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Flame and Wall Temperature Visualization on Spark-Ignited Ultra-Lean Combustion Engine

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ABSTRACT

This paper presents a method of two dimensional visualization and measurement of chamber wall temperature. It also includes a three dimensional measurement method of flame speed in the lean combustion of spark-ignited engine. Moreover, monochromatic images of flames are taken by an image spectroscope.

Ultra-lean Combustion, which is defined as air fuel ratio is more than 20, is known to be effective in point of combustion improvements such as emission gas cleaning and thermal efficiency improving. However, the combustion has its own difficulties like combustion instability.

Swirl is an effective method of stabilizing lean combustion. It is important from a combustion stability standpoint to understand the relation between swirl and wall temperature or between swirl and flame.

INTRODUCTION

Ultra-lean Combustion, which is defined as air fuel ratio is more than 20, is known to be a promising and effective method for combustion improvement, namely emission gas cleaning and thermal efficiency improving[1]. However, it has some unsolved problems such as combustion instability.

It is known that the swirl is an effective technique of stabilizing lean combustion, while over-swirling has a possibility to reduce thermal efficiency[2]. In order to study lean combustion's stability and thermal efficiency by swirl, it is important to understand how the swirl influences the wall temperature and flame behavior. Moreover, image-based analysis of the combustion is apparently more effective than point-based measurement. So, visualization of flame and wall temperature is an important method of comprehensive understanding of lean combustion in the cylinder. For example, in the case of wall temperature, single point measurement by means of thermocouple has difficulty in understanding combustion chamber wall temperature as a whole. In the case of flame observation, the combustion flames propagating three dimensionally are usually observed as two dimensional flame images projected on the observation window. Furthermore, in the case of ultra-lean combustion, even flame observation has difficulty in viewing because of its weak luminous intensity.

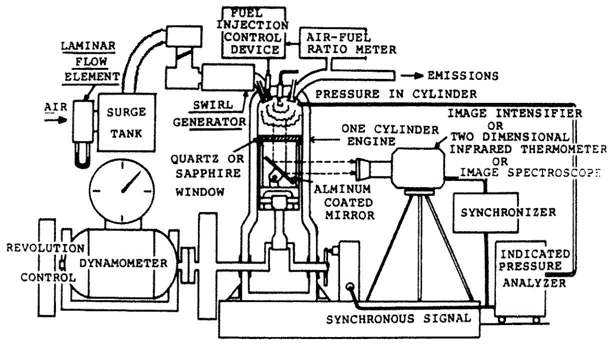


Fig.1 Experimental Apparatus

This paper presents measurement methods of two dimensional visualization on hemisphere chamber wall temperature and three dimensional flame speed in spark-ignition engine ultra-lean combustion by using an image intensifier. Moreover, the relations between flame speed and wall temperature are discussed. In addition, the relation between flame and monochromatic flame images by an image spectroscope are discussed.

EXPERIMENTAL APPARATUS AND METHODS

Experimental Apparatus

Fig.1 shows Experimental apparatus. The used engine is a single cylinder engine of bottom-view type[3], whose has a piston head of quartz or sapphire window and an observation mirror coated with aluminum. The engine is controlled to keep a constant speed by the dynamometer. Intake air flow is measured by a laminar flow meter. Swirl generator is used to control swirl ratio in the cylinder. The specifications of the engine are as follows; Bore: 85mm, Stroke: 90mm, Compression ratio: 8.5, Combustion chamber: hemisphere type.

Swirl generator[3], which generates swirls in the cylinder, is installed on the intake port in Fig.1. Swirl ratios are measured by an impulse swirl meter. Swirl Generator is controlled at two points of swirl ratio 0 and 6.6 in this paper.

Flame Propagation Observation by means of Image Intensifier

Flame Propagation of Ultra-Lean Combustion.

The luminous intensity of the flame under ultra-lean combustion is very weak. The image intensifier shown in Fig.1 is used. Because the weak luminous intensity of the flames prohibits to use any high speed camera and a very short exposure time is not sufficient for getting a clear image on a film.

