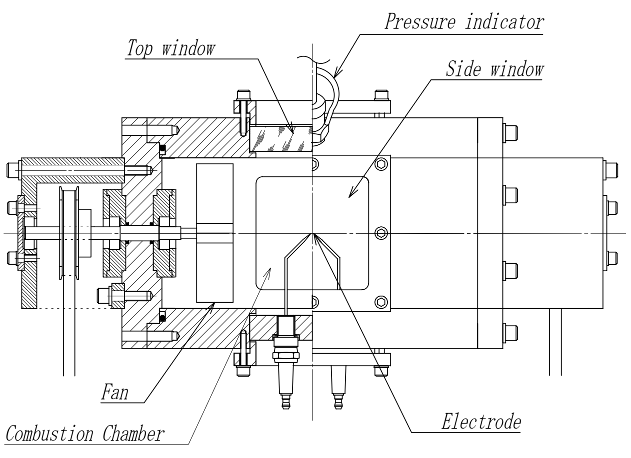


Fig.1 Constant Volume Combustion Bomb

velocity. Two fans to generate gas flow were set at opposed side of the combustion bomb, and they were rotated the other way.

Pressure indicator, that is the strain gage type with the mounting size of 14 mm, was set to measure combustion pressure.

Glass windows were set at the both side of the combustion chamber to measure the gas velocity and also to project laser light sheet to take flame images. Also a glass window was set at the top of combustion bomb to take flame propagation images through the glass windows using TV camera. The size of glass window is 90 mm square available to observe.

Ignition electrodes were set at the center of the bomb so that the flame propagation would be expanded symmetrically. At the bottom of the bomb, smoke generating device was set to measure gas velocity and flame propagation.

Combustion gas used in this experiments is the mixture of propane and air at equivalent ratio.

### 2.2 Flow Generating System

Two types of fans are prepared. One is the four blades fan in size of 144 mm, that we call four blades fan, as shown in Fig. 2 (a). And the other is four blades that are slightly slanted to fan axis and have a side wall, that we call shovel fan, as shown in Fig. 2 (b).

Two fans are equipped at the combustion bomb and are driven by electric motors. So as to change flow revolution of fans are from 0 to 3,500 rpm in case of four condition, the fan speed are changed. Conditions of blades fan and from 0 to 2500 in case of shovel fan by the input voltage to motors.

### 2.3 Measuring System

**(1)Flow characteristics** Flow velocity in the combustion bomb was measured by LDV system of forward or backward scattering. Tracer particles are very little particle of oil smoke that was generated from heavy duty lubrication oil heated by electric heater. The diameter of particles is about 5 micro meters. They are satisfactory to trace the flow velocity in the combustion bomb. Signal processor of the burst signals scattered light from tracer particles is the type of frequency tracker and that can be able to measure the turbulent flow up to the frequency of 10 kHz. Velocity data were recorded by the recording system of personal computer with high speed A/D converter.

Turbulence scales, that are the integral and micro scale, were measured by hot wire anemometer. The probes used here are 5 micro-meters in diameter of fine wire of tungsten.

