

Temperature Measurement by Modified Na D Line Reversal Method*

· By

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Summary. An automatic recording pyrometer fitted for the pyrometry of working gases in the rocket engine has been constructed. Two methods of pyrometry are established in the present pyrometer: the first is of Na D line reversal type (self-balancing method) and the second is of its modified type (non-balancing method). The both methods are performed by using the photo-electric devices and the bichromator. In the self-balancing method, the accuracy of measurement is 30°K at 2000°K and the response time is about 6 sec. On the other hand, the non-balancing method has the accuracy of 10°K at 2000°K and the response time of 0.1 sec, and besides makes it possible to observe the temperature of the gas having a low emissivity. Certain requirements for the spectrum line reversal method are mentioned, and the results obtained by the present pyrometer are given.

1. INTRODUCTION

Pyrometry of high temperature gases is one of the most important requirements for the fundamental researches of chemical reaction or combustion. Also, it is meaningful to know a temperature of working gases in a jet or rocket engine, whose thrust is caused by the high speed jet of combustion gases expanding through *de Laval* nozzle. This expansion transforms the internal energies of the gases to the kinetic energy; in other words, the temperature of the gases is lowered by the expansion. Hence, the pyrometry of the gases in a jet or rocket engine will give two main information: first, about the chemical reaction of propellant in the combustion chamber, and second, about the expanding process through *de Laval* nozzle. In order to discuss the above situations, the pyrometer for measuring a transient flame temperature has been constructed.

In the case of pyrometry of working gases in a rocket engine, it is necessary that a pyrometer is of an automatic recording type and also that its response time is short enough to follow a variation of temperature of combustion gases. Pyrometer using a thermocouple or a pneumatic cell is not appropriate for hypersonic gas flows owing to an aerodynamic heating of an inserting material. Here, an optical method is considered suitable. There are several methods in the optical pyrometry of high temperature gases, and these methods have been reviewed somewhere [1]–[3].

The automatic recording pyrometer constructed here is a modified Na D line reversal method, and the same trials have been achieved by many others. Their

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methods are divided into two main types: self-balancing [4]–[5] and non-balancing method [6]–[8]. The characteristic of the present pyrometer lies in the use of the bichromator and it can be used as a self-balancing or non-balancing method. In the case of non-balancing method, the pyrometer is essentially similar to Heidmann et al or Millar et al's technique, which has been much improved on the accuracy of measurement in this apparatus.

2. PRINCIPLE OF SPECTRUM LINE REVERSAL METHOD

Thermal radiation of any body with thermodynamic equilibrium satisfies Kirchhoff's radiation law: that is, an energy of light emitted from a body is equal to that of light absorbed by a body. Therefore, the body which absorbs all energy of incident light can emit the maximum energy as compared with any other bodies of same temperature, and such a body is called 'black body'. Radiation density $\rho(\nu, T)d\nu$ of the black body can be formulated from the statistical point of view by the above mentioned law (Planck's equation).

$$\rho(\nu, T)d\nu = (8\pi h\nu^3/c^3)[1/\{\exp(h\nu/kT) - 1\}]d\nu, \quad (1)$$

where ν is vibrational frequency of light, T temperature of the system, c velocity of light, and h and k are Planck's and Boltzmann's constant, respectively. The spectral radiancy, which is radiant flux emitted from the black body per unit area of the emitter into an angle of 2π steradians, is,

$$\begin{aligned} B(\lambda, T)d\lambda &= (c/4)\rho(\lambda, T)d\lambda \\ &= (2\pi c^2 h/\lambda^5)[1/\{\exp(hc/\lambda kT) - 1\}]d\lambda, \end{aligned} \quad (2)$$

where λ is spectral wave-length. Instead of Planck's equation, Wien's equation can be used for the visible region.

$$B(\lambda, T)d\lambda = (2\pi c^2 h/\lambda^5) \exp(-hc/\lambda kT)d\lambda. \quad (3)$$