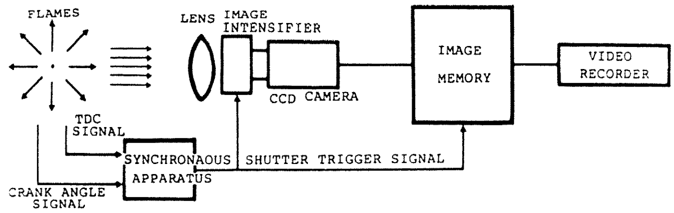
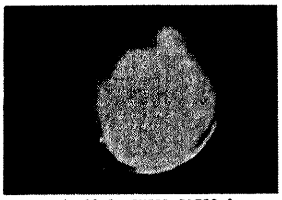


Fig.2 Diagram of Flame Observation by Image Intensifier



A/F:22.5 SWIRL RATIO:0
TDC(60 DEG. AFTER IGNITION)
(a)

A/F:22.5 SWIRL RATIO:6.6
TDC(17 DEG. AFTER IGNITION)
(b)

Fig.3 Flame Observation in the case of A/F(air fuel ratio)=22.5

Fig.2 shows the diagram of flame observation by the image intensifier. Lights from flames are focused on the sensor of the image intensifier by optical lens. The image intensifier is high speed gated type and has been used as an electronic shutter which amplifies images when a gated pulse is on. The window of the piston head is made of quartz. The mirror by which the combustion chamber is observed is a mirror coated with aluminum. The flame images are recorded by a video recorder for later image processing. Fig.3 shows an example of flame in the case of A/F(air fuel ratio)= 22.5. In the pictures, the exhaust valve is located in the right hand of the combustion chamber and the intake valve is in the left hand. The spark plug is in the distance of about half a radius below the combustion chamber center. The images of ultra-lean combustion flames are taken clearly by the image intensifier. The use of an image intensifier makes it possible to observe not only ordinary combustion flame but also ultra-lean combustion flame of spark ignition engine.

Three Dimensional Measurement of Flame Speed. In the case of flame observation from the bottom of piston head, the combustion flames propagating three dimensionally are usually observed as two dimensional flame images projected on the observation window, although the engine has a hemisphere combustion chamber and flames propagate three dimensionally. So, particularly in order to measure combustion flame

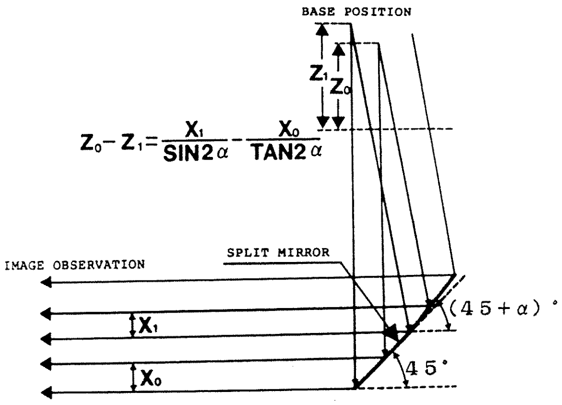


Fig.4 Principle of Stereo Method

speed in the vicinity of the chamber wall, flames have been observed by means of Stereo Method and Double Exposures. Fig.4 illustrates the principle of Stereo Method. Two split mirrors coated with aluminum are applied instead of an usual observation mirror. In Fig.4, the mirror(A) is inclined at 45 degrees and the mirror(B) is inclined at $45+\alpha$ degrees. These mirrors are like human two eyes. X_0 is the distance between the base position (an spark plug) and some flame point reflected by the mirror(A). X_1 is the distance between the base position and the identical flame point reflected by the mirror(B). The identical points are determined with the eye. The criteria of the points are to recognize parallel movement of the point in each mirror and to be a convex flame surface because of having little influence on the visual angle. The depth Z is calculated by the visual difference between X_0 and X_1. (X,Y) is measured on the plane

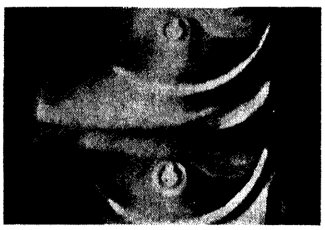


Fig.5
Combustion Chamber in the vicinity of Spark Plug by Two Split Mirrors

parallel to the piston head by mirror(A)'s image. The three dimensional distance between two points is calculated from the (X,Y,Z) of the two points. α has been decided for the spark plug to be within each split mirror and the value is 6.3 degrees. Fig.5 shows the combustion chambers in the vicinity of the spark plug by two split mirrors.

