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Temperature Measurement of Premixed Fuel-Air Mixture by an Infrared Radiation Pyrometer*

(3rd Report, Influence of the Mixture Composition and Pressure)

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The temperature of a premixed gas during the compression stroke in a rapid compression machine and an engine may be measured by using infrared radiation. The infrared radiation pyrometer mentioned in this work employs the ratio of the absorptivity to the emissivity of water vapor at 2.7μ band. The spectrum at 2.7μ band is affected by the presence of CO_2 as well as the water vapor density. Besides, the dry air which is inactive in the infrared region may change the spectrum. Therefore, the influences of the change of the spectrum on the pyrometer reading were checked under the following conditions; (1) variation of water vapor density, (2) variation of CO_2 density, (3) mixture of the two gases and (4) pressurization by dry air.

No influence upon the measured temperature was perceived in the experiment under all these conditions.

1. Introduction

The analysis of accuracy of the infrared radiation pyrometer, which has been developed for the measurement of the temperature history of the end gas in engines, was made in the first report of the series of these papers.⁽¹⁾ In the second report,⁽²⁾ the influence of temperature distribution on the measured temperature was investigated. The density and pressure distribution, in those preceding reports, was regarded as uniform except a certain local density non-uniformity due to the temperature distribution. However, the composition and pressure of intake gas in an engine varies with engine conditions. The density of water vapor (H_2O herefrom) which is used as the measuring medium of the pyrometer changes due to the H_2O from air and the residual gas of a preceding cycle in an engine and to the H_2O added artificially in a rapid compression machine as well as to the advancement of compression stroke. Some carbon dioxide (CO_2 herefrom) which is active at the 2.7μ band used in this pyrometer comes from the residual gas and the density changes. Meanwhile the pressure of the mixture increases due to the compression by a piston and to the expansion of a burnt gas. The pressure reaches as high as

tens of atm just before combustion.

The factors stated above may change the structure of the spectrum of the medium. The infrared radiation pyrometer now under study, however, uses a ratio of absorptivity to emissivity so that the change of both factors cancel each other in case of the temperature measurement. This condition is fulfilled only at thermal equilibrium where the temperature of the black body which is used as a standard is equal to the gas temperature which is to be measured. But the condition differs slightly as the equilibrium is broken. Therefore, it must be known how greatly the change of spectrum may influence the measured temperature.

In this report H_2O and CO_2 which are active at 2.7μ band are used as the medium gas of the pyrometer. The influences of these individual gases and that of the mixture are investigated experimentally with an eye to practical usage. The effect of other components in the residual gas is not investigated because it can be reduced by careful selection of the wave length. The influence of pressure is also checked experimentally by the pressurization with dry gas when the gas concentration is held constant.

2. Nomenclature

- C_2 : the second constant of Planck's law
- D_1 : deflection of the synchroscope image due to the black body source
- D_2 : deflection of the synchroscope image due to the gas radiation
- D_3 : deflection of the synchroscope

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- image due to the composite radiation from both the mixture and the black body source
- E_{λ} : energy of black body radiation at wave length λ
- $E_{g\lambda}$: energy of black body radiation at wave length λ and gas temperature
- k_{λ} : spectral response of the infrared detector
- n : a constant which is a function of the pyrometer components and the gas spectrum
- P : total pressure of the gas
- T_b : temperature of the black body
- T_c : temperature of the chopper blade
- T_g : measured temperature of the gas
- T_{gco} : true temperature of the gas
- T_{gch} : measured gas temperature with carbon dioxide and water vapor as the media
- T_{gh} : measured gas temperature with water vapor as the medium
- T_w : temperature of the window
- t_{λ} : spectral response of the interference filter
- X : a function of synchroscope deflections (Eq. (16) in the 1st report with $X = \infty$)
- x : reference density of water vapor (see Chapter 3)
- y : reference density of carbon dioxide (see Chapter 3)
- α : apparent absorptivity⁽³⁾
- α_0 : apparent absorptivity at the standard state⁽¹⁾
- α_{λ} : spectral absorptivity of the medium gas
- β : transparency of the window
- γ : blackness of the black body
- ϵ : apparent emissivity⁽³⁾
- ϵ_{λ} : spectral emissivity of the medium gas
- λ : effective wavelength
- $\lambda_1 \lambda_2$: upper and lower wave length limits defined by the apparatus
- ρ_{co_2} : density of carbon dioxide
- ρ_{H_2O} : density of water vapor
- φ : absorptivity of the window = $1 - \beta$
- Temperature : absolute temperature is used in equations, while centigrade scale is used in diagrams
- Reference state : a state of the gas before compression starts for a combustion chamber, while a state of vacuum is used for the pressure cell. And they serve as the reference states for temperature measurement.

