Measurement of the Combustion Gas Temperature in the Spark Ignition Engine*

By Hideo Shoji**

For the purpose of analyzing the combustion process in a spark ignition engine, it is necessary to know the combustion temperature in the combustion chamber. The author has developed a new technique of measuring the combustion temperature using the sodium line reversal method. By this new technique, it is possible to scale temperature for the output of flame radiation from the combustion chamber. The distribution of flame temperatures in the cylinder could be measured by this method even near the cylinder wall.

For the purpose of measuring the flame temperature in the commercial engine, a compact sensor with prisms and optical fibers was developed. The measured values obtained from these techniques are discussed for various operating engine conditions.

Key Words: Internal Combustion Engine, Combustion, Gas Temperature, Sodium-Line Reversal Method, Thermal Radiation

1. Introduction

The gas temperature in the combustion chamber of the spark ignition engine has a great effect on the performance of the engine and the composition of the exhaust gas. When analyzing the spark ignition combustion process, it is necessary to determine gas temperature quantitatively. It is well known that the gas temperature varies very rapidly and from cycle to cycle, and is distributed unevenly in the combustion chamber. Various attempts have been made by a number of researchers (1)-(6) to measure gas temperature in the combustion chamber, without providing any simple and practical methods. The author (7) used the spectral D-line reversal method to measure rapidly and continuously varying gas temperatures in combustion processes. Using a light path method (holder-type) with two observation windows, the new technique allowed the output waveform of the flame radiant energy to be scaled in terms of temperature, making a continuous display of gas temperature possible as a function of angle. With this system, temperature distribution within the light path gap was measured, including combustion gas temperatures near the cylinder wall. Furthermore, a small prism-type temperature sensor was manufactured and used for measurement. Easily adapted to the commercial engine, this sensor uses optical fibers and quartz prisms for temperature measurement with one observation window. The author analyzes the combustion gas temperatures obtained by these different methods.

2. Principles of Temperature Measurement

The spectral D-line reversal method usually observes the spectrum produced when

a beam from a reference light source is passed through a flame containing sodium vapor at an absolute temperature of T_F as shown here in Fig. 1. As the temperature of the light source is gradually elevated,

Fig.1 Principles of D-line reversal method

a bright sodium D-line appears in the spectrum, turning darker when the temperature of the reference light source exceeds the flame temperature. The point at which the D-line turns from bright to dark is called the reversal point. By knowing the brightness temperature S_R of the reference light source at the reversal point, flame temperature T_F can be obtained. This method makes use of Kirchhoff's Law, stating that at the reversal point, the absorptivity and emissivity of the gas within the light path through the flame are equal. Hence, when the light intensity of the reference light source through the flame equals the intensity without the flame, the temperatures of both the light source and the flame will be equal. In Fig.1, let I_L be the energy input into the flame from the reference light source, I_L' be the portion of I_L not absorbed by the flame, and I_F be the radiant energy of the flame itself. Here, a trace of sodium has been added to the flame before hand so as to emit the sodium D-line. Thus, we have

$$I_L = \epsilon_L(\lambda_D, T_1) E(\lambda_D, T_1)$$

$$I_L' = [1 - \alpha_F(\lambda_D, T_F)] \epsilon_L(\lambda_D, T_1) E(\lambda_D, T_1)$$

$$I_F = \epsilon_F(\lambda_D, T_F) E(\lambda_D, T_F)$$

where,

λ_D : wave length of D-line (0.5893 μm)

T_1 : true temperature of light source K

$\epsilon_L(\lambda_D, T_1)$: emissivity of tungsten at λ_D, T_1

$\alpha_F(\lambda_D, T_F)$: absorptivity of flame at λ_D, T_F

* Received 23rd April, 1984
** Associate Professor
College of Science and Technology,
Nihon University
1-8 Kanda Surugadai, Chiyoda-ku, Tokyo

$\epsilon_F(\lambda_D, T_F)$: emissivity of flame at λ_D, T_F
 $E(\lambda_D, T_1)$: energy at λ_D, T_1 with reference light source as black body
 $E(\lambda_D, T_F)$: radiant energy of flame assumed as black body at λ_D, T_F