In order to measure the moving distances of the flame, the combustion flames are double exposed to CCD camera by the image intensifier triggered by serial two gated pulses. The flame speed is calculated as the above three dimensional moving distance of flame divided by the time between serial two pulses. From these results, three dimensional flame speeds in the vicinity of the chamber wall are obtained. Two gated pulses are generated at time intervals of crank angle 2 degrees by both TDC pulses and crank angle pulses. Time intervals are variable by one degree step.

Wall Temperature Visualization Method

It is an superior method to use infrared rays' energy for the measurement of wall surface temperature. The advantages of the method are as follows; to be able to measure objects' temperature undisturbedly, to be able to know two dimensional temperature distribution easily, to be able to understand the temperature distribution easily by the image data processing and so on.

In Fig.1, the window of piston head is made of sapphire, because sapphire has high mechanical strength and high heat-resistance and high transmittance in the region of infrared rays. The observation mirror is an aluminum coated mirror which has high reflectance in the region of infrared rays. Fig.6 shows two dimensional infrared thermometer system[4]. The principle of thermometer is the Stefan-Bolzmann's principle. The thermal image is obtained by rotating 10 mirrors at high speed. The detector is InSb. Time constant of infrared ray detector is 0.3 μs. The mirrors rotate synchronously with trigger pulses. When the trigger pulse is on, infrared rays' energy is measured by one of 10 rotating mirrors. One thermal image's frame is created by 10 trigger pulses. Therefore, the image is an integrated image by a cyclic data sampling. Table 1 shows the infrared thermometer specifications.

Fig.7 illustrates infrared rays' (IR) contribution to the infrared thermometer. The IR's contribution from the atmosphere is compensated by the circuit of the thermometer. The IR's contribution from the mirror is negligible, because the emissivity is very small (0.03 at 27 degrees[5]). The IR's contribution from the sapphire window is obtained by measuring the sapphire window's temperature. The sapphire window's temperature is measured from blackbody radiation of a black paint which are painted on a part of the sapphire window. The radiation from the flames is cut off by the narrow band-pass infrared filter. The detector's sensitivity range is between 3 μm and 5.4 μm. Main infrared absorption radicals among combustion generated matters of hydrocabons are CO, $-CH_2$, $-CH_3$, H_2O in this range. These absorption wavelengths (center) are 4.67 μm in CO, 3.42 and 3.51 μm in $-CH_2$, 3.38 and 3.48 μm in $-CH_3$[6]. Transmission wavelength range of combustion flames is between 3.6 and 4.1 μm[7]. Therefore, the narrow band-pass filter of center wavelength 3.78 μm and half-width 0.26 μm has been adopted in order to eliminate the influence of infrared rays from combustion flames.

The absorption wavelength range of H_2O unlike other combustion generated matters is broad. But the absorption by H_2O has almost no influence on measuring the temperature in the wavelength range of the used band-pass filter because of the narrow band by the filter[8]. So, the influence of water vapor is negligible on the temperature measurement of the combustion chamber wall in this wavelength range.

Moreover, the wall temperature has been examined by the axial thermocouple. At the same time, the temperature of that has been measured by the infrared thermometer. In the condition of 1000rpm, stoichiometric air-fuel ratio, and swirl ratio 0, the thermocouple temperature is 140.2 degrees at TDC of intake stroke. On the other

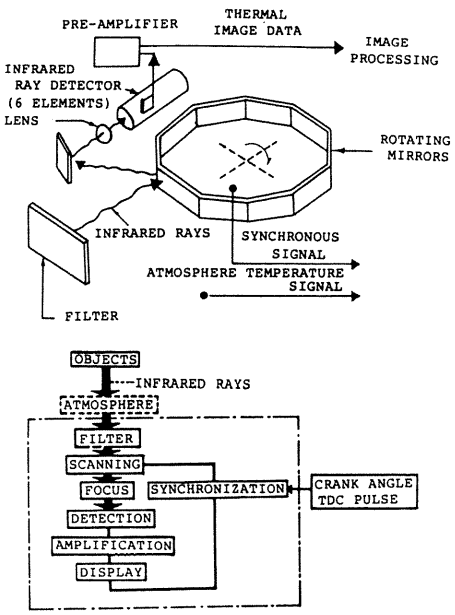


Fig.6 Two Dimensional Infrared Thermometer

Table 1 Infrared Thermometer Specifications

FIELD OF VIEW	7.5° × 1.5° (VERTICAL)(HORIZONTAL)
OBSERVED DISTANCE	MORE THAN 20 cm
FRAME SPEED	20 FRAMES/SECONDS
SCANNING LINES	60 LINES
DETECTOR	InSb(INDIUM-ANTIMONY)
WAVE RANGE	3 ~ 5.4 μ