3. Spectrum of the mixture and the ratio of apparent absorptivity to emissivity

The fundamental equation of the pyrometer is derived from Eq. (10) in the 1st report with the condition of $T_w = T_g$ and $\alpha_0 = 0$, and T_g will be

$$\frac{1}{T_g} = \frac{1}{T_b} + \frac{\lambda}{c_2} \left\{ \ln X - \ln \gamma \beta - \ln \frac{\alpha}{\epsilon - \varphi \alpha} \right\} \dots (1)$$

T_b is a measurable value and λ is a predetermined value of wavelength. γ , β and φ

are able to be calibrated beforehand. Therefore the measured value of gas temperature T_g can be calculated by Eq. (1) with X when α and ϵ are known.

The relation between α and ϵ and the state of gas is discussed. α and ϵ are used in Eq. (1) as a form of $\alpha/(\epsilon - \varphi \alpha)$. But, in general, $\varphi \ll 1$ (less than 0.2) and it is approximated as follow,

$$\alpha/(\epsilon - \varphi \alpha) \cong \alpha/\epsilon \dots (2)$$

Then the relation has a form of ratio of the two factors, α and ϵ . Form the definitions of α and ϵ , on the other hand, α/ϵ is expressed by the following equation,⁽³⁾

$$\frac{\alpha}{\epsilon} = \left\{ \int_{\lambda_1}^{\lambda_2} \alpha_{\lambda} k_{\lambda} t_{\lambda} E_{\lambda} d\lambda \int_{\lambda_1}^{\lambda_2} k_{\lambda} t_{\lambda} E_{g\lambda} d\lambda \right\} / \left\{ \int_{\lambda_1}^{\lambda_2} \epsilon_{\lambda} k_{\lambda} t_{\lambda} E_{g\lambda} d\lambda \int_{\lambda_1}^{\lambda_2} k_{\lambda} t_{\lambda} E_{\lambda} d\lambda \right\} \dots (3)$$

where k_{λ} , t_{λ} , λ_1 and λ_2 are decided by the characteristics of the elements of the pyrometer, and E_{λ} and $E_{g\lambda}$ are calculated by Planck's equation of radiation with a certain value of the wavelength and the temperatures of the gas and the black body.

α_{λ} and ϵ_{λ} , however, change with the state of medium gas⁽⁴⁾ ⁽⁵⁾, especially with the pressure and composition of the mixture. Therefore, α/ϵ which includes α_{λ} and ϵ_{λ} may be affected by the pressure and composition. As a result, the relation between X and T_g may change by Eqs. (1) and (2). α_{λ} and ϵ_{λ} , nevertheless, are in the numerator and denominator respectively in Eq. (3), and their effects cancel each other and the over all effect of the pressure and concentration will not be so big. Especially when the range of $\lambda_1 \sim \lambda_2$ is narrow and T_g and T_b are equal or nearly equal, $\alpha/\epsilon \cong 1$. Many investigations have been done on α_{λ} and ϵ_{λ} ⁽⁴⁾ ⁽⁶⁾ but no rigorous solution is given yet; the results acquired by Weiner⁽⁴⁾ have an error of $\pm 10\%$ R M S for the coefficient of band absorption, besides the equation used is complicated. It is not a proper method to solve Eq. (1) with Eq. (3) using a theoretical equation of spectral absorptivity when not only single medium such as H_2O but also CO_2 and air are added as in this study. Therefore, in this paper, the relation between the state of gas and the measured temperature is experimentally discussed, with a view to practical usage.

α/ϵ using the value of α_{λ} obtained experimentally by other researchers⁽⁴⁾ ⁽⁷⁾ ⁽⁸⁾ from Eq. (3) is compared and discussed with the value of α/ϵ derived from Eq. (1) using T_g and X obtained experimentally. The influence of total pressure exerted by dry air (mixture of N_2 and O_2) which is inactive in infrared region can be numerically calculated by the semiempirical formula given in reference (9). But an experimental method was used for the same reason as stated above. The relation between the band absorptivity and emissivity is expressed by the

following approximate equation.⁽¹⁰⁾

$$\frac{\alpha}{\epsilon} = (T_g / T_b)^n \dots \dots \dots (4)$$

Using this form of equation for the apparent absorptivity and emissivity of the pyrometer, the value of n may be obtained from Eqs. (1) and (4) with T_g and X when gas composition and pressure are changed in experiment. If α_λ and ϵ_λ are given by some means, n can be calculated by Eqs. (3) and (4) with the characteristics of the elements of the pyrometer⁽³⁾, and n can be used as a means in discussing the effect of the composition and pressure. The value of n , in general, is both positive and negative but very close to zero.

