Temperature Measurement of Flame in a Gasoline Engine*
(2nd Report, Measurement of Temperature Distribution)

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The temperature measured in the 1st Report is the one which is averaged through an optical path in the luminous flame zone.

In the first step of this paper, the physical meaning of this average temperature is discussed. For this purpose, the flame is divided into many layers and the radiation from the whole flame is considered as the result composed of radiation and absorption of each layer.

In the second step, based upon the above consideration, the temperature distribution in a flame is measured. To divide the flame into many layers, and to measure the radiation effect of each layer, a light-intercepter is inserted into the flame and displaced successively across the flame. By this technique, a change of the flame temperature distribution versus crank angle is measured on a CFR engine. As one of the results, Hopkinson's effect is ascertained. Namely, at the instant when the flame spreads over the combustion chamber, it is found that the temperature of gas around the spark plug is about 300°C higher than that of gas near the cylinder wall.

1. Introduction

In the 1st Report, the temperature of burning gas in a gasoline engine was measured by detecting the radiation energy of Na atoms emitting light in an optical path within the combustion chamber. However, since the gas temperature must have a three-dimensional distribution, the result obtained in the 1st Report is one averaged in some way along an optical path by which the measurement was conducted. Therefore, the results must differ depending on the location of the measuring path.

Rassweiler et al. have measured the burning gas temperature by means of the Na D-line reversal method, and obtained three different results corresponding to three different optical paths. Besides, it has been known previously as Hopkinson's effect that a temperature difference amounting to about 300°C will occur between the gas around the ignition plug and the end gas. Moreover, there will be a remarkable temperature drop near the wall. It becomes necessary to clarify the physical meaning of the temperature averaged along the optical path.

In the first step of the present paper, the physical meaning of the average temperature obtained in the 1st Report is discussed. In the second step, the temperature distribution along one optical path is measured at any crank angle. However, in contrast to the average temperature measured at any instant as shown in the 1st Report, measurements over many cycles at the same crank angle were necessary to obtain the temperature distribution.

2. Physical meaning of the average temperature

As shown in Fig. 1(a), let us consider the radiation of D-line emitted from a thin composite layer which consisted of two layers having different temperatures, \( T_1 \) and \( T_2 \), and different atomic densities of Na, \( z_1' \) and \( z_2' \). Since one part of radiation energy emitted from \( 2 \) is absorbed by \( 1 \), the following intensity of D-line will be measured on the leftside of this layer.

![Fig. 1](image-url)
\[ I = \frac{C_1}{\lambda_0^5} \exp \left( -\frac{C_2}{\lambda_0 T_1} \right) \times \left[ 1 - \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_1} \right) \right] \]
\[ + \exp \left( -\frac{C_1}{\lambda_0 T_0} \right) \left[ 1 - \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_1} \right) \right] \times \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_0} \right) \]
\[ \times \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_1} \right) \] \hspace{1cm} (1)

where the notations used here are the same as those used in the 1st Report.

Radiation energy \( E \) can be obtained by integrating this from \( \lambda = 0 \) to \( \infty \). Therefore, \( E \) for a layer consisting of \( n \) elementary layers, such as shown in Fig. 1(b), can be written as follows.

\[ E = \frac{C_1}{\lambda_0^5} \sum_{k=1}^{n} \left[ \exp \left( -\frac{C_2}{\lambda_0 T_k} \right) \right] \int_{0}^{\infty} \left[ 1 - \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_1} \right) \right] \times \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_0} \right) \times \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 z'_1} \right) \times \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 \sum_{m=0}^{k-1} z'_m} \right) \] \hspace{1cm} (2)

where \( z'_0 \) is equal to 0. For simplicity, writing,

\[ \int_{0}^{\infty} \left[ 1 - \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 \sum_{m=0}^{k-1} z'_m} \right) \right] \times d\lambda = F \left( \sum_{m=0}^{k} z'_m \right) \] \hspace{1cm} (3)

then, Eq. (2) becomes as follows.

\[ E = \frac{C_1}{\lambda_0^5} \sum_{k=1}^{n} \left[ \exp \left( -\frac{C_2}{\lambda_0 T_k} \right) \right] \times \left[ F \left( \sum_{m=0}^{k} z'_m \right) - F \left( \sum_{m=0}^{k-1} z'_m \right) \right] \] \hspace{1cm} (4)

On the other hand, denoting the temperature, which is averaged so as to make equal the radiation energy to the above \( E \), as \( T_m \), then \( E \) can be written in another way as follows.