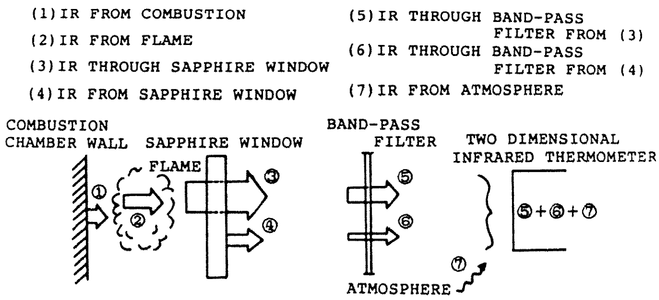


Fig.7 Infrared Radiation's Contribution to Infrared Thermometer

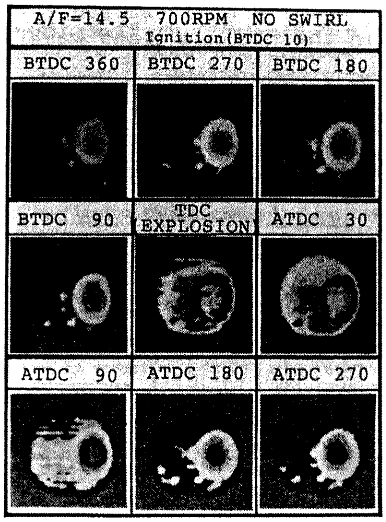


Fig.8 Wall Temperature Visualization at Each Crank Angle

hand, the compensated temperature of infrared thermometer is 142 degrees.

Fig.8 shows the wall temperature visualization at each crank angle. This figure shows relative wall temperature distribution for various crank angle from TDC in the suction stroke. The exhaust valve is located on the right hand and the intake valve is on the left hand. The exhaust valve's temperature is always high. On the other hand, the intake valve's temperature becomes low at the intake stroke. The exhaust valve's temperature is observed even at the explosion stroke. The wall temperature visualization shows well the behavior of wall temperature distribution.

Image Spectroscope

The effective information of a reaction area and a reaction mechanism is obtained by measuring emission intensity distribution of radials such as OH, CH and C_2. As radicals emits intrinsic lights, the kinds and distributions of radicals can be estimated by measuring intensity distribution of radical's intrinsic emission.

Fig.9(a) shows Image Spectroscopic System. Spectroscopic images are obtained from flame emissions by an image spectroscope. The images are amplified by an image intensifier. Shuttering is the same way as stated above. Amplified image are taken by SIT camera and are recorded by a video recorder. Fig.9(b) shows Image Spectroscope[11]. A monocrometer is Czerny-Turner type. Flame images are focused on diffraction grating DG by quartz lens L_1 and concave mirror M_1. Spectroscopic image are focused on the sensor plate of an image intensifier by concave mirror M_2 and quartz lens L_2. Table 2 shows Image Spectroscope Specifications.

In hydrocarbon's flame, C_2 radical generates in the early decomposition process and then CH radical generates[9]. C_2 dominates in the rich mixture area and CH dominates in the lean area[10]. Swan band (516.5nm) is typical in C_2. The three bands of 314.3, 390.0 and 431.5nm are observed in CH[9]. 516.5nm in C_2 and 431.5nm in CH have been chosen because of visible radiation.

To avoid the influence of continuous spectrum caused by carbon particles in flames and so on, the radicals' emission images have been obtained from the difference between the monochromatic image in the radicals' band wavelength and that in the adjacent wavelength. The adjacent wavelength of CH is 433nm and that of C_2 is 517.2nm. The averaging process have been applied to the monochromatic image to remove the fluctuation of flames. The averaging number is 512.