**(2)Combustion Pressure** Combustion pressure in the bomb was measured by an indicator that is the type of strain gage.

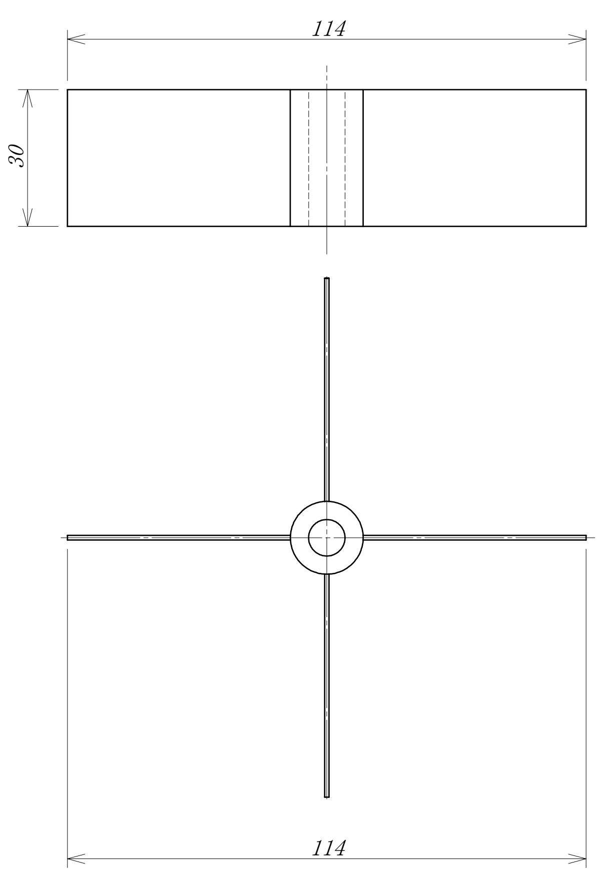


Fig. 2 (a) Four Blades Fan

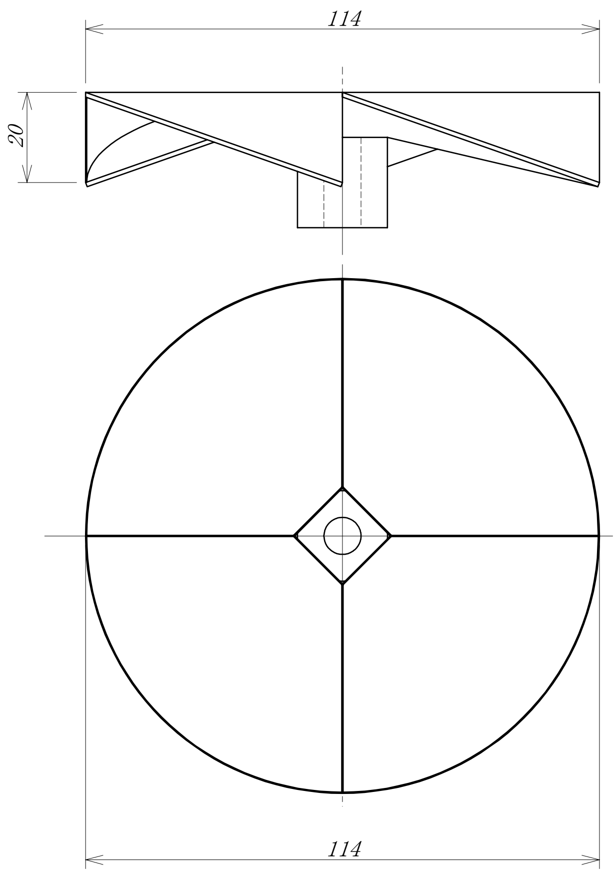


Fig. 2(b) Shovel Fan

This pressure indicator was set at the side wall of the bomb. It is suitable for measure the combustion pressure because of its stability. Output signal of pressure was also recorded by the recording system as already mentioned above.

**(3)Measuring Flame Propagation** Cross sectional image of flame at the instance was taken by the laser sheet method. As the light source, a very short duration about 5-7 ns of YAG laser was used. The emitting light of the laser was changes to a light sheet of 0.3 mm thickness and 100 mm width as shown in Fig. 3. This light was incidented to the combustion area in the bomb which are filled with the premixture of propane and air with scattering particles. When combustion is occurred, particles inside the flame are to be so weak and scattered light from the flame to be rare. Then the brightness of area of burned gas is considerably dark so that the boundary of the flame front to be clarified. Flame front can be taken as the image by TV camera and be stored in the memory of the image acquisition system. The resolution power of flame images is 0.2 mm, that is dependent on the scale of CCD pixel. This measuring system is shown in Fig. 4.

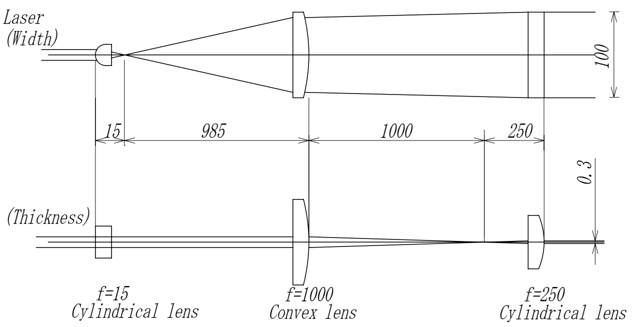


Fig. 3 Laser Sheet Optical System

## 3. EXPERIMENTAL PROCEDURE

### 3.1 Experimental Conditions

Combustion gas is propane-air mixture at stoichiometric fuel air ratio as mentioned before.

