Temperature Measurement of Flame in a Gasoline Engine*
(1st Report, Measurement of Average Temperature)

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One method to measure the instantaneous flame temperature within the cylinder of a gasoline engine by means of the absolute radiation method is proposed. The radiation energy of D-line emitted from a trace of sodium, which is added to fuel, is measured by an optical-electronic system. Then, the measured energy is converted into the equivalent black body temperature. This temperature may be considered as the flame temperature which is averaged through an optical path in the luminous flame zone. In the process of conversion, the half-width of D-line is determined experimentally and the number of Na atoms radiating in the optical path is evaluated theoretically.

As the optical system, a quartz window, 4 limiting diaphragms, an interference filter and a fiberscope are arranged in order. And a light beam having 1 mm in diameter is introduced to a photomultiplier by means of the fiberscope.

By this technique, the flame temperature in CFR engine is measured under various operating conditions.

1. Introduction

In order to describe the combustion process in an internal combustion engine, it is required to know not only the pressure and volume, but also the temperature of gas at any instant. Even if a gas diagram, in which temperature dependence of specific heat and thermal dissociation are taken into account, were given, and the pressure and volume at any crank angle were measured, the gas temperature could not be determined correctly. Moreover, uneven temperature distribution must exist in the combustion chamber due to flame propagation and due to Hopkinson's effect(1). For the above reason, several methods to measure the burning gas temperature directly have been proposed in accordance with each research object.

The object of the present study is to measure the varying gas (or flame) temperature in a combustion and expansion stroke of a gasoline engine. For such a purpose, El Wakil et al.(2) have already devised an excellent method capable of continuous measurement, based upon the principle of spectral line reversal technique. However, it is complicated considerably in structure of apparatus and in calibration of instruments.

In the present paper, the authors propose a different continuous method of measuring the flame temperature by means of absolute radiation technique. The radiation energy of Na-D line emitted from hot gas, in which a trace of metered sodium has been added, is measured by an optical-electronic system. Then, the measured energy is converted into the equivalent black body temperature.

By employing this method, it has become possible to make the apparatus much simpler than that of the spectral line reversal technique. Especially, as for the number of quartz windows, through which the light beam from the flame is taken out, one window instead of two required in the latter case is sufficient. On the other hand, because of this simplification, it can not be denied that preliminary tests and process of calculation become cumbersome a little.

However, by this method, the temperature distribution of the burning gas in the combustion chamber can be measured at any crank angle. This item will be discussed in the 2nd Report.

2. Fundamentals of measuring method

2.1 Assumption and measuring principle

According to spectroscopic studies on the gas burning in gasoline engines, it has been reported that any spectral lines do not appear in the neighborhood of Na-D line in the case of normal combustion(3).
And, it has been known also that a trace of sodium, added to fuel, does not change the engine performance. And, since the relaxation rate of molecular phenomena is much faster than the rate of temperature change of gas, it may be assumed that the optically measured temperature of Na represents the thermodynamic temperature of gas around it at any instant.

Based upon the above facts, the following procedure is adopted in our study. A trace of metered sodium is mixed into fuel, in the form of sodium-ethylene (C2H4Na). Then, Na-D line is contained in the light from the flame. This yellow light is introduced to a photomultiplier, after passing through a quartz window and an interference filter. Since its output corresponds to the radiation energy emitted from Na of known quantity, the corresponding black body temperature can be calculated from its reading.

### 2.2 Fundamental theory

Radiation intensity distribution of D-line at an absolute temperature \( T \) is given by the following Wien's equation.

\[
I = a(\lambda) C_1 \lambda^2 \exp(-C_2/\lambda T) \quad \text{(1)}
\]

where \( C_1 = 3.742 \times 10^{-5} \text{ erg cm}^2\text{sec} \), \( C_2 = 1.438 \text{ cm}^6\text{K} \), and \( a(\lambda) \) is emissivity of D-line. Then, the radiation energy \( E \) can be obtained by integrating \( I \) between \( \lambda = 0 \) and \( \infty \). By spectroscopic study, it has been known that \( I(\lambda) \) of the D-line consists of two bell-shaped curves having two peaks at 5890 and 5896 Å, respectively. But, they are usually put together into a single curve having a peak at \( \lambda_D = 5893 \text{ Å} \), so as to have equal energy in both cases, as shown in Fig. 1. Since the half-width of this composed curve is very narrow, it may be assumed that the black body radiation over this range has a constant intensity and its value is equal to that at \( \lambda_D \). Then the energy of D-line can be given by

\[
E = (C_1/\lambda_D^3) \exp(-C_2/\lambda_D T) \int_\lambda^{\infty} a(\lambda) \text{d}\lambda \quad \text{(2)}
\]