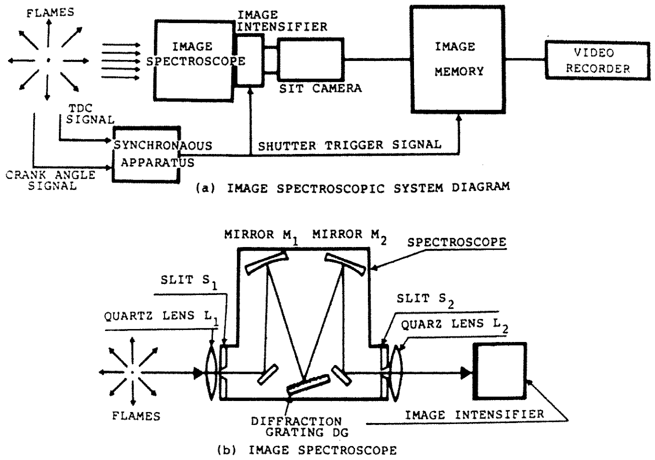


Fig.9 Image Spectroscopic System

Table 2 Image Spectroscopic Specifications

DIFRACTION GRATING RULED AREA GROOVE/mm BLAZE WAVELENGTH	 52×52mm 1200/mm 300.0nm
WAVELENGTH RANGE	200~1500nm
EFFECTIVE WAVELENGTH RESOLUTION	0.15nm
SPACE RESOLUTION (SLIT WIDTH 2mm) VERTICAL RESOLUTION HORIZONTAL RESOLUTION	 0.32mm 0.14mm

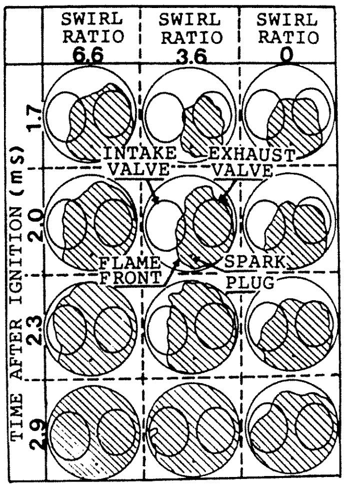


Fig.10 Flames at Each Swirl

EXPERIMENTAL CONDITIONS

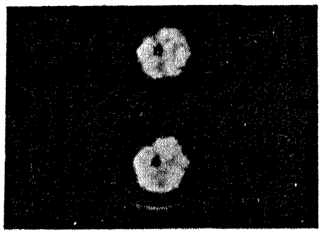
The engine speed is 1000rpm and all of the spark timing is MBT. The air fuel ratios (A/F) are 14.5 (stoichiometric A/F), 20.5 (lean combustion A/F), 22.5 (Ultra-lean combustion A/F). The intake air flow has been set to the setting air fuel ratio in the constant fuel injection flow. The atmosphere temperature is 20 degrees. The temperature of intake air is 25 degrees and the humidity of that is 60%. The swirl ratios are 0 and 6.6.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Fig.10 shows the trace of flame front in each swirl condition of stoichiometric A/F. The swirl's rotation is counterclockwise. The stronger the swirl becomes, the more rapid the flame front speed. The flame rotation's center moves counterclockwise. It is recognized that the flame speed at the exhaust valve side shows a tendency to high speed in the case of swirl ratio 0.

Fig.11 shows the stereo measurement of flame and double exposure. This is the case of A/F 14.5, Swirl Ratio 0 and 10 degrees after ignition. (a) is the image taken by CCD camera with an image intensifier. The flame front's movement have been obtained by the double exposure. (b)is the image obtained from (a) by an image processing. The exhaust valve is located on the right hand and the intake valve is on the left hand. The average process has been carried out to reduce images' noises. White arrows in

A/F:14.5 SWIRL RATIO:0
10 DEG. AFTER IGNITION



(a) IMAGE BY CCD CAMERA

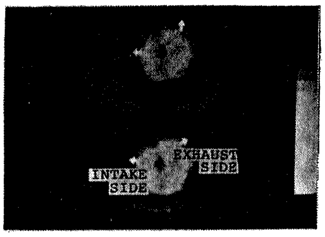


Fig.11 (b) IMAGE PROCESSED FLAME
Stereo Measurement of Flame and Double Exposure

Fig.11 show flames' movements by means of the double exposure. Two points, which are regarded as the movements of flames' identical points by human eyes, have been found out. The distance between the two points has been measured by the stereo method.