Parameters of this experiment are flow characteristics such as mean flow velocity of the gas, turbulence intensity, turbulence scale and the time after ignition. Parameters of the flow conditions and the time to be taking flame propagation images are shown in Table 1.

Table 1 Experimental Conditions

| | Fan speed [rpm] | Turbulence intensity [m/s] | Timing after Ig. [ms] |
|---|---|---|---|
| Four blades fan | 0 | 0.0 | 4, 6, 8 |
| | 350 | 0.5 | |
| | 1500 | 1.6 | |
| | 2500 | 2.7 | |
| | 3500 | 3.9 | |
| Shovel fan | 0 | 0.0 | 4, 6, 8 |
| | 500 | 0.5 | |
| | 2500 | 2.0 | |

### 3.2 Flow Measurement of Mean Velocity and Turbulence Intensity

Gas flow in the bomb was generated by the two fans which are set at the both side of the bomb. They were driven at the designated revolution by electric motors at the other way. Flow velocity was measured by LDV of forward scattered type at the case of measuring axial and

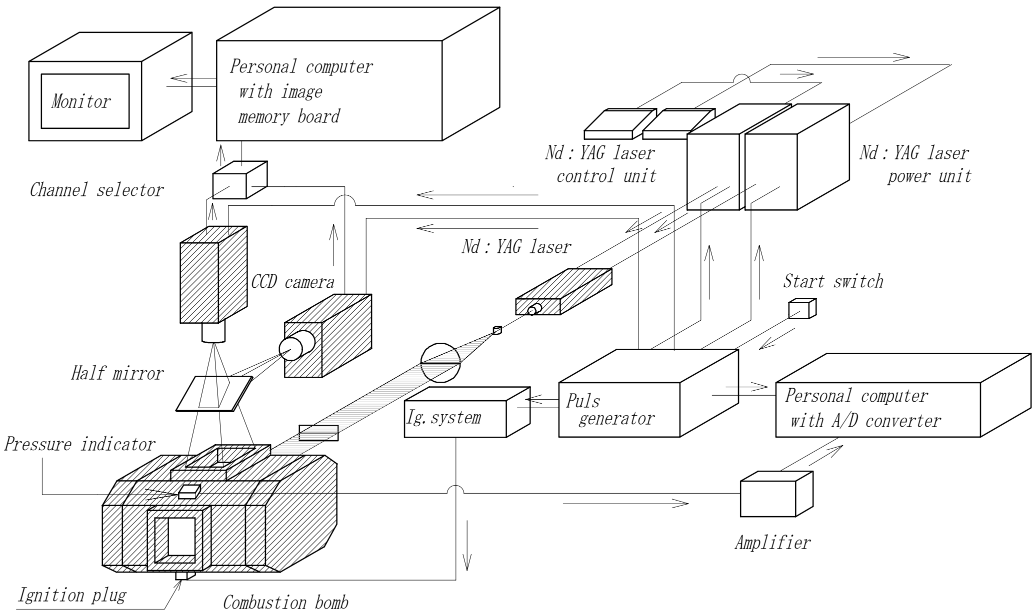


Fig.4 Flame Cross Section Measurement System

radial flow direction and backward scattering type was used to measure the circumferential direction flow. Laser light source was He-Ne of 50 mW power. Detection of scattering light from particles was received by the photo-multiplier as burst signals. Signal processor was the frequency tracker type so that it is convenient to low S/N and weak signals. Analogue velocity data was converted to digital data and saved to memory of the personal computer.

Measuring points are mainly at around the center of the bomb. They are from 0, 10, 20, 30 mm from the center of the combustion bomb. Measured flow directions were three directions at orthogonal coordinates.

### 3.3 Turbulence Scale

To measure turbulence scale, hot wire anemometer was used. Two probes of fine wire were set at designated position. One probe was set to the position of desired point of measuring. The other was set just near the measuring position and was traversed to 30 mm distance every 0.5 mm/1 mm from original measuring position. Two output signals from the probes were recorded. After that, the cross correlation of them was calculated, as an example, as shown in Fig. 5, and integral length scale and micro scale were obtained.