\[ E = \frac{C_1}{\lambda_0^5} \exp \left( -\frac{C_2}{\lambda_0 T_m} \right) \int_{0}^{\infty} \left[ 1 - \exp \left( \frac{-1}{1 + (\lambda - \lambda_0)^2/W_{p_\alpha}^2 \sum_{k=1}^{n} z'_1} \right) \right] d\lambda \]
\[ = \frac{C_1}{\lambda_0^5} \exp \left( -\frac{C_2}{\lambda_0 T_m} \right) \times F \left( \sum_{m=1}^{n} z'_1 \right) \] \hspace{1cm} (5)

Equating Eqs. (4) and (5), the average temperature \( T_m \) can be obtained from the following equation.

\[ \exp \left( -\frac{C_2}{\lambda_0 T_m} \right) = \sum_{k=1}^{n} \left[ \exp \left( -\frac{C_2}{\lambda_0 T_k} \right) \right] \times \left[ F \left( \sum_{m=0}^{k} z'_m \right) - F \left( \sum_{m=0}^{k-1} z'_m \right) \right] \] \hspace{1cm} (6)

The gas temperature measured by a method described in the 1st Report, or by the spectral line reversal method means the above \( T_m \).

Specially when the Na density \( z'_0 \) is homogeneous throughout the whole layer, the following relation holds.

\[ e^{-C_2/\lambda_0 T_m} F(nz') = e^{-C_2/\lambda_0 T'_1} F(z'_1) + e^{-C_2/\lambda_0 T'_2} F(2z'_1 - F(z'_1)) + \ldots + e^{-C_2/\lambda_0 T'_n} F(nz'_1 - F(n-1)z'_1) \ldots \ldots \ldots \ldots (7) \]

To calculate \( T_m \) by the above equation, the flame must be divided into \( n \) elementary layers.

For example, let us calculate \( T_m \) for a given pattern of flame temperature distribution. Corresponding to two given patterns A and B shown in Fig. 2(a), the results calculated by Eq. (7) are shown in Fig. 2(b) as the families of curves A and B respectively. \( n \) in Fig. 2(b) means the number of divided elementary layers and \( nz' \) indicates the total number of Na atoms in the light path having unit cross sectional area. Namely, the above two families of curves are each drawn for a parameter \( n \). By this figure, it may be seen that, with an increasing \( n \), \( T_m \) approaches a constant value. Besides, comparing (a) and (b), it may be found that the above \( T_m \) shows a higher temperature than the arithmetic mean temperature of the given pattern.

Zeise(2) has deduced a formula expressing the average temperature for the result obtained by the D-line reversal method. Curves \( A_1 \) and \( B_1 \) are the results calculated by his formula for the same temperature distributions as the above. But they are obviously unreasonable, because the average temperature, which must be a constant, varies with \( n \) and \( z'_1 \). It may be considered as the reason for it that he has applied the condition of spectral line reversal to only a central wave-length of D-line and ignored the energy balance over its whole wave-
length.

3. Measuring procedure for the temperature distribution in a flame

The temperature distribution in a flame can be measured by applying the above principle.

In the case of a stationary flame, instead of dividing it into \( n \) layers, a partition plate is inserted into the flame and is displaced successively by a pitch of \( 1/n \) of flame-thickness. The temperature distribution can be found by measuring the radiation energy each time.

In the case of an engine, assuming that the same temperature history repeats from cycle to cycle, the light emission, which is taken out from the combustion chamber at a definite crank angle, can be regarded approximately as that from a stationary flame. In the following experiment, the temperature distribution was obtained in such a way. Moreover, instead of the partition plate, a thin water-cooled steel bar was used and inserted into the combustion chamber from the opposite side of a quartz window. Its sketch was shown in Fig. 3 in the 1st Report. The bar was threaded so as to be displaceable by turning. Requirements regarding the bar are as follows: (1) It does not change the burning condition. Especially it does not play the role of a hot spot. (2) Energy due to both radiation and reflection from its end surface is negligibly small compared with that from the flame.

In our experiment, these requirements were assumed to be satisfied. But, these points will be discussed in Chapter 6.

Now, let us consider again the case of a stationary flame. And, let us consider that the flame is divided into \( n \) layers having equal thickness, as shown in Fig. 3, and assume that the number of Na atoms per unit cross sectional area of light path, \( N \) atoms/cm\(^2\), is the same through them. Then, under the situation shown in Fig. 3, radiation energy from the first layer must be read on the oscilloscope as a following reading \( \delta_i \):

\[
\delta_i = K' \exp\left(-C_2/\lambda_0 T_i\right) F(i'z'), \quad z' = BN/W_p \tag{8}
\]

where \( K' \) is a constant for instrument.