Emission or absorption of light by a non-black body is defined by the comparison with the black body as follows:

$$I/I_b = \text{emissivity } \epsilon_\lambda, \quad A/A_b = \text{absorptivity } \alpha_\lambda,$$

where I and A are energy emitted from and that absorbed by a body, respectively, and I_b and A_b shows those of the black body. Kirchhoff's radiation law can be described as an emissivity and absorptivity of any body are the same. Therefore, an emissivity of a gas can be shown by using an absorption coefficient,

$$\epsilon_\lambda = 1 - \exp(-P_\lambda X), \quad (4)$$

where P_λ is absorption coefficient of a gas at a wave-length λ and X is optical depth. Usually, an absorption coefficient of a gas depends largely upon the wave-length of an incident light, and as a monochromator used has only a finite resolving power, an observed spectrum line is not strictly monochromatic, so that the above emissivity Eq. (4) is not practical. Here, an effective emissivity E_λ , which is characteristic to a monochromator, is defined,

$$\begin{aligned}
 E_\lambda &= \int g(\lambda', \lambda) \{1 - \exp(-P_\lambda X)\} d\lambda' / \int g(\lambda', \lambda) d\lambda' \\
 &= \int g(\lambda', \lambda) \{1 - \exp(-P_\lambda X)\} d\lambda' / \Delta\bar{\lambda},
 \end{aligned} \quad (5)$$

where $g(\lambda', \lambda)$ is a spectral slit function which is a distribution function of spectral intensity at wave-length λ , and $\Delta\bar{\lambda}$ is a spectral slit-width of a monochromator.

When an emission from a gaseous body is observed by a monochromator having a slit function of $g(\lambda', \lambda)$, an intensity of light beam from an exit slit of a monochromator is as follows:

$$I_\lambda = \int g(\lambda', \lambda) \varepsilon_\lambda B(\lambda', T) d\lambda' \Delta\Omega \Delta s, \quad (6)$$

where $\Delta\Omega$ is a solid angle of light beam incident on a monochromator and Δs is an area of an entrance slit. The spectral radiancy $B(\lambda, T)$ of the black body scarcely varies according to a small change of the wave-length, and therefore

$$I_\lambda = E_\lambda B(\lambda, T) \Delta\bar{\lambda} \Delta\Omega \Delta s, \quad (7)$$

is practically held.

Light beam from the standard light source, whose spectral radiancy is same as the black body of temperature T_0 (in other words, the brightness temperature of the source is T_0), passes through a gaseous body of temperature T_g , and the intensity of light at a wave-length λ is measured by the monochromator, as shown in

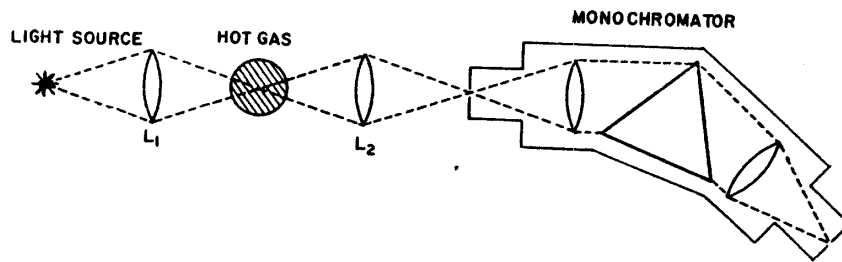


FIGURE 1. Optical system of spectrum line reversal method.

Fig. 1. The intensity of total light entering the monochromator is described to be the sum of spectral emission and absorption of the gas.

$$I_\lambda = \{E_\lambda B(\lambda, T_g) + (1 - E_\lambda) B(\lambda, T_0)\} \Delta\bar{\lambda} \Delta\Omega \Delta s, \quad (8)$$

If the intensity described in Eq. (8) is same as the intensity measured without the gaseous body (this is so-called reversal condition),

$$B(\lambda, T_0) \Delta\bar{\lambda} \Delta\Omega \Delta s = \{E_\lambda B(\lambda, T_g) + (1 - E_\lambda) B(\lambda, T_0)\} \Delta\bar{\lambda} \Delta\Omega \Delta s, \quad (9)$$

then,

$$B(\lambda, T_0) = B(\lambda, T_g), \quad T_0 = T_g.$$

As shown in the above equations, the spectrum line reversal method is based on the fact that the temperature of the gas and the brightness temperature of the light source are the same, when the spectrum line emitted from the gaseous body is neither stronger nor weaker than the neighboring back-ground spectrum of the light source.