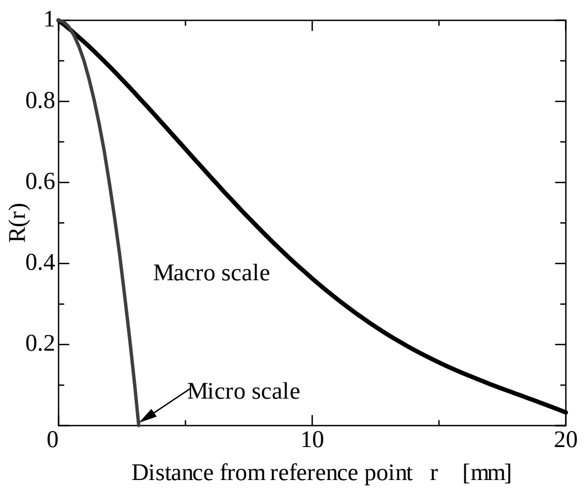


Fig.5 Relation between correlation coefficient R(r) and distance r

### 3.4 Flame Propagation

To take the image of flame cross section, laser sheet method was used as already mentioned above. The time sequence of taking flame propagation is as shown in Fig. 6. First of all, combustion bomb was made empty by the vacuum pomp and then was filled with premixture of propane-air. Ignition switch was pushed to ignite the premixture at the center of the bomb. The time to taking image was set by the electrical circuit at the interval step of 100 μs of digital counting switch. Fundamental timing of taking images is from 2 to 8 ms from ignition timing. The propagation of flame had already be out of observation window when the timing of more than 10 ms from ignition.

To take more resolving power of flame image, two set of TV camera was adopted. One is the whole image of flame propagation of all directions and the other is used to take high resolving image compared with the former at the same instance. The resolution power of whole flame is 0.2 mm and height resolving image is 0.05 mm.

Only one image can be taken at once a combustion. Then the continuous discussion about the flame propagation could not be done.

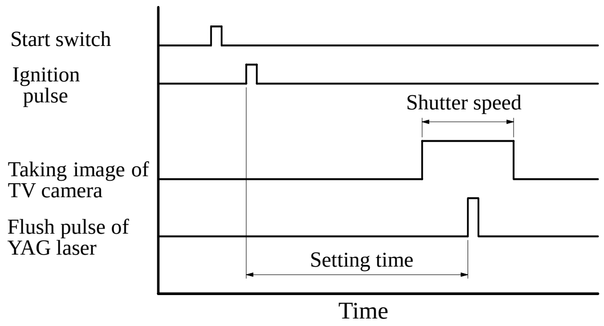


Fig.6 Time Sequence of Taking Image

### 3.5 Experimental Procedure

Before combustion experiment, measurement of flow field, such as mean velocity, turbulence intensity, turbulence scale was examined. After that, combustion experiments were carried out. And combustion pressure and flame images were obtained at the time to desired.

## 4. RESULTS AND DISCUSSIONS

### 4.1 Mean Flow Velocity

Mean velocity in the bomb was less than 3 m/s at maximum fan speed condition and almost everywhere it was about 1 or 2 m/s. So it was considered to be slight effect to flame propagation. But this should be confirmed.

### 4.2 Turbulence Intensity

Figure 7 shows the example turbulence intensity of x-direction at the case of fan speed of 350, 1500, 2500, 3500 rpm in using four blades fan. Turbulence intensity

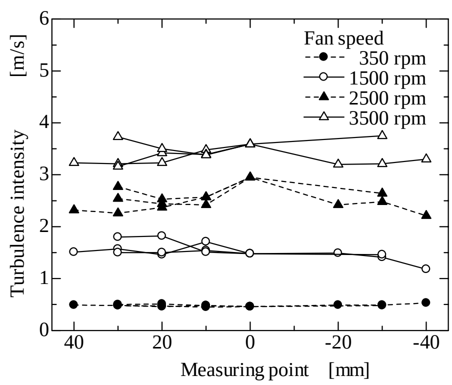


Fig.7 Turbulence intensity of x-direction

was nearly the same order at each fan speed condition. The difference according to three directions is about less than 15%. It was almost homogeneous in three directions in the bomb, and was suitable to this experiment. Turbulence intensity was from 0.5 m/s to 3.9 m/s as shown in Fig. 7. In case of shovel fan, turbulence intensity was from 0.5 to 2.0 m/s.

### 4.3 Scale of Turbulence

Macro scale of turbulence was shown in Fig. 8. The order of it is about 5 mm to 10 mm changed according to fan speed at near the center of the bomb. Using shovel fan, it was the same order.