If this energy \( E \) is introduced to a photomultiplier, as shown in Fig. 2, the oscilloscope must show a deflection \( \delta \) in proportion to it. Denoting this proportionality constant as \( K \), we have,

\[
\delta = KE = K' \exp(-C_2/\lambda_D T) F \quad \text{(3)}
\]

where

\[
F = \int_\lambda^{\infty} a(\lambda) \text{d}\lambda, \quad K' = KC_1/\lambda_D^3 \quad \text{(4)}
\]

Therefore, if \( \delta, K', F \) are given the gas temperature \( T \) can be obtained from the above equation. Because the constant \( K' \) can be determined by a calibration test using a flame of known temperature, the unknown gas temperature \( T \) can be found, provided that the value of \( F \) is given. \( F \) will be considered in the following.

Generally, the emissivity of gas, \( \alpha \), is given by

\[
\alpha = 1 - \exp[-f(\lambda)z] \quad \text{(5)}
\]

In this equation, \( z \) is a dimensionless quantity giving the concentration of Na atoms in the gas. And, \( f(\lambda) \) is a shape factor specifying the bell-shaped intensity distribution curve mentioned in the above, and it is a function such that its integrated value over the range of \( \lambda = 0 \sim \infty \) makes unity. This \( f(\lambda) \) is characterized by the half-width \( W \) (Fig. 1). \( W \) is a function which is broadened by Doppler's effect and pressure effect. Denoting such \( W \) as \( W_D \) and \( W_p \) respectively, \( f(\lambda) \) can be written as follows:

Doppler broadening:

\[
f(\lambda) = \left(1/\sqrt{\pi}\right) \left(1/W_D\right) \exp(-\Delta\lambda/W_D^2)^2, \quad \text{(6)}
\]

Pressure broadening:

\[
f(\lambda) = \left(1/\pi\right) \left(W_p/(W_p^2 + \Delta\lambda^2)\right) \quad \text{(7)}
\]

\[
W_D = 1.18(\lambda_D/\epsilon) \sqrt{\gamma N_0 \sigma M} \quad \text{(6)}
\]

\[
W_p = 2\sigma^2/\epsilon \quad \text{(7)}
\]

where \( \Delta\lambda = |\lambda - \lambda_D| \); \( \epsilon \) is the velocity of light; \( \gamma \) is the universal gas constant; \( M \) is the molecular weight of the gas; \( N_0 \) is Avogadro's number; \( \sigma \) is the collision diameter of the molecule; and \( p \) is the pressure. The relation between \( W_D \) or \( W_p \) and \( T \) under atmospheric pressure is shown in Fig. 3(4). \( W_D \) is the half-

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Fig. 1

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Fig. 2

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Fig. 3
width in which both effects are put together into $W_p$ from the standpoint of energy. As shown in this figure, even when the gas temperature is high, both effects are nearly of the same order, provided that the gas is kept at atmospheric pressure. When the pressure is raised, $W_p$ increases proportionally, while $W_D$ remains the same. However, in a case where $p$ and $T$ are 10 ata and 2800 K, respectively, the radiation energy due to $W_D$ contributes by only 2% of that of $W_p$. Therefore, in the condition prevailing in the gasoline engine cylinder, it is sufficient to consider only the pressure effect.

Though several quantities difficult to treat as variables strictly are contained in $W_p$, it can be assumed that those excepting $p$ and $T$ can be lumped together into a constant $A$, approximately. This assumption will be verified later by the results of calibration tests carried out on $K'$. Then, $W_p$ can be written approximately as follows:

$$W_p = ApT^{-3/2} \tag{8}$$

Substituting this into Eqs. (7) and (5), we have,

$$\alpha = 1 - \exp \left( \frac{W_p}{W_p + \lambda W_p} \right) \tag{9}$$

where $z$ is a quantity proportional to $N$, and $N$ is the number of Na atoms existing in the light path of unit sectional area. Further, rewriting $z$ into

$$z/\pi = BN \text{ or } z = \pi W_p / (\pi W_p + BN) \tag{10}$$

then $\alpha$ can be written as follows:

$$\alpha = 1 - \exp \left( \frac{1}{1 + (\lambda - \lambda_D)^2 / W_p} \right) \tag{11}$$

In making the integration shown by Eq. (4), if the variable is changed from $\lambda$ to $(\lambda - \lambda_D)/W_p$, the lower limit changes from 0 to $-\lambda_D/W_p$. However, according to the calculation by Bundy et al., the value of $\lambda_D/W_p$ is so large that the lower limit can be replaced by $-\infty$ approximately. So, $F/W_p$ is determined by only a quantity $z'$ or $N$. Figure 4 shows such a curve expressing $F$ for any given $z'$. Then the problem reduces to the determination of $N$.