Fig.12 shows three dimensional flame speed in the vicinity of each valve on A/F 14.5 and Swirl Ratio 0. The flames are examined within 2 to 9 mm in the z direction from the spark plug. It is considered that these flames are in the vicinity of the combustion chamber wall. It is found that, in the vicinity of the combustion chamber wall, the flame speed at the exhaust valve has a tendency to be higher than one at the intake valve. This tendency shows on all A/F of swirl ratio 0. The tendency is not clear on swirl ratio 6.6 because of the influence of swirl.

Fig.13 shows the temperature distribution of the combustion chamber wall on TDC of the suction stroke. Fig.14 shows the temperature distribution of the combustion chamber wall on TDC of the explosion stroke. The exhaust valve is located on the right hand, the intake valve is on the left hand and the spark plug is in the center below the combustion chamber center. It shows that the temperature measurement of the combustion chamber wall on explosion states are possible because the images of each valve are found on explosion states. It has been found that, on all the case of Fig.8, 13 and 14 the temperature of the exhaust valve is higher than that of the intake valve. This is considered that the exhaust valve is heated by combustion gases on the exhaust stroke, while the intake valve is cooled by mixture gases on the intake stroke.

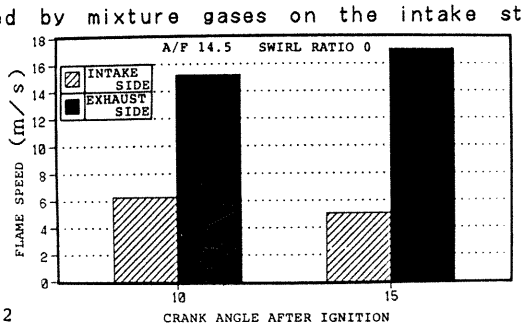


Fig.12
Three Dimensional Flame Speed in the vicinity of Each Valve on A/F=14.5 and Swirl Ratio 0

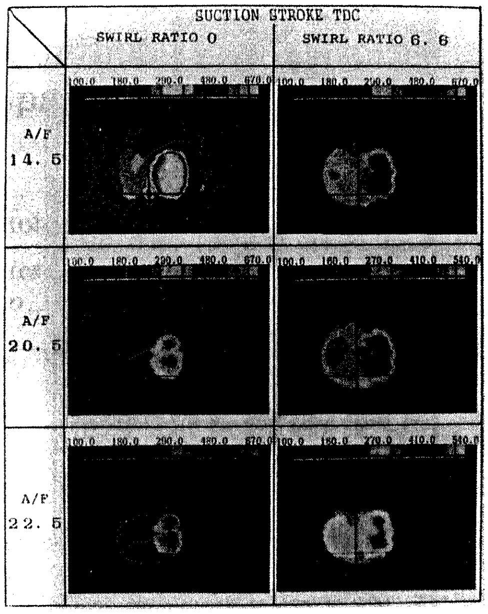


Fig.13 Temperature Distribution of Combustion Chamber Wall on TDC of Suction Stroke

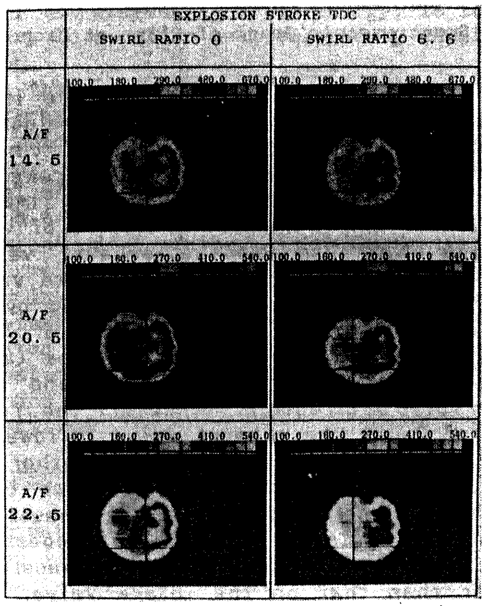
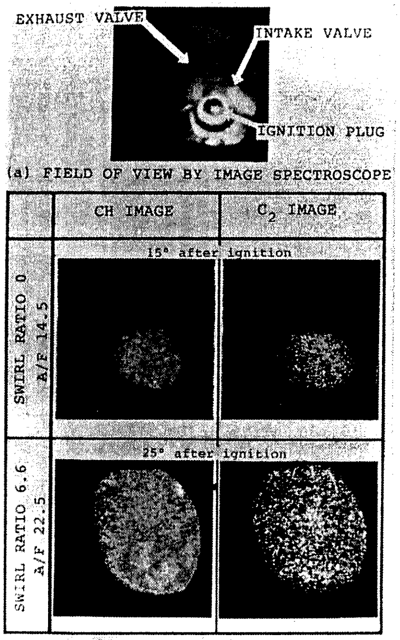