The difference between the energy absorbed by the flame ($I_L - I_{L'}$) and radiation energy I_F of the flame is given by Equation (1).

$$R = (I_L - I_{L'}) - I_F = \epsilon_F(\lambda_D, T_F) \epsilon_L(\lambda_D, T_1) \times E(\lambda_D, T_1) - \epsilon_F(\lambda_D, T_F) E(\lambda_D, T_F) \quad \dots (1)$$

At the reversal point, $R=0$ and from Kirchhoff's Law, emissivity ϵ_F equals absorptivity α_F of the gas in thermal equilibrium. Thus we have

$$E(\lambda_D, T_F) = \epsilon_L(\lambda_D, T_1) E(\lambda_D, T_1) = E(\lambda_D, S_D) \quad \dots (2)$$

$$\therefore T_F = S_D \quad \dots (3)$$

The temperature T_F of the flame and brightness temperature S_D of the reference light source for λ_D are the same. Since the brightness temperature S_D of the reference light source is related to the true temperature T_1 as shown by Equation (2), from Wien's radiation approximation, we have

$$\epsilon_L(\lambda_D, T_1) (C_1/\lambda_D^5) \exp(-C_2/\lambda_D T_1) = (C_1/\lambda_D^5) \exp(-C_2/\lambda_D S_D)$$

Hence we have

$$1/T_1 - 1/S_D = (C_2/C_1) \log \epsilon_L(\lambda_D, T_1) \quad \dots (4)$$

If here the brightness temperature S_R of the reference light source is obtained from an optical pyrometer using a red filter with $\lambda_R = 0.650 \mu\text{m}$ the true temperature T_1 and the brightness temperature S_R are related by the following equation, similar to Equation (4):

$$1/T_1 - 1/S_R = (\lambda_R/C_2) \log \epsilon_L(\lambda_R, T_1) \quad \dots (5)$$

From Equations (3) through (5), we have

$$1/T_F = 1/S_D = 1/S_R + 1/C_2 [\lambda_R \times \log \epsilon_L(\lambda_R, T_1) - \lambda_D \log \epsilon_L(\lambda_D, T_1)] \quad \dots (6)$$

where,

$$C_1 = 3.742 \times 10^{-16} \text{ kW} \cdot \text{m}^2$$

$$C_2 = 1.439 \text{ cm} \cdot \text{K}$$

3. Test Apparatus

3.1 Test apparatus for light path method (holder-type)

Fig. 2 shows the optical system test apparatus. In order to use the spectral D-line reversal method, 0.1 g of sodium in the form of sodium ethylate ($\text{C}_2\text{H}_5\text{ONa}$) is mixed in each liter of gasoline. An automobile halogen lamp is used as a reference light source. The beam from the lamp is passed through the combustion chamber. Using a non-metallic interference filter (central wavelength $\lambda_{\text{max}} =$

Fig.2 Test apparatus for light path method

$0.5894 \mu\text{m}$ and half-width value of $\lambda(1/2) = 0.001 \mu\text{m}$), only the portion of light around the D-line emerges and is introduced into a photoelectric multiplier for output on the oscilloscope. The crankshaft is directly coupled to a disk shutter S.1, having an opening of $\theta = 170^\circ$ in order to facilitate viewing the photoelectric multiplier output during the 4-cycle engine intake and combustion processes.

3.2 Prism-type test apparatus using optical fibers

Fig. 3 shows the schematic diagram of a prism-type test apparatus using optical

Fig.3 Prism-type test apparatus using optical fibers

fibers. For a reference light source and a non-metallic interference filter, the same apparatus mentioned in Section 3.1 is used. Also, 40 mg of sodium in the form of sodium ethylate is mixed in each liter of gasoline. The beam from the reference light source is first passed through an optical fiber, a lens and prism A, then through the flame and again passed through another prism B, a lens and an optical fiber before it enters the photoelectric multiplier. Its output is displayed on the oscilloscope. Instead of a disk shutter S.1 used in the optical system shown in Fig.2, a rotary encoder is used to pick up the crank signal of the crankshaft, together with a signal processor, electrically operating in the same manner as the disk shutter.