3. Determination of Na concentration in the light path

In order to measure $N$ (or $z$ or $z'$), we have devised two methods. Though the first method is not used in the present study, it will be outlined below, because its experience is utilized in the second method.

Figure 2 shows the optical system which will be used later in the second method. In the first method, one more window is mounted on the right side wall of combustion chamber, and, to the right of it, a light chopper (~20,000 rpm) and a mirror are arranged in line. When the chopper is closed, radiation from the flame comes to a photomultiplier directly. But, when the chopper is opened, radiation reflected from the mirror is added to the above. Therefore, the deflection of oscilloscope varies alternately from $\delta$ to $\delta_m$ depending on the revolution of the chopper. On the other hand, when the transmissivity of window, $\tau$, and the reflectivity of mirror, $\rho$, are given, $(\delta_m - \delta)/\delta$ can be calculated theoretically as a function of $z$. Therefore, $z$ can be determined when $\delta$ and $\delta_m$ are measured.

In this method, the quantities difficult to evaluate can be omitted and only the number of Na atoms emitting light in the path can be measured. However, the slope of the curve of $(\delta_m - \delta)/\delta$ versus $z$ is so gentle, especially in the region $z > 3$, that it is difficult to read $z$ accurately from a given $(\delta_m - \delta)/\delta$. For this reason, this method is not used in the present study. But, conversely, it may be said that the gas temperature to be measured is not so sensitive to $z$. Based upon the above, in the 2nd method, $N$ will be evaluated by calculation with some approximations. Its procedure will be outlined as follows.

Let Na concentration in a fresh charge before the inlet valve be $N_0$ atoms/cm$^3$, and the charging efficiency considering the residual gas be $\eta$, then Na concentration in the charge just before compression can be written as $\eta N_0$. Denoting the compression ratio at any crank angle, $\phi$ degree, by $e_\phi$, the concentration will increase $e_\phi$ times. Therefore, let the length of a luminous part in the light path be $l$, then,

$$N = e_\phi \eta N_0$$

atoms/cm$^3$ \hspace{1cm} \tag{12}$$

where $l$ increases with the distance of flame travel. However, to evaluate $l$ and $N_0$, correction due to thermal expansion must be considered. This correction is conducted by using the mass fraction of burned
gas, \( m \), which is measured on the indicator diagram. The detail of this procedure will be given in Chapter 5.

4. Experimental apparatus

As shown in Fig. 5, the cylinder head of a CFR engine (1 200 rpm) was rebuilt and a quartz window was mounted on its left side wall. But, a window and a bar shown on the right side in the figure were not used in the present experiment and they will be used later in the 2nd Report. A surge tank for measuring the air quantity was installed at the entrance of a suction pipe. A long spark plug was used so as to make the gas ignite at the center of the combustion chamber. Engine speed was changed by varying the load of hydraulic dynamometer which was coupled directly with the engine.

Figure 6 shows the optical system. The ray from the flame was introduced into a photomultiplier after passing through a window, 4 aperture limiters, an interference filter (for Na-D line use; 50 Å half-width) and a fiberscope. Then, it may be considered that only D-line is passed through the filter without any deformation in its spectroscopic shape. This radiation energy was recorded on the oscilloscope as the output of photomultiplier. As the photomultiplier, 1P21 was used.

5. Calculation of \( N_0 \), \( \eta_f \), \( \varepsilon_f \) and \( I \)

In the following, the quantities involved in Eq. (12) are considered.

5-1 Na concentration in fresh charge, \( N_0 \)

Adding \( x \) mg of Na to 1 cc of methanol, and mixing it into fuel at the rate of \( \gamma \% \) in volume, the number of atoms contained in 1 g of fuel can be expressed by

\[
1 \times \frac{N_0}{\gamma_f} \times 10^{24} \text{ atoms/g}
\]

Denoting the molecular weight of fuel and air by \( M_f \) and \( M_a \) (g/mole) respectively, and the inlet temperature by \( T_r \), then the volume of mixture composed of \( \mu \) g of air and 1 g of fuel is given by the following under the standard atmospheric pressure.

\[
22.416 \times 10^{-3} \left( \frac{1}{M_f} + \frac{\mu}{M_a} \right) \frac{T_r}{T_0} \text{ cm}^3 / \text{g}
\]

Regarding the pressure in intake pipe as the standard atmospheric pressure, then \( N_0 \) can be written by the ratio of the above mentioned quantities as follows.

\[
N_0 = 1.176 \times 10^{13} \frac{x \gamma}{T_r} \left( \frac{1}{M_f} + \frac{\mu}{M_a} \right) \frac{1}{T_r} \frac{T_0}{T_r} \text{ atoms/cm}^3
\]

In the following experiment, values of \( M_a = 28.96 \), \( M_f = 114.23 \) (for octane) will be used.