4. Outline of the apparatus

The H_2O which is contained in a pre-mixed gas comes from both atmospheric air and residual gas. Density of water vapor of 0.01296 kg/m^3 , which is the H_2O density of the standard humid air (20°C , 760mmHg , 75%), is used as the reference density x_0 . The average fraction of the residual gas in a cylinder is assumed to be $0.12^{(1)}$. And when the mixture is compressed to a compression ratio of 10, the range of the H_2O densities will be covered safely by the range of $5x_0 \sim 30x_0$. The apparatus to prepare the mixture is shown in Fig. 1. The part surrounded by dashed line is a pyrometer whose detail is given in the 1st re-

1 vacuum pump	15 chopper blade
2 vacuum tank	16 optical window
3 thermocouple's	17 pressure cell
potentiometer	18 filter
4 cold junction	19 lens
5 steam generator	20 I.R. detector
6 U-manometer	21 synchroscope
7 pressure gauge	22 light source
8 drier	23 lens
9 pressure redu-	24 reflecting
ing valve	mirror
10 CO_2 bomb	25 camera
11 high pressure	26 valves
drier	27 thermocouple
12 compressor	28 thermocouple
13 drier	[] infrared radia-
14 black body	tion pyrometer

Fig. 1 Experimental apparatus

port⁽¹⁾. 1 and 2 in the figure consist of the vacuum system by which an electrically heated pressure cell 17 (optical axis length 85mm) is evacuated so as to give a reference state for the temperature measurement. H_2O density in 17 is controlled by a steam generator 3~5.

CO_2 comes from the residual gas whose CO_2 content is a fraction of 0.14 by volume^(1,2). Then the partial pressure of CO_2 is $0.0168P \text{ kg/cm}^2$, and CO_2 density $\rho_{CO_2} = 0.0233 \text{ kg/cm}^3$ at $P = 1 \text{ kg/cm}^2$ and $T = 373^\circ\text{K}$ is made the reference density y_0 . The range of $5y_0 \sim 30y_0$, like that of H_2O , is used corresponding to the state of the premixed gas. The apparatus for it is shown in Figs. 1. 8 ~ 10.

Fig. 2 $X - T_g$ curves and the results of measurement

The influence of pressure is checked by pressurising with dry air up to 30 kg/cm^2 . The apparatus used is 11~13 in the same figure. The range of the temperature $200 \sim 500^\circ\text{C}$ is the same as in the preceding report⁽¹⁾.

5. Results and discussion

5.1 Measured value and the theoretical $X - T_g$ curves

The circles in Fig. 2 are the results of the gas temperatures measured by the thermocouple 27 of Fig. 1 and of X obtained from the synchroscope deflections. The group of curves, on the other hand, are the calculated values of X and T_g by Eq. (1), (2) and (4) with the measured value of γ and β . The circles are distributed along the curves of constant value of n as parameters. The results of calculation of n for the circles with the method described in chapter 3 are shown in Fig. 3. The values of n as T_g approaches T_b diverge very far from the mean value, while they converge to a constant value of -0.41 as T_g departs from T_b . It is due to the nature of Eqs. (1), (2) and (4). The dotted line in Fig. 2 is the curve for $n = -0.41$ and from which T_g , the measured temperature of the pyrometer, can be obtained for any value of X . In this way $X - T_g$ curves for respective states of gas

are obtained and the influence upon T_g is discussed.

5.2 Influence of H_2O density

Measured gas temperature for constant x is plotted in the range of $\rho_{H_2O} = 5x \sim 30x$ in Fig.4. The deviations of the points are within the range of measuring errors and no influence of ρ_{H_2O} is perceived. n , which is shown by circles in Fig.5, has greater scattering but the change of the average is little. Simmons⁽⁸⁾ measured the spectra of H_2O at 2.7μ band for $T_g = 500 \pm 13^\circ C$, and 77.5mm of optical axis length (85mm in this experiment). This datum is used to calculate n which is shown by the dotted line in Fig.5 by Eqs. (3) and (4). It is seen that its value is different a little from that of the measured, but the tendency is nearly the same. And it is also possible to measure at such a low ρ_{H_2O} as $5x$ without great degradation of accuracy. Therefore, this pyrometer is able to measure the temperature in the combustion chamber with the axis

Fig. 3 n for the gas temperature

Fig. 4 Relation between H_2O density and the measured gas temperature

Fig. 5 n for H_2O density (comparison of the experimental values with calculated values)

length of 85mm and smaller when the mixture is moistened to the extent of just changing the condition of combustion, except in the case of carbon monoxide being used as the fuel.