Fig. 4 shows a prototype temperature sensor, and Fig.5 shows its cross-sectional view. Prisms A and B are detachable. The establishment of calibration curves between voltage and temperature of the reference light source is done without prism B and with some input losses on a lens next to

Fig.4 Prototype temperature sensor

Fig.5 Cross sectional view of temperature sensor

prism A, an optical fiber and a mirror. The optical fibers and the sensor unit are also made detachable to accommodate optical fibers of a desired length. Sensors with 4 mm and 8 mm gap widths W between prisms A and B were manufactured. The sensor with an 8 mm gap is used to measure gas temperature in the combustion chamber. The seat of this sensor head is 27 mm in diameter. The unit is water cooled since the adhesive around the optical fibers is not heat resistant. Fig. 6 shows an internal view of the signal processor and the light source.

Fig.6 Internal view of the signal processor and the light source

3.3 Test engine

Table 1 Specification of the test engine

4-Cycle Aircooled Gasoline Engine			
Number of Cylinders	1		
Bore × Stroke	85 × 70 (mm)		
Piston Displacement	397 (cm ³)		
Compression Ratio	6.1 (Head A,C,D) 5.8 (Head B)		
Valve Arrangement	Side Valve		
Valve Timing	Intake	Open	42° (B.T.D.C)
		Close	72° (A.B.D.C)
	Exhaust	Open	77° (B.B.D.C)
		Close	37° (A.T.D.C)

Fig.7 Cylinder heads and locations for temperature measurements

Table 1 gives the specifications of the test engine, and Fig.7 shows cylinder heads and their locations for temperature measurements. Small differences in the head shape were recognized in different methods of measurement. Aluminum alloy head A was used to in the light path method. Case iron head B was used to obtain temperature distribution in the light path. Cast iron head C was used for comparison tests between prism-type and holder-type temperature sensors. Aluminum alloy head D was also used as a commercially available head. Compression ratios for these heads are shown in Table 1. The light path in the observation window is 4 mm in diameter.

4. Indication of Gas Temperature

4.1 Continuous indication of gas temperature (temperature scaling)

When the engine is fired without the light source using the light path method shown in Fig.2, a humped output waveform as shown in Fig.8(a) for the flame alone is displayed on the oscilloscope during the

Fig.8 Temperature scaling

combustion process. Elevating the temperature of the light source causes a rectangular waveform for the light source alone during the suction process, and a superimposed waveform of the rectangular and the humped ones for the flame during the combustion process appears as shown in Fig.8(b). At both intersections A_1 and B_1 of the rectangular and curved waveforms in Fig. 8(b), the radiation energy I_F of the flame equals the energy of the light source absorbed by the flame ($I_L - I_L'$); thus $I_L' + I_F = I_L$. In other words $I_L' + I_F$ during the combustion process equals I_L during the suction process. These are the reversal points at this temperature. Flame temperature T_{F1} equals brightness temperature S_{D1} of the light source during the suction process. From the crank angles θ_1 and θ_1' corresponding to these reversal points A_1 and B_1 respectively, it can be seen that flame temperature T_{F1} for θ_1 and θ_1' equals brightness temperature S_{D1} of the light source, as shown in Fig.8(a); Likewise by increasing the temperature and voltage of the light source, reversal points A_2 and B_2 are set, corresponding to θ_2 and θ_2' , enabling T_{F2} to be scaled on the flame waveform as shown in Fig. 8(a). Thus, by varying brightness temperature S_D of the light source, a temperature scale can be established on the output waveform of the flame shown in Fig. 8(a).

Variations in Fig. 8 were observed on the oscilloscope. The results are shown in photos with a multiple-exposure in Fig.9. In this test, reversal points were decided by reading mean values for about 25 cycles. In Fig. 9(a), the top display represents cylinder pressure P , the middle represents output waveform I_F of the flame and the bottom represents crank angles C.A. Figs. 9(b) through 9(d) show some outputs obtained by elevating the voltage and temperature of the light source, and the horizontal lines represent voltage V . Fig.9(d) also shows that the maximum point of flame temperature is inverted.