Fig.14 Temperature Distribution of Combustion Chamber Wall on TDC of Explosion Stroke

The reason, that the flame speed in the vicinity of the exhaust valve in Fig.12 is high, is considered that mixture gases are heated by the exhaust valve and the reaction activity of mixture gases increase. This is remarkably in the case of swirl ratio 0, on which the temperatures of mixture gases is not uniform and the flame's movement caused by swirl is negligible. In both swirl ratio 0 and 6.6 on TDC of the explosion stroke, the temperatures of all over the combustion chamber wall is high. In the swirl ratio 0 on TDC of the suction stroke, the temperature near only the exhaust valve is high. On the other hand, in the swirl ratio 6.6 on TDC of the suction stroke, the temperatures near both valves are high. The reason is considered that the wall temperature has become uniform by swirl. In the condition of strong swirl, the heat loss from the combustion chamber wall increases by rising the temperatures of all over the wall on TDC of not only the explosion stroke but also the suction stroke. This corresponds to the tendency of increase of heat loss on the condi-



(b) DISTRIBUTION OF CH AND C_2

Fig.15 Spectroscopic Image of Flame at Each Swirl

tion of excessive swirl[2]. Moreover, the increase of heat variance factors may be considered by the heat loss over a long period of time from the suction stroke to the explosion stroke.

Fig.15 shows the spectroscopic image of flame at each swirl.(a) shows the field of view on the image spectroscope. The exhaust valve is located on the left hand and the intake valve is on the right hand because of inverting by spectroscope. (b) shows the distributions of CH and C_2. The field of view is the same as (a). The distributions of both CH and C_2 extend to the exhaust valve's direction. Moreover, the relative density of C_2 on the exhaust valve is lower than that on the intake valve. On the other hand, there is not the remarkable difference between the relative density of CH on the exhaust valve and that on the intake valve. This suggests that the decomposition of fuel on the exhaust valve is faster than that on the intake valve. In the case of swirl 0, this may correspond to the relation between the high temperature and the high flame speed on the exhaust valve.
In swirl 6.6, both CH and C_2 extend to the whole combustion chamber by swirl.

CONCLUSION

Wall temperature distribution and three dimensional flame speed in the ultra-lean combustion are clearly observed by the visualization method. The method is confirmed to be effective for comprehensive understanding of the combustion.

As for the visualization, the followings are confirmed ;
(1) The image intensifier is useful for the visualization since the equipment can amplify the light emitted from the ultra-lean combustion flame, which is originally very weak.
(2) The stereo method with double exposure is developed for the measurement of three dimensional flame speed.
(3) The distribution of the wall temperature averaged in a cycle is measured by means of the two dimensional infrared thermometer with a suitable narrow-band filter. Furthermore, the measurement is possible under the condition of explosion stroke as well as suction stroke.
(4) When there is no swirl, it is observed that the flame speed is higher in the vicinity of the exhaust valve than in the other part of the chamber. Under the same condition, the surface temperature of the exhaust valve reaches high. Discussion is made on the possible relation between the valve temperature and the flame speed. Moreover, the image spectroscope has measured the distributions of CH and C_2 respectively. When there is no swirl, the distributions differ considerably in the vicinity of the exhaust valve.

Since this seems to be the first attempt to apply visualization method for the comprehensive understanding of the ultra-lean combustion, there are many things to do for future progress. For example, improvement of the performance of the image intensifier will enable the method to make more precise analysis of flame.

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