5-2 Charging efficiency, \( \eta \)

Denoting the weight of gas actually presents in the cylinder by \( G \), and the theoretical weight of gas occupying the total cylinder volume under the standard atmospheric pressure by \( G_{th} \), then \( \eta \) is defined as follows.

\[
\eta = \frac{G}{G_{th}}
\]

Further, denoting the stroke volume by \( V_s \), the compression ratio by \( \varepsilon \), and the compression ratio at the exhaust valve closing by \( \varepsilon_s \), then the volume of residual gas is given by \( V_s(1/\varepsilon_s) (\varepsilon / (\varepsilon - 1)) \). Converting this into the state under temperature \( T_s \) from the exhaust gas temperature \( T_e \), and denoting the volume of inlet air by \( V_e \), then the volume corresponding to \( G \) can be written as follows.

\[
V_e = V + (V_s/\varepsilon_s) \frac{\varepsilon}{(\varepsilon - 1)} \frac{T_s}{T_e} \]

On the other hand, \( V_{th} \) corresponding to \( G_{th} \) is

\[
V_{th} = V_e(1/\varepsilon - 1)
\]

Then, \( \eta \) is given by \( \eta = V_e/V_{th} \) approximately.

The above \( V \) can be written in another way by using the weight of inlet air, \( G_a (g / h) \). For a case of four stroke cycle engine of \( n \) rpm, the following equation is well known.

\[
V = \frac{G_a}{60n/2} \left( \frac{1}{M_f} + \frac{\mu}{M_a} \right) \frac{T_r}{T_0} \times 22.416 \times 10^{13} \text{ cm}^3
\]

Assuming \( T_r = 273.2^\circ \text{K}, T_e = 100^\circ \text{K}, \) and substituting \( V_s = 398.5 \text{ cm}^3 \) for the engine to be tested in the above equation, the following relation is obtained.

\[
\eta N_0 = 2.205 \times 10^{13} \frac{x \gamma}{T_r} \frac{G_a}{n \mu / \varepsilon} + 3.835 \left( \frac{M_a}{M_f} \right) \frac{T_s}{T_e} - 3.835 \left( \frac{M_a}{M_f} \right) \frac{T_s}{T_e}
\]

5-3 Compression ratio at crank angle \( \phi \), \( \varepsilon_f \)

Denoting the ratio of the lengths of connecting rod and crank arm by \( b \), \( \varepsilon_f \) is given in the following well-known form.

\[
\varepsilon_f = \frac{2 \varepsilon}{(\varepsilon + 1)} + (\varepsilon - 1)(b - \cos \phi)
\]

\[
- \sqrt{b^2 - \sin^2 \phi}
\]

By this equation, \( \varepsilon_f - \phi \) curve can be drawn beforehand. For the engine to be tested, \( b = 40/9 \).

5-4 Length of luminous part in light path, \( l \)

On the relation between the mass fraction and the volume fraction of burned gas in a
combustion bomb, many studies have been reported\(^{(9)}\). But, in the present case, the volume change of the chamber during combustion must be also considered.

Denoting the pressures at initial and final stages of flame propagation by \(p_i\) and \(p_f\) respectively, the mass fraction of burned gas, \(m\), at any pressure \(p\) is given by

\[
m = \frac{(p-p_i)}{(p_f-p_i)}
\]

In the case of engine, both \(p_i\) and \(p_f\) are variables. Rewriting \(p_i\) into \(p_t\), which varies with degree of compression, we have,

\[
m = \frac{(p/p_t)-1}{(p_f/p_t)-1}
\]  \((17)\)

Figure 7(a) shows the pressure curves under firing and motoring conditions. Since \(p_f/p_t\) may be approximated with a maximum value of \(p/p_t\), \(m\) can be obtained by Eq. (17) and Fig. 7(a). The volume fraction of burned gas, \(v\), can be related with \(m\) as follows. Denoting the polytropic exponent by \(\nu\), the following relation holds.

\[
p_t(1-m)^{\nu} = p(1-v)\nu
\]

Therefore,

\[
v = 1 - (1-m)(p_f/p_t - 1)m + m - \frac{1}{\nu}
\]  \((18)\)

During the period of flame propagation, the density of Na in the burned gas will be decreased due to thermal expansion. Then, Eq. (12) must be modified as follows.

\[
N = \frac{\epsilon \eta N_0 \delta m}{v}
\]  \((19)\)

In this equation, \(l\) can be replaced by \(v\) in the following way. When the flame propagates cylindrically from the center of combustion chamber, \(v\) and \(l\) are given respectively by

\[
v = \frac{r^2}{2l}, \quad l = 2r = 2R\sqrt{v}
\]

where \(l\) is the length of optical path perpendicular to the cylinder axis. Therefore,

\[
N = 2R\epsilon \eta N_0 \delta m/v
\]  \((20)\)

When the flame spreads throughout the chamber, \(m/v\) becomes equal to unity. Figures 8(a) and (b) show cases in which the flame propagates cylindrically and spherically, and (c) shows the results calculated on each case. Comparing two curves given in (c), it will be seen that the difference is small. For a case when the spark plug is located at the end of combustion chamber, the flame shape must be assumed beforehand. Concerning this, we have used a result measured by Curry\(^{(9)}\).