Fig.9 Reversal process

Fig.10 Continuous indication of gas temperature

Fig. 10 shows a flame output waveform with a temperature scale obtained by this method. From this, gas temperature for any crank angles can be known.

4.2 Effect of clouding of observation windows

Clouding of the observation windows is significant during cold starting. This can be reduced by running at a lean mixture ratio after a sufficient warm-up period. Keeping the voltage of the light source constant, the output of the light source alone is observed during the suction process of a firing run. Fig.11 shows variations in transmittance during the operation, with the output at the start-up rated

Fig.11 Variations in transmittance of observation windows

as 1. If a measurement is started after a sufficient warm-up period, transmittance will not significantly decline for about 3 min. This transmittance is affected by the clouding of both observation windows. When establishing calibration curves between temperature and voltage of the light source, only the effect of the clouding of observation window W.1 has to be taken into consideration. It is safe to assume that transmittance will not practically decline for about 6 min, twice the time mentioned above. Directly after an operation for a period in which no practical decline is caused in the transmittance of the observation windows, observation window W.2 on the interference filter side is removed to establish calibration curves for the light source considering the effect of window clouding.

5. Test Results and Review

5.1 Results of measurement by continuous indication of gas temperature

The temperature of combustion gas as continuously indicated in Fig. 10 is under the following operational conditions with head A: net mean effective pressure $P_{me} = 0.35$ MPa (3.54 kgf/cm²), mixture ratio $MR = 12.5$, speed $N = 2000$ rpm and spark timing $\theta_{ig} = 30^\circ$ (BTDC). The point for measurement of gas temperature is at 44 mm toward the center of the combustion chamber from the spark plug. As shown in the photo, the point at which the flame reaches the observation window is near the top dead center. The gas temperature reaches its maximum, around 2050 °C, at about 12° after the top dead center. The relationship between temperature T and interval H shown in the temperature scale is given by $H \propto T^{11.5}$, as shown in Fig.12(a). The

(a) Relationship between temperature T and interval H

(b) Calculated radiation energy

Fig.12 Temperature scaling and calculated radiation energy

results obtained by substituting the wavelength of the D-line (interference filter center wavelength $\lambda_{max} = 0.5894 \mu\text{m}$) and the range of temperature measured (1600–2500 K) into Planck's equation for mono-chrome radiation energy

$$E_\lambda = C_1 \lambda^{-5} / [\exp(C_2/\lambda T) - 1]$$

are shown in Fig.12(b). From this, $E_\lambda \propto T^{12}$ is obtained, which generally agrees with the test result $T^{11.5}$ shown in Fig.12(a). Fig.13 shows the relationship between flame

Fig.13 Measured and calculated gas temperature

temperature T_f and crank angle θ obtained from the results of visually reading the mean values of about 25 cycles by the temperature scaling method shown in Fig. 8 of Section 4.1. Operational conditions are

speed $N=2000$ rpm, spark timing $\theta_{ig}=30^\circ$ (BTDC) and mixture ratio kept nearly constant while net mean effective pressure P_{me} is varied. Fig.13 shows measured gas temperatures together with calculated ones obtained from the combustion-pressure waveform by using $PV=mRT$ [$R=0.294$ kJ/(kg.K) assumed to be constant]. The calculated gas temperatures are mean values in the entire combustion chamber. In practice, there are local differences in gas temperature. If there is any temperature distribution in the light path, measured values will be than the maximum temperatures in the center and higher than the arithmetic means. In the initial phases of combustion, measured values of gas temperature are found to be higher than the calculated ones. In the later phases, there is less discrepancy. This is because of large variations in the mol number of the gas in initial phases, which will decline in the later phases. Also, it is presumed that in the range over 30° after the top dead center, the difference between measured and calculated values is smaller because the flame reaches the cylinder edge and the temperature becomes even on account of the expansion of the cylinder volume resulting from piston descent.