In the spectrum line reversal method, the following attentions must be paid to the adjustment of slit-illuminating system in Fig. 1. First, the solid angles of light beams from the light source and the gaseous body emitting the spectrum line, should be same, and so the aperture of the lens L_1 must be larger than or equal to that of the lens L_2 . Second, the image of the light source on the entrance slit, must be sharp as far as possible and must cover the entire slit, or else the brightness temperature of the source would be lowered effectively.

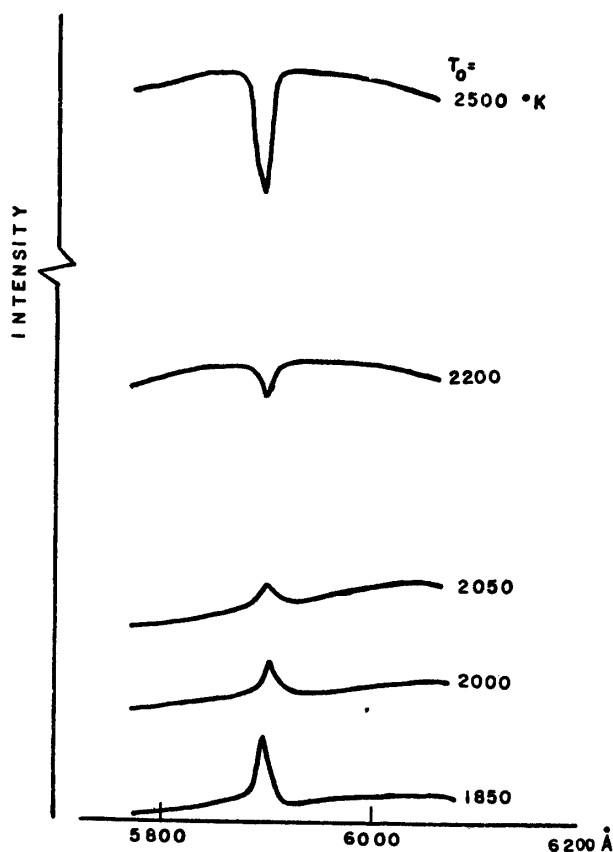


FIGURE 2. Emission or absorption of Na D line with various brightness temperatures of standard light source. This spectrum was obtained by the recording monochromator (CaF_2 prism) which was constructed in our laboratory.

As shown in Fig. 2, it is found that the emission to the back-ground spectrum of the source becomes the absorption as the brightness temperature of the light source has a higher value.

For the pyrometry of the flame gas, the Na D resonance line is most frequently used as the spectrum line. The Na D line is easily observed by the visual or photo-electric device, and as the absorption coefficient of sodium vapor is very large, the emissivity enough to observe the Na D line is achieved by introducing very little quantity of sodium vapor. These situations are the reasons for the Na D line being used in the spectrum line reversal method. There have been several studies of the reversal pyrometry using the other spectrum line; Gaydon and Wolfhard used other alkali metal's resonance lines [9], Curcio et al, OH radical's spectrum in the oxy-acetylene flame [10], and Silverman, the vibration

rotation band of carbon dioxide in the infra-red region [11].

The principal requirements for the spectrum line reversal method are summarized below.

- (i) This method can be attributed to the pyrometry of the gaseous system when the radiation of the spectrum line occurs under the thermal equilibrium in the internal energies of the system. In the non-equilibrium system such as some reaction zone of a flame, the observed reversal temperature cannot be considered as in the case of the equilibrium system. The physical meaning of the above temperature may depend on the mechanism of the spectrum line's emission. Gaydon et al observed the Na D line reversal temperature of the shock-behind of nitrogen gas, and estimated that the reversal temperature had a close relation with the vibrational temperature of nitrogen under the existence of vibrational relaxation [12].
- (ii) The introduction of sodium vapor must bring little disturbance of the true temperature of the system.
- (iii) In the gaseous body having a temperature distribution, the observed reversal temperature gives only an effective value. Strong et al discussed these problems [13].