When the end surface is positioned at \( i \)-th layer, the reading \( \delta_i \) can be written generally as

\[
\delta_i = K' \exp\left(-C_2/\lambda_0 T_i\right) F(i'z'), \quad z' = BN/W_p \tag{9}
\]

The difference in readings, \( \delta_i - \delta_{i-1} \), may be considered the contribution of the radiation from \( i \)-th layer. Then, the following equation containing the temperature of \( i \)-th layer, \( T_i \), holds.

\[
\exp\left(-C_2/\lambda_0 T_i\right) = \frac{\delta_i - \delta_{i-1}}{K' (F(i'z') - F(i-1'z'))} \tag{10}
\]

When \( n \) is increased, the above equation becomes

\[
\exp\left(-C_2/\lambda_0 T_i\right) = \frac{1}{K'} \frac{d\delta}{dF} = \frac{1}{K'} \frac{d\delta}{dz'} \tag{11}
\]

Since the record of \( \delta \) versus the position of bar can be replaced by that of \( \delta \) versus \( z' \), \( d\delta/dz' \) can be found at any position in the flame. Therefore, if \( dF/dz' \) is given elsewhere, the local flame temperature can be determined. \( dF/dz' \) can be calculated for \( z' \) as follows. Since \( F \) is given by an integration of Eq. (11) in the 1st Report and its lower limit can be approximated by \(-\infty\), it can be written as follows.

\[
F = 2W_p \int_0^{\infty} \left(1 - \exp\left(-\frac{z'}{1 + \Delta z'/W_p}\right)\right) \frac{d(\Delta z')}{W_p} \tag{12}
\]

Changing the integration variable, the above equation is rewritten as

\[
F = \frac{2W_p}{\int_0^{\pi/2} 1 - \exp\left(-z' \cos^2 \theta\right) \cos^2 \theta d\theta} \left(\frac{\lambda}{W_p}\right) \tag{13}
\]

Therefore,

\[
\frac{d}{dz'} \left(\frac{F}{2W_p}\right) = \int_0^{\pi/2} \exp\left(-z' \cos^2 \theta\right) d\theta \tag{14}
\]

The calculated result of this equation is given in Fig. 4.

As described in the above, if \( W_p \) is assumed to be a constant, the temperature distribution can be found by Eq. (11).

In the case of an engine, a change of \( W_p \) due to pressure change by piston displacement must be considered. However, at a given crank angle, \( W_p \), may be assumed approximately as a constant along the optical path.

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Fig. 3.

![Fig. 3](attachment:image.png)

Fig. 4.

![Fig. 4](attachment:image.png)
4. Measurement of temperature distribution in a burner flame

As a preliminary experiment, the temperature distribution in a Meker burner flame was measured. Metered town-gas and air were fed to the burner and metered sodium ethylate was injected as a mist into the feeding air. As the light intercepting bar, a mild steel bar having 2 mm in diameter was used. But only its end part was thickened up to 7 mm in diameter. The burner flame was kept in a stationary state and the bar was traversed forward or backward direction across the flame by a motor-driven mechanism. By a preliminary test, it was verified that the effects of radiation and reflection from the end surface of the bar were negligibly small, even if the bar was not water-cooled.

Two curves shown in Fig. 5(a) are the records for two cases of forward and backward motion of the bar. Since the velocities of the bar and the oscilloscope sweeping were adjusted to 1.7 and 5 cm/sec respectively, one scale of abscissa is equivalent to the distance of 3.4 mm within the flame. These two curves coincide with each other. White circles written in Fig. 5(b) indicate the first approximation and black circles the corrected values. The former is a result calculated by Eq. (11) under the assumption of uniform Na concentration and the latter is the second approximation in which the local variation of Na concentration due to thermal expansion was considered on the basis of the former result. Average temperature $T_m$ written in the figure is an experimental result measured by the method described in the 1st Report. Figure 5(c) shows the results measured repeatedly under the same condition. Since a Merker burner has no inner flame cone, its temperature distribution is considerably flat.

5. Measurement of temperature distribution in combustion chamber of a gasoline engine

As mentioned in the above, after setting the bar at one position, $\delta$ versus crank angle $\phi$ was recorded over many cycles. This procedure was repeated by shifting the position of the bar. By such a successive procedure, the temperature distribution was calculated by Eq. (10).