5.2 Temperature distribution in light path for measurement

The optical system in Fig.2 uses a non-metallic interference filter, central wavelength $\lambda_{max}=0.5922$ μm and half-width value $\lambda(1/2)=0.002$ μm . The maximum point of the flame is observed for 1 minute as shown in the photo in Fig. 9(d) to read a reversal point. While net mean effective pressure P_{me} is varied, using cast iron head shown in Fig.7, with speed $N=2800$ rpm and spark timing $\theta_{ig}=20^\circ$ (BTDC), measurements are made by dividing the distance 66 mm along the X-X' line by the tip gap d of the observation window holder. The results of the measurements with $d=7.5$ mm around the center of the cylinder, and $d=6.75$ mm and 3 mm near the wall are shown in Fig.14.

Fig.14 Temperature distribution in light path for measurement

With $d=1$ mm, the flame hardly gets into the gap, making measurement impossible. Around the cylinder center, measured values are nearly constant and at about 3 mm from the wall, the gas temperature drops.

5.3 Results of measurement using optical fiber prism-type temperature sensor

Table 2 Alcohol flame temperature

W	Sensor (prism type) [°C]	Pt-Rh [°C]
4 (mm)	1060	960 (1010) *
8 (mm)	1190	1110 (1180) *

* Correction due to radiation effect

Table 2 shows the results of simultaneous measurements, as a preliminary test, of alcohol flame temperature with a prototype prism-type temperature sensor and a thermocouple (Pt-Rh; wire diameter $d=0.1$ mm). Correction for radiation effects is based on the assumption of a flame flow speed of 0.1 m/s. The flame temperatures obtained with the prototype prism-type sensor agree with those with the thermocouple.

Fig.15 Comparison between prism-type (sensor) and holder-type

Fig. 15 compares the measured values obtained with a conventional holder-type having 2 observation windows with those obtained with the prism-type. These gas temperatures tested were compared in reading reversal points by observing about 500 cycles with cast iron head C shown in Fig. 7 and in varying net mean effective pressure. The operational conditions were speed $N=2000$ rpm, and spark timing $\theta_{ig}=30^\circ$ (BTDC). As shown in Fig. 15, there is no significant difference in measured values between the two methods. The lengths of the light path were 8 mm for the prism-type temperature sensor and 27 mm for the holder-type. It was presumed that the measured values with the temperature sensor might be lower due to water cooling of the

sensor. In fact, there is no such trend recognized, and the effect of the temperature sensor tip on the combustion gas is considered small.

Fig.16 Comparison between cast iron head(Fe) and aluminium head(Al)

Fig. 16 shows, as an example of measurement, gas temperatures measured with the prism-type temperature sensor having cast iron head C and aluminum alloy head D, with respect to net mean effective pressure Pme. It also shows the temperature of the plug center pole and the spark plug washer. In relation to net mean effective pressure Pme, these temperatures with the aluminum head are all lower than those with the cast iron head.

6. Conclusions

This study developed a new technique for indicating gas temperatures in the spark ignition engine by using the spectral D-line reversal method. The following conclusions were obtained.

(1) The new method enables a temperature scaling of the output waveform of the energy emitted from the flame and a continuous indication of gas temperatures for given crank angles. And, it has been proved valid.

(2) The new technique discloses temperature distribution in the light path in the combustion chamber.

(3) The prism-type temperature sensor having one observation window enables measurement at any location. The sensor is made compact by consolidating the optical fibers with prisms and lenses, thus enabling comparison of measured values with those obtained by the light path method (holder-type).

Finally, the author expresses his gratitude to Professor A.Saima who offered useful suggestions in this study.

References

- (1) Rassweiler, G., SAE J. (Trans.), 36-4(1935), 125
- (2) Awano, Rept. Aero. Res. Inst. (in Japanese), 18-242(1942), 369
- (3) Ogasawara, Trans. Jpn. Soc. Mech. Eng. (in Japanese), 37-304(1971), 2336
- (4) Shimizu, Trans. Jpn. Soc. Mech. Eng. (in Japanese), 38-310(1972), 1495
- (5) Sasaki, et al., Trans. Soc. Auto. Eng. (in Japanese), 752-84(1975), 543
- (6) Klick, D., et al., SAE Technical Paper Series, 810227(1981), 1
- (7) Shoji, Prepr. of Jpn. Soc. Mech. Eng. (in Japanese), 790-6(1979-6), 111