3. BICHROMATOR

Bichromator is utilized in the present apparatus. There are two types of the bichromator: the first having two Littrow mirrors, the other having two exit slits. The bichromator adopted here is of the former type, and the optical system of the present bichromator is shown in Fig. 3.

The two Littrow mirrors up and down are mounted behind the glass prism P_2 ,

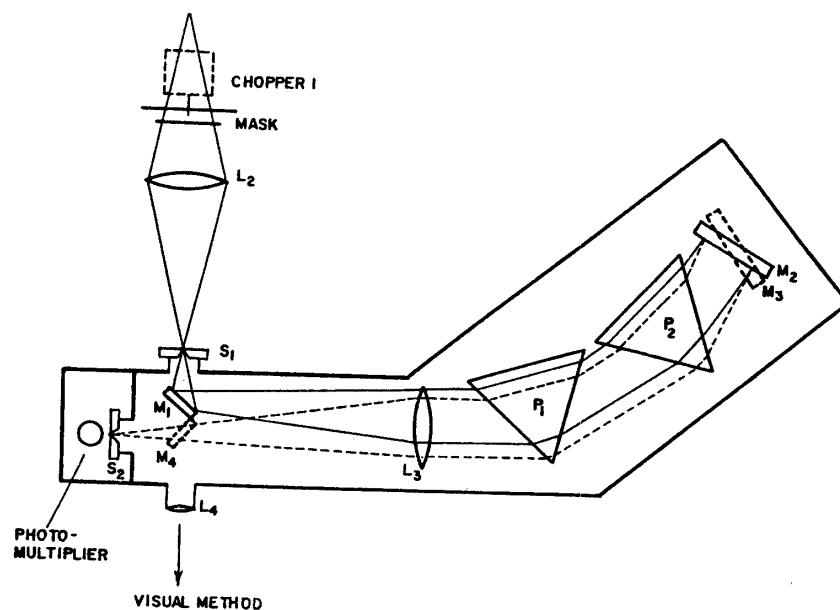


FIGURE 3. Optical system of bichromator. Prisms P_1 and P_2 are glass prisms of apex angle 60° .

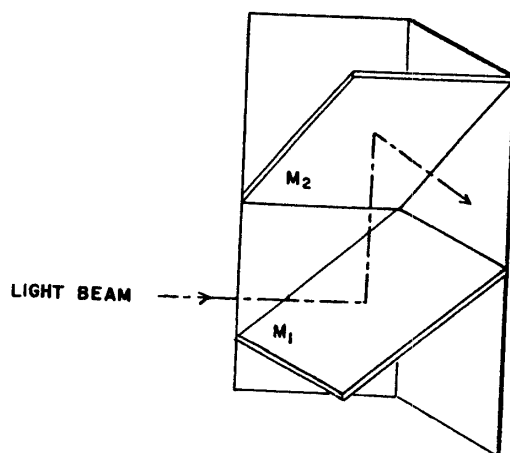


FIGURE 4. Mirror system which converts vertical relation of a image to horizontal.

and these two Littrow mirrors can be set at certain angles different from each other. The mask in front of the slit-illuminating lens L_2 is located at such a position that the mask's image may produce on the two Littrow mirrors, and divides the light beam entering the bichromator into upper and lower beams. After these two divided beams enter the bichromator, the upper beam reflects on the lower Littrow mirror and the lower, on the upper. Consequently, the two monochromatic light beams of different wave-lengths are emitted out from the exit slit, corresponding to the upper and lower light beams divided by the mask. The chopper I beside the mask interrupts the upper and lower beams alternately at a rate of 10c/s (self-balancing method) or 318c/s (non-balancing method). Therefore, the two monochromatic light beams are emitted out from the exit slit alternately every 1/10 or 1/318 sec. The photomultiplier 1P22 receives these alternating light, and the photo-current produced is amplified.