As stated before, since the gas temperature \(T\) is not so sensitive to the Na concentration, \(l\) may be evaluated with sufficient accuracy by the above procedure.

In Fig. 7(b), one set of the calculated results of \(m\), \(v\) and \(m/v\) are shown.

Since \(N\) may be evaluated by the above procedure, if \(B\) is assumed to be given, \(z\) can be determined by Eq. (10). Or again, provided that \(A\) is given, \(W\) and \(z\) can be determined by Eqs. (8) and (10) respectively, and then \(F\) can be found from Fig. 4. Therefore, if \(K'\) is measured elsewhere, \(T\) can be determined by Eq. (3). However, since unknown \(T\) is involved in Eq. (8), the above procedure must be conducted by iterative method.
As stated above, to find $T$, constants $A$, $B$ and $K$ must be determined elsewhere.

**6. Preliminary experiments**

To find $A$, $B$ and $K$, the scale of oscilloscope reading must be calibrated by comparing the radiation energy of D-line emitted from the flame of known temperature and known Na concentration. As such a light source, we used the flame in the combustion chamber of the test engine itself. By taking out the light stroboscopically at a specified crank angle, its temperature was determined by the D-line reversal technique which had been developed already.

However, if another steady and uniform light source in high temperature and pressure is available, it is preferable for the present purpose.

**6.1 Determination of $A$ and $B$**

As stated above, taking the burning light out of the combustion chamber stroboscopically, and regarding it as a steady flame, its temperature was measured by D-line reversal method. And the pressure was recorded by indicator. At the same time, spectroscopic pictures of the above D-line were taken and intensity distribution curves were obtained from them by means of a microphotometer. Figure 9 shows such a typical curve smoothened a little.

Denoting the half-width of D-line having the Na concentration $N$ by $W_N$, then, from its definition,

$$\alpha_{1-2D} = 2\alpha_{1-2D} W_N$$

Substituting this into Eq. (11), then

$$\frac{1}{2} \left[ 1 - \exp \left( -\frac{BN}{W_p} \right) \right] = 1 - \exp \left( -\frac{1}{1 + (W_N/W_p)^2} \frac{BN}{W_p} \right)$$

where $W_p$ is a half-width of the normalized shape function which is generally larger than the actual half-width $W_N$. Equation (22) can be rewritten as follows.

$$\left( \frac{W_N}{W_p} \right)^2 = \ln \left[ \frac{1 + \exp \left( -\frac{BN}{W_p} \right)}{2} \right] - 1$$

(23)

Now, supposing that, at the same crank angle, $W_{N1}$ and $W_{N2}$ were measured corresponding with the concentrations $N_1$ and $N_2$ respectively, then, since both cases are in the same state,

$$W_{N1}^2 = \frac{DN_1 - \ln \left[ 1 + \exp \left( \frac{DN_1}{2} \right) \right]}{2}$$

$$W_{N2}^2 = \frac{DN_2 - \ln \left[ 1 + \exp \left( \frac{DN_2}{2} \right) \right]}{2}$$

$$\times \ln \left[ 1 + \exp \left( \frac{DN_2}{2} \right) \right]$$

(24)

where $D = -B/W_p$. From this, $D$ can be determined by trial method. Then, $A$ and $B$ can be found as follows.

$$A = \frac{W_N \sqrt{T}}{p} \left[ \ln \left( \frac{DN}{1 + \exp (DN)} \right) \right]^{-1/2}$$

$$B = -D W_p$$

(25)

To find $D$ from Eq. (24), it is convenient to prepare a curve of $\ln \left( 1 + \exp (DN) \right)$ versus $DN$ beforehand.

In the present experiment, $A$ and $B$ were determined by the data of $p$ and $T$ obtained at five different $\phi$ in the expansion stroke. Three sets among them are shown in Table 1. In the following experiment, their average values were used.