Micro scale of turbulence was about 1 mm or 1.5 mm at the fan speed of 350 to 1500 rpm. But it was rather large value in case of fan speed of 2500 or 3500 rpm.

From overall views, the relation between turbulence intensity and macro or micro scale of turbulence was almost without correlation as shown in Fig. 9.

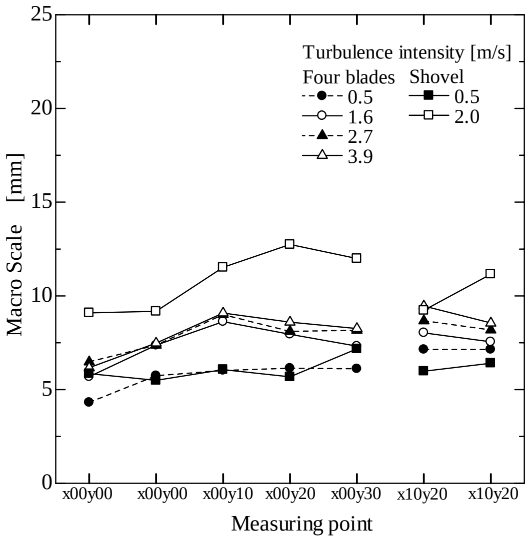


Fig.8 Macro Scale

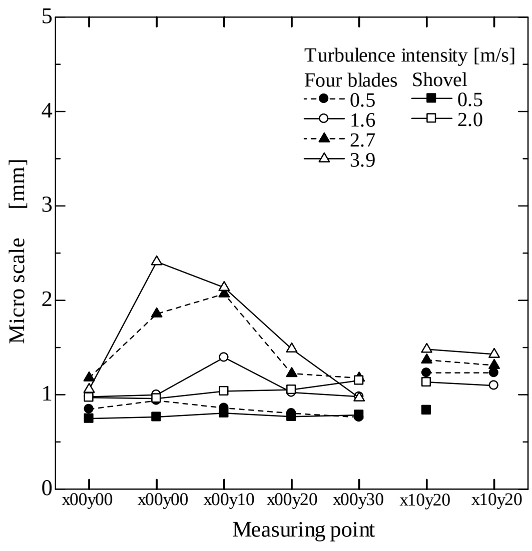


Fig.8 Micro Scale

### 4.4 Combustion Pressure

Pressure diagrams along the time are shown in Fig. 10. Combustion pressure was raised rapidly after a little time from ignition because of ignition delay and after that flame kernel was increased. Turbulence intensity derives fast flame propagation as shown in this figure. Generally speaking, it was cleared that turbulence intensity affects to the combustibility. In case of without gas velocity, that is the stationary condition, the combustion period is nearly 65 ms. But it was shortened to be about 10 ms in case of large turbulence intensity.

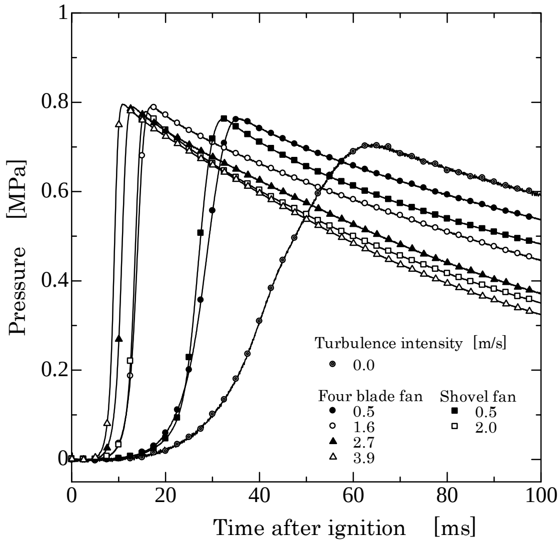


Fig. 10 Pressure diagrams

### 4.5 Structure of Flame Cross Section

**(1) Extract flame outline from flame images** The image of flame propagation was taken by the TV camera as monochromatic image. The change of intensity of the flame image was occurred just at the flame front therefore the density of seeding particles was changed by the change of gas density caused by the temperature of combustion. The observed and stored image in the computer was digitized to two values, that is 0 or 1, from the threshold revel. In actual operation of this digitizing, noise of image and nonuniform of the brightness of the image affected wrong result. To avoid this problem, statistical procedure was used. This is the method to determine the threshold revel to be determined by the local minimum value between statistical value of the high and low intensity of the image pixels as shown in Fig. 11. As an example, the real image and the flame front outline distinguished by statistical procedure to the original image was shown in Fig. 12.