CFR engine was used as the test engine. As shown in Fig. 5 in the 1st Report, a thin light-intercepting bar was inserted into the combustion chamber from the opposite side of a quartz window. As the light beam, a parallel beam having 1 mm in diameter was used. As the bar, a threaded mild steel bar having 3 mm in diameter and having water-cooled guiding part was used.

Measurement was conducted under the following conditions. Compression ratio: $\varepsilon=5$, air-fuel ratio: $\mu=12$, central ignition, ignition timing: $\phi_{i}=23^\circ$ BTC, intake mixture temperature: $t_i=100^\circ$C, revolving speed: $n=1200$ rpm.

Each measurement was conducted during 15 seconds by shifting the bar by 5 mm at a time. Therefore, each record covered about 150 cycles. To indicate a position of the end surface of the bar, the number written in Fig. 5 in the 1st Report will be used in the following. As the fuel, non-led PF naphtha was used. As an example, one pressure record averaged over many cycles is shown in Fig. 6. Engine running was very stable and the pattern of pressure change during expansion stroke was little varied by cycle. A pressure change due to the bar being shifted could not be recognized, because volume of the bar was less than 0.5% of that of the combustion chamber.

Figure 7 is a record of $\delta$ obtained for one setting position of the bar. As seen from this photograph, though the cyclic pressure fluctuation was little, $\delta$ during the period of flame propagation fluctuated
considerably by cycle. Figure 8 shows a summarized result of δ-curves obtained for several positions of the bar. In Fig. 9, the above δ-curves are replotted with the position of the bar as an abscissa.

The values of the apparatus constant K' and the transmissivity of a quartz window τ were found as 4.02 × 10⁵ and 0.895 respectively by the preliminary experiments, which had been conducted under the same experimental condition as the above.

The measured values of η and ζ, and the calculated values of Tₘ are listed for every φ in Table 1.

In Fig. 10(a), the above Tₘ are plotted for φ. Comparing this with a curve, which has been obtained under the same experimental conditions, shown in Fig. 14 in the 1st Report, it may be seen that both curves are well reproduced.

Curves shown in Figs. 10(b) and (c) are the temperature distributions for several crank angles. They were measured along an optical path on which the above Tₘ was obtained. Figure 10(b) shows its changing process during the period up to the top dead center. Dotted lines drawn at the end of curves of 7.5° and 5° BTC indicate the positions of the flame front at each instant. From this figure, it may be found that the flame spreads throughout the combustion chamber at an instant of φ=2.5° BTC. The same fact is also seen from a a-curve written in Fig. 6. Also it may be found from Fig. 10(b) that, at an instant of φ=2.5° BTC, the temperature at the center of combustion chamber, where the spark plug is located, is about 300°C higher than that at the vicinity of wall. This may be explained as Hopkinson's effect. Figure 10(c) shows the change of temperature distribution during the period of expansion stroke. The mode of temperature decrease and the trend toward uniform temperature can be seen from this figure. The gas in the left part is cooled faster than one in the right part. Though the reason for it is not clear, it may be explained by the cooling effect due to an inlet valve which is mounted on the left side.

6. On the light-intercepting bar

In the first place, the effect of the bar upon the measured results will be considered. Even when the
burning gas temperature exceeds 2000°K, the temperature of the bar is supposed to be 1000°K in the highest estimate. The ratio of their radiation intensities amounts to about 10^8. In terms of radiation energy, their ratio is estimated as about 10^8. The effect of radiation from the bar was not detected actually on the oscilloscope. Besides, ignition was not caused by the bar.

In the second place, the effect of reflection from the end surface of the bar must be considered. δ-curves in Fig. 11 are the oscilloscope readings calculated for various reflectivities ρ under a given temperature distribution. For a mild steel bar used in the present experiment, it was measured as ρ = 0.56 for D-line even in the polished condition. So, for the oxidized condition, it may be estimated to be lower than 0.1 and its effect may be ignored.

7. Summary

In the Ist Report, the burning gas temperature averaged along a path in the combustion chamber has been measured at any crank angle. In the present report, extending the above method, one method to measure the temperature distribution along the path was developed and the results measured on a CFR engine were described.

To measure the temperature distribution, the thickness of gas layer involved in an optical path was varied by displacing a light-intercepting bar successively and the increment of radiation energy due to the increment of the thickness of gas layer was measured and its result was converted to a temperature. Thus, to obtain a temperature distribution at one specified crank angle, measurements over many cycles were required.

By the present study, though it was conducted only on a CFR engine, the circumstance of gas temperature variation occurring in the combustion chamber of a gasoline engine was clarified in part and the existence of the local temperature difference due to Hopkinson’s effect was verified.

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References

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