In the above preliminary experiment, $p$ was measured by a strain gauge type indicator. To measure $T$, one more quartz window was mounted on the right side of cylinder wall and a calibrated tungsten lamp was located behind it. Then the flame temperature $T$ was determined from the input of the lamp under the condition of spectral line reversal. However, the apparent temperature $T'$ at the reversal point is not equal to the true temperature $T$, because the window between the lamp and flame may absorb some radiation energy.

| $\phi$, $\%$ | ATC | 12.2 | 23.7 | 35.2 |
| $\varepsilon_\phi$ | 5.45 | 4.70 | 3.80 |
| $10^{-19} N_1$ | 0.585 | 0.504 | 0.407 |
| $10^{-19}$ atoms/cm$^2$ | 1.0 | 1.168 | 1.007 |
| $N_2$ | 1.5 | 1.755 | 1.503 |
| $N_3$ | 1.5 | 1.755 | 1.503 |
| $W_N$ | 0.700 | 0.535 | 0.405 |
| $W_{N1}$ | 0.810 | 0.627 | 0.472 |
| $W_{N2}$ | 0.910 | 0.736 | 0.553 |
| $W_{N3}$ | 1.010 | 1.319 | 1.523 |
| $W_{N1}/W_{N2}$ | 0.861 | 1.546 | 1.884 |
| $W_{N2}/W_{N3}$ | 28.63 | 22.60 | 17.10 |
| $T$, °C | 2595 | 2443 | 2252 |
| $10^4 A$ | 1.080 | 0.984 | 0.960 |
| $W_{N1}$ | 6.14 | 6.00 | 5.45 |
| $W_{N2}$ | 1.128 | 0.941 | 0.907 |
| $W_{N3}$ | 5.45 | 6.66 | 6.15 |
correct this effect, we used the following well-known formula.
\[ 1/T = 1/T' - (\lambda_0/C_2)\ln\tau \] ..............................(26)
where \( \tau \) is the transmissivity of a quartz window for D-line.

6.2 Calibration of \( K' \)

Under the same conditions as mentioned above, \( K' \) can be found from the oscilloscope reading \( \delta \). To calculate \( K' \), Eq. (3) is available. But, in order to take the absorption by quartz window into account, \( \tau \) must be multiplied to its denominator. For a case when 1% of \( C_2H_5OH \) has been added to the fuel (nonleaded PF naphtha), we get \( K' = 6.26 \times 10^{18} \) as an average value for five measured points. Three sets of data among them are shown in Table 2. As a matter of course, \( K' \) varies with the degree of amplification. \( \Delta T \) given in the Table indicates the differences between the temperatures calculated using the above average value and those using the individual values of \( \delta, A \) and \( B \). Thus, \( \Delta T \) due to errors of \( A \) and \( B \) did not exceed \( 5^\circ \)K. But, as a total error, the error due to the reversal technique must be added to it.

In the above process, it must be noted that the unknown \( T \) is involved in \( W_p \) which is needed in the course of calculation of \( F \). However, calculating \( z' \) up to 50, it was found that the following relation exists approximately.

\[ F \propto W_p \sqrt{z'} \text{ or } F \propto T^{-1/4} \] ..............................(27)
In this manner, the influence of \( T \) upon \( F \) is relatively weak. Therefore, \( T \) may be calculated by using a value of \( F \) corresponding with a mean temperature within the presumed range. For example, considering a case in which \( T \) varies from 2 100 to 2 700^\circ\)K, a value of \( T \) which was calculated by using \( F \) at 2 400^\circ\)K differed only \( 3^\circ \)K from the value calculated by successive approximations.

7. Remarks on the measurement

(1) In the above discussion, we have ignored the absorption by the non-luminous Na atoms which exist in the light path. However, when \( N \) is increased, self-reversal appears. In our preliminary experiment, it was experienced that, when \( y \) was raised over 1%, an apex of the intensity curve, such as shown in Fig. 9, began to sink. But, as shown later (Fig. 12), it was confirmed that the gas temperature to be found was scarcely affected by this effect. In general, to reduce the above effect, a lower \( y \) is desirable, but, to make the measurement easier, a higher \( y \) is convenient. So, the value of \( y = 1\% \) was adopted in the following experiment.

(2) To mix \( C_2H_5OH \) into fuel, considerable stirring was required. Especially when a pure substance such as iso-octane was used as a fuel, \( C_2H_5OH \) was apt to separate from it. In such a case, fuel must be stirred over feeding.

(3) In the above discussion, it was assumed that the detected D-line depends solely upon Na added to the fuel. However, it was found in our experiment that, in the cases when the air-fuel ratio has been decreased below 10 or when the knocking has occurred, soot was formed in the flame and a continuous spectrum appeared as the background. For these cases, our method is unavailable.