5.3 Influence of CO_2 density

No influence of CO_2 density is seen in Fig.6 which, like that of H_2O , shows T_g against ρ_{CO_2} . n in this case is shown in Fig.7. Taking account of the points stated in Fig.3 in calculating n , -0.73 is taken as the average. In the experiment, T_g is smaller compared with T_B and T_g and $\alpha = 0$. Therefore, the apparent absorptivity α will be,

$$\alpha = 1 + (D_2 - D_3) / D_1 \dots \dots \dots (5)$$

The spectrum of CO_2 at 2.7μ band is weaker compared with that of H_2O and α is $0.005 \sim 0.07$ which is about a quarter of water vapor's. S/N is poor for such a small value of α but the temperature can be measured. The measuring error shown in Fig.8 is not so big comparing with the case of H_2O , and the measured points distribute along the line of $T_g = T_B$ within the range of several degrees.

5.4 Influence of the mixture composition

The mixture in a combustion chamber is simulated by a mixture of H_2O and CO_2 , and T_g is shown in Fig.9 with the mixture ratio changed in the range of $\rho_{H_2O} = 5x \sim 30x$, and $\rho_{CO_2} = 5y \sim 30y$. T_g at fixed values of

Fig. 6 The relation between CO_2 density and the measured gas temperature

Fig. 7 n for CO_2 density

X changed little for any combination of ρ_{H_2O} and ρ_{CO_2} . n is shown in Fig. 10. The measured value is a little different from the calculated value with the spectrum absorptivity obtained by Ferriso⁽⁷⁾, but both of them are nearly constant for ρ_{CO_2}/ρ_{H_2O} . The measured temperature T_{GH} with medium of H_2O alone and T_{GHC} with both H_2O and CO_2 are compared in Fig. 11. They agree with each other within the measuring errors. In calibration of the pyrometer, therefore, only H_2O is used as the medium because it is easier to operate than when using both H_2O and CO_2 .

5.5 Influence of the pressurising air

H_2O in a pressure cell is pressurised by dry air and the results are shown in Fig. 12. Only a little effect of pressure is seen between 0 and 1 kg/cm² but practically no change is seen beyond that pressure. Fig. 13 shows the results of n , that is, no change is seen in it. The measured temperature is compared with the true temperature

Fig. 8 The relation between the true gas temperature and the measured gas temperature

Fig. 9 Influence of mixing ratio of H_2O and CO_2

Fig. 10 n for ρ_{CO_2}/ρ_{H_2O} (comparison of the experimental values with calculated values)

Fig. 11 The measured gas temperature (T_{GH}) with medium of H_2O alone and the measured gas temperature (T_{GHC}) with a mixture of H_2O and CO_2

Fig. 12 Influences of pressurization by dry air

T_{∞} which is measured by a thermocouple in Fig.14. Both distribute along the line of 45° in all the cases of using H_2O and CO_2 as the medium. Therefore, no compensation for the pressure change during the compression stroke of a rapid compression machine and an internal combustion engine is required.

6. Conclusions

Taking account of the composition and pressure of the premixed gas, the characteristics of the pyrometer is investigated experimentally under the following conditions,

- (1) in the range of 5~30 times the H_2O density of the standard humid air (20 °C, 760 mmHg, 75%),
- (2) in the range of 5~30 times the CO_2 density of a mixture which contains 12% of residual gas with CO_2 content of 14% by volume,
- (3) at a variety of mixture ratios of H_2O and CO_2 which are specified in (1) and (2), and
- (4) mixtures of H_2O and both H_2O and CO_2

Fig. 13 n for the total pressure

Fig. 14 Influences of the pressurized air on the measured gas temperature

are pressurised in the range of 0 ~ 30 kg/cm² by dry air.

No influence is seen under any one of these conditions. And the calibration is done first with H_2O as the medium and the measured value is corrected as stated in the 1st report for the element of the pyrometer and for the compression ratio.

The lower limit of the H_2O density is only five times that of the standard humid air. So it means that the pyrometer functions for a gas layer whose depth is shorter than the one used in this experiment (85mm) when the premixed gas is moistened to the extent which will not affect the combustion process. Some instructions are given on use of the infrared radiation pyrometer to measure the temperature of a premixed gas in a combustion chamber.

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