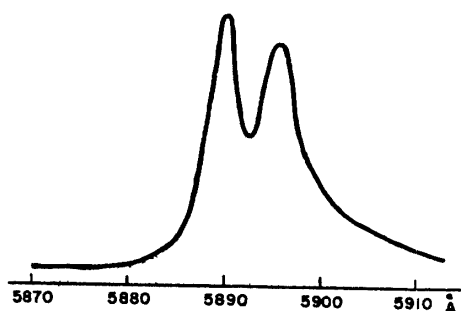


FIGURE 5. Na D spectrum of the sodium discharge lamp measured with the present bichromator used as a monochromator.

In the pyrometry of a gaseous body like a flame which has a vertical distribution of temperature, the image of the gaseous body on the entrance slit must be horizontal, and so the mirror system shown in Fig. 4 is used. In this case, the vertical relation of the mask and chopper I above mentioned is changed to the horizontal relation.

4. SELF-BALANCING METHOD

In order to judge whether the reversal condition Eq. (9) is satisfied or not, the reversal point where the Na D line converts from emission to absorption or *vice versa*, must be found while changing the brightness temperature of the light source. This can be done with a visual or photographic method. Here, the reversal point is detected by the photo-electric device.

Fig. 2 shows that at the reversal point the spectrum near the Na D line is same as the continuous spectrum of the source lamp. Therefore, by comparing Na D line with a continuous spectrum near the Na D line, the reversal point can be determined, and the bichromator is utilized for this comparison.

The two Littrow mirrors in the bichromator are adjusted so as to give the monochromatic light beams of 5890\AA (one of the Na D doublet lines) and 5885\AA , and the mask is positioned so that these two monochromatic light beams may have the equal intensities. The above two light beams are emitted out alternately from the exit slit at a rate of 10c/s by the chopper I, and the alternate out-put of the photomultiplier is zero under the reversal condition, and has a finite value when the Na D line has emission or absorption. The self-balancing method is based on the principle that the brightness temperature of the source lamp varies automatically to make the alternate out-put from the bichromator zero.

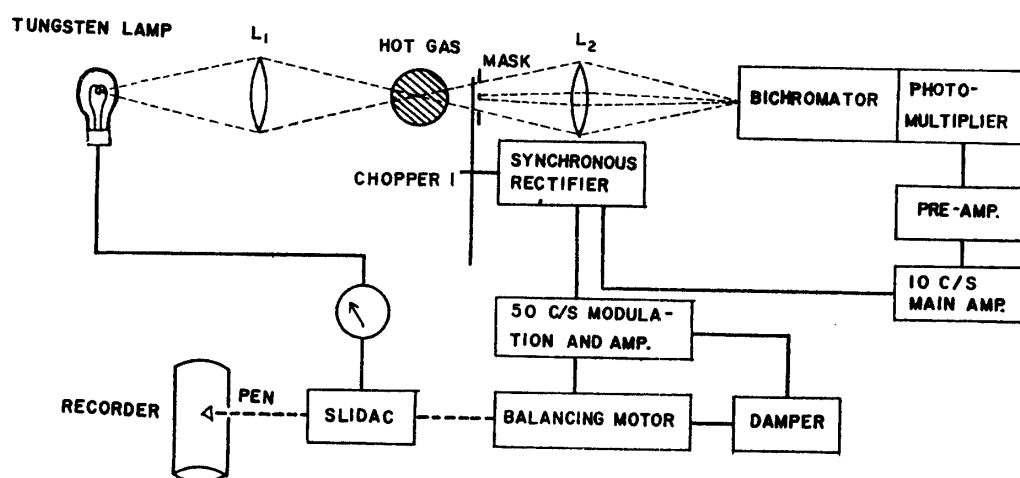


FIGURE 6. Block-diagram of self-balancing method.