(4) Blurring of window during measurement is inevitable. Figures 10(a) and (b) show the change of \( \tau \) of a window versus the time of operation. From

<table>
<thead>
<tr>
<th>Table 2</th>
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<tbody>
<tr>
<td>( K' ) (( y=1% ))</td>
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<tr>
<td>( \delta ) cm</td>
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<tr>
<td>( F(W_p, z') )</td>
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<tr>
<td>( W_p ) Å</td>
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<tr>
<td>( z' )</td>
</tr>
<tr>
<td>( 10^9F )</td>
</tr>
<tr>
<td>( 10^9exp(-C_2/\Delta T) )</td>
</tr>
<tr>
<td>( 10^{-18}K' )</td>
</tr>
<tr>
<td>( \Delta T ) °K</td>
</tr>
</tbody>
</table>

Fig. 10
these curves, it may be seen that non-led gasoline having the inlet mixture temperature above 90°C did not cause the window to blur within a few minutes. The blurring, which occurred in a case of low inlet temperature, was not caused by soot, but by a pitch-like substance. But, under the knocking condition, the surface of the window was eroded perhaps by the heat-checking.

8. An example of the measurement and its calculation procedure

As an example, an experiment conducted under the following conditions will be shown.

Test engine: CFR-engine, revolving speed: \( n = 1200 \) rpm, compression ratio: \( \varepsilon = 6 \), air-fuel ratio: \( \mu = 12 \), location of spark gap: center of combustion chamber, ignition timing: \( \phi_i = 25^\circ \text{BTC} \), inlet mixture temperature: \( t_i = 100^\circ \text{C} \).

Figures 11( a ) and ( b ) show the oscillographs of \( \delta \), \( \rho \) and \( p_t \) taken under the above conditions. Calculation procedure based on these records is shown in Table 3. Taking the ratio \( p/p_t \) from ( b ), its maximum value \( p_f/p_t \) is given by 3.60. Then, \( m \), \( v \) and \( m/v \) can be obtained. Besides, \( \eta N_0 \) is found as \( 8.72 \times 10^{13} \) atoms/cm² from Eq. (15). Then, substituting \( R = 5 \) cm into Eq. (20), \( N \) can be written as

\[ N = 8.72 \times 10^{14} \varepsilon m v \]

Since \( \varepsilon m v \) is found from Eq. (16), \( N \) can be found for any crank angle.

To get \( x' = BN/W_p \), half-width \( W_p = ApT^{-1/2} \) must be known. And further, to get \( W_p \), \( T \) must be given. However \( T \) is an unknown quantity to be found. Meanwhile, as mentioned above, a roughly estimated \( T \)-value is sufficient for the first step of calculation. So, assuming \( T = 2000^\circ \text{K} \), then \( W_p \), \( x' \) and \( F \) can be obtained as shown in the Table.

Besides the instrument constant \( K' \) has been determined as \( 5.12 \times 10^{10} \) by a preliminary test conducted under the same condition. Using this \( K' \)-value and a measured value of \( \tau = 0.795 \), the required flame temperature \( T \) can be calculated from the following equation.

\[ \exp(-Ce/\lambda o T) = 2.46 \times 10^{-15} \delta/F \]

These calculated \( T \)-values are shown in the Table. In its bottom line, other \( T \)-values calculated from the above each \( T \) as a first step instead of \( 2400^\circ \text{K} \) are shown. Comparing both results, it may be found that the flame temperature can be obtained with sufficient accuracy by using a roughly estimated \( T \)-value as a first step.

The results thus obtained are shown as one of the curves (\( \phi_i = 25^\circ \text{BTC} \)) in Fig. 14.

9. Results of measurement

Using non-led PF naphtha as a fuel, the flame temperature which varies during the expansion stroke of CFR-engine \( (n=1200 \) rpm) was measured under various running conditions. Though the measurement is possible in a single cycle, the following are the results obtained by averaging over scores of cycles.

9-1 Effect of Na quantity added to fuel

Figure 12 shows the effect of Na quantity added to fuel, \( y \%), upon the maximum flame temperature

<table>
<thead>
<tr>
<th>Table 3</th>
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<tbody>
<tr>
<td>( \phi^\circ )</td>
</tr>
<tr>
<td>( p ) ata</td>
</tr>
<tr>
<td>( p_t ) ata</td>
</tr>
<tr>
<td>( p/p_t )</td>
</tr>
<tr>
<td>( m )</td>
</tr>
<tr>
<td>( v )</td>
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<tr>
<td>( m/v )</td>
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<tr>
<td>( e )</td>
</tr>
<tr>
<td>( 10^{14}N )</td>
</tr>
<tr>
<td>( W_p ) A</td>
</tr>
<tr>
<td>( x' )</td>
</tr>
<tr>
<td>( 10^8F ) cm</td>
</tr>
<tr>
<td>( \delta ) cm</td>
</tr>
<tr>
<td>( 10^8(=Ce/\lambda o T) )</td>
</tr>
<tr>
<td>( T^\circ ) K</td>
</tr>
</tbody>
</table>

\( \Delta T^\circ \) K | 0 | -1 | -2 |
in a cycle, $T_{\text{max}}$ K, under a constant running condition. It may be found that, even for the maximum temperature, which is most liable to vary from cycle to cycle, nearly the same results were obtained independently of $y$.