**(2) How to calculate fractal dimension to evaluate complexity of flame** Fractal dimension is one of the evaluation methods of complexity of shapes. Fractal dimension of the shape of flame front was calculated by box-counting method. This method is as follows. The image of flame front was

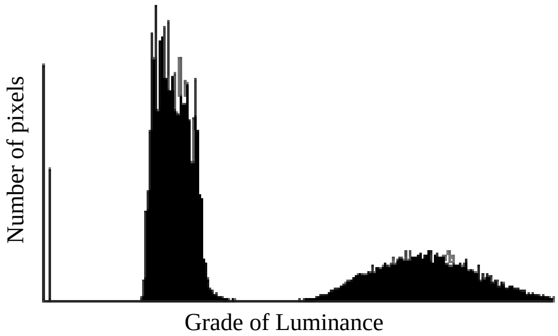


Fig.11 Histogram of Luminance

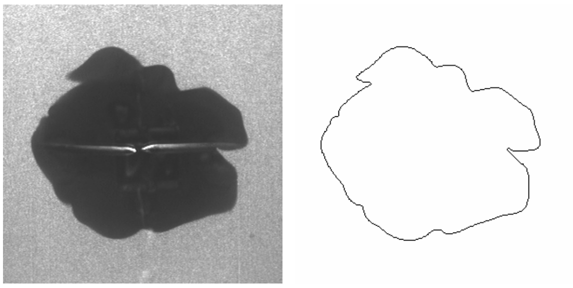

Fig.12 Real Image and Flame Front Outline

divided to 1/1 and 1/2 and 1/4 and so on of square, and if the shape of flame front is exist in the divided square, counter number of N(r) is added by one. Where, N is the total number of square exited flame front and r is the length of one side of square. The relation between fractal dimension D and N, r is

$$N(r) = k \cdot r^{-D}$$

where k is the constant value.

Then the fractal dimension D was calculated by the following equation.

$$D = -\frac{\log N(r)}{\log(r)}$$

This fractal dimension is to be the complexity of the shape of flame front.

**(3)Evaluate by Fractal Dimension** The relationship between turbulence intensity and fractal dimension of flame shape was shown in Fig. 13. At the range of turbulence intensity of from 0 to 3.9 m/s, tendency of fractal dimension of flame shapes is increased according to turbulence intensity. But fractal dimensions were not changed by time from ignition. That is, the shape of flame front expanded with same complexity according to turbulence intensity. These tendencies were confirmed several case of turbulence intensity and also in case of different type of fans. These tendencies were observed also the magnified images of same combustion conditions.

These experimental results show that the relation between turbulence intensity and fractal dimension is to be in some correlations.

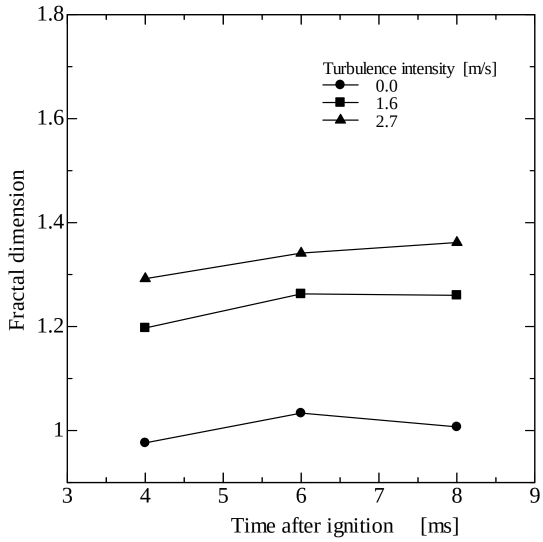


Fig.13 Fractal Dimension

## 5. CONCLUSIONS

To research the term of influence to flame structure, premixture combustion in the bomb was carried out in changing the turbulence intensity, turbulence scale. And the complexity of flame structure was evaluated by fractal dimension. And it was obtained following results.

1. Experimental apparatus that can be changed turbulence intensity and turbulence scale was designed and manufactured.
2. Flame structure evaluated by fractal dimension was affected by turbulence intensity. The influence of turbulence scale might not be influence on flame structure but cannot be declared clearly.

More experiments should be done about these problems.


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