For this purpose, the system shown in Fig. 6 is established. The 10c/s alternate photo-current produced in the photomultiplier is amplified by the pre-amplifier and 10c/s main amplifier. The main amplifier is of a RC feed back type using a 10c/s twin T net, and has about 80db of the amplification factor. The out-put from the main amplifier is synchronously rectified by the mechanical rectifier attached to the axis of the chopper I, and the rectified signal of positive sign is obtained when the intensity of 5890\AA is larger than 5885\AA (at $T_o > T_0$), and *vice versa*. This rectification decides the rotational direction of the balancing motor. The positive or negative DC signal is modulated to the 50c/s alternate signal, which is amplified passing through the limiter network, and the out-put drives

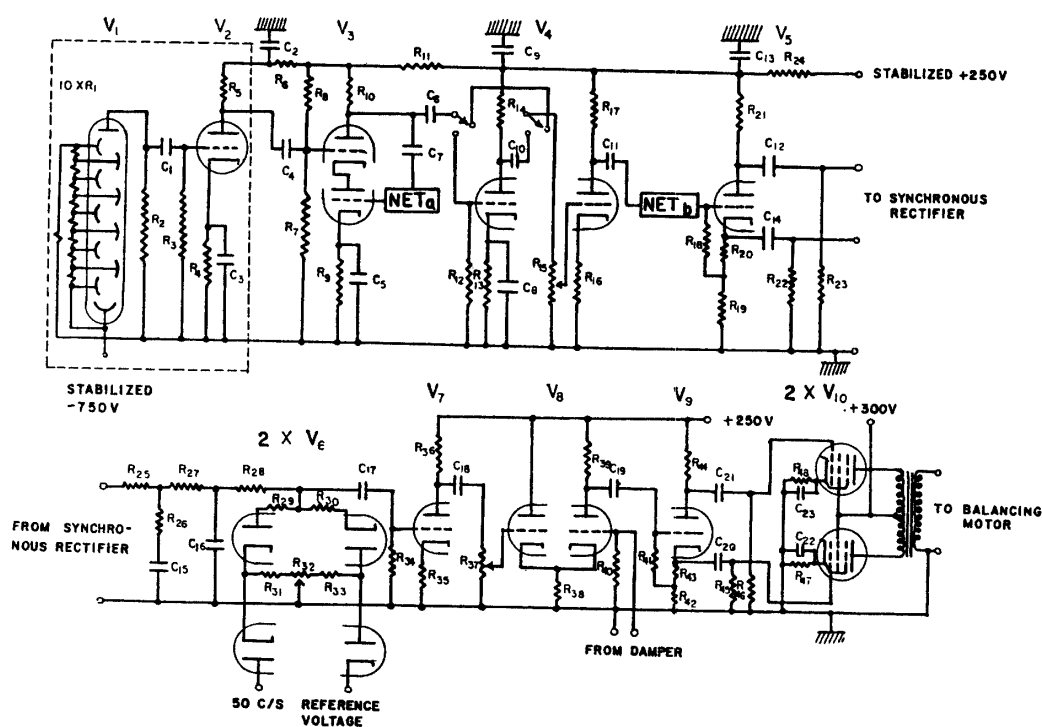


FIGURE 7. Amplifier used in self-balancing method.

V_1 : 1P22 V_2 : 6J4 V_3 : 12AT7 V_4 : 12AX7 V_5 : 1/2 12AU7
 V_6 : 6AL5 V_7 : 1/2 12AX7 V_8 : 12AT7 V_9 : 1/2 12AX7 V_{10} : 6AR5
 VET a: 10c/s twin T net, NET b: 50c/s twin T net for rejection of hum.

the balancing motor, which is connected with the slide regulator, to control the brightness temperature of the source lamp. The limiter network prevents the balancing motor from overshooting the reversal point by using the feedback signal, which is produced by the rotation of the balancing motor's axis.

The reversal point is automatically recorded by the pen which is attached to the axis of the slide regulator. The relation between the brightness temperature of the source lamp and the current or voltage supplied to the lamp, is known by the calibration (ref. Section 6), and so the temperature of the gas can be obtained. The source lamp used here is a 200W projector lamp of a coiled filament type.

The response time is limited by a time necessary to change the brightness temperature of the source lamp and by the large inertia of the slide regulator's rotation. In the present apparatus, it requires