The following experiments were conducted under $y=1\%$.

9.2 Effect of inlet mixture temperature, $t_i$.

Figure 13 shows the effect of $t_i$ upon $T_{\text{max}}$. Its test condition is written in the Figure. As shown in it, $T_{\text{max}}$ rises with $t_i$.

9.3 Effect of ignition timing, $\phi_i$, and compression ratio, $\varepsilon$

Figure 14 shows the measured results of $T$ versus crank angle $\phi$ for the cases in which $\phi_i$ and $\varepsilon$ were varied. And the curves of $p$ and $m$, which were used in the process of calculation, are also shown. From these results, the following may be found. (1) With decreasing $\varepsilon$ or retarding $\phi_i$, $T_{\text{max}}$ is decreased. When $\varepsilon$ is increased, the slope of temperature rise becomes steeper. In the present experiment, $T_{\text{max}}$ was increased by about 100° K when $\varepsilon$ was increased by 1. (2) A maximum temperature among a family of curves is attained at TDC. And, with an increased deviation from $\phi_i=0$, $T_{\text{max}}$ decreases. (3) Even if $\phi_i$ remains constant, the crank angle corresponding to $T_{\text{max}}$ is retarded with a decreasing $\varepsilon$. Besides, the crank angle corresponding to $T_{\text{max}}$ is also retarded by delaying the ignition timing. Same tendency is also observed for $p_{\text{max}}$, but its retardation is far smaller than that for $T_{\text{max}}$.

9.4 Effect of engine speed, $n$, and air-fuel ratio, $\mu$

By varying the load of a hydraulic dynamometer, which was coupled with the test engine directly, $n$ was varied from 800 to 1 400 rpm. In such a speed range, it was found that the changes of $p$ and $T$ with respect to $\phi$ were nearly independent of $n$. This may be explained by the well-known fact that the flame velocity increases in proportion to $n$, provided that the effect of ignition delay can be ignored.

Figure 15 shows the change of $T_{\text{max}}$ due to $n$ and $\mu$. As shown in this Figure, $T_{\text{max}}$ increases with $n$ and its increment increases with $\varepsilon$. And $T_{\text{max}}$ becomes highest in the neighborhood of $\mu=13.5$ at which the flame velocity becomes also highest. This has been known theoretically by considering the thermal dissociation.

9.5 Effect of location of spark gap

In the above experiment, the mixture was ignited at the center of combustion chamber. If it is displaced, the above results must be changed. Figure
Fig. 16 shows the results comparing two cases in which, in the one case, the mixture was ignited at the center, and, in the other, at the end of combustion chamber. As shown in this Figure, these results differ not only in their absolute values, but also in their crank angles corresponding to $T_{\text{max}}$. It may be considered as the reason that, not only the flame travelling distance from the ignition point to the window is changed, but also the configuration of temperature field may be changed due to the above alteration. Besides, as observed in Fig. 14, the crank angles for $T_{\text{max}}$ and $\varphi_{\text{max}}$ coincided not always with each other. This discrepancy may be also explained by similar reasoning. Then, it becomes necessary to clarify the physical meaning of the gas temperature measured by the optical method such as the present one. This subject will be discussed in the 2nd Report.

9-6 Comparison with the results obtained previously

In Fig. 17, our results and those of measurement by many observers are summarized for reference. However their direct comparison has little meaning, because their experimental conditions are different from each other.

10. Summary

One method to measure the instantaneous temperature of gas burning in the gasoline engine was proposed and the results measured by this method were shown. In this method, the radiation energy of D-line emitted from a trace of Na, which has been added to fuel, was measured and the thermodynamic temperature of gas was calculated from it.

The characteristic feature of this method is as follows:

1. Instantaneous flame temperature can be found continuously.
2. Optical system of this method is much simpler than that of the methods reported previously. As a light beam to measure the radiation energy, one having 1 mm in diameter was sufficient, and it can be guided to any place by means of a fiberscope. As the window through which the light beam is taken out from the combustion chamber, only one quartz window was enough.

On the other hand, because of this simplification, it can not be denied that preliminary tests and process of calculation became cumbersome a little.

References

(1) Hopkinson, B., Phil. Mag., Vol. 13, Ser. 6 (1907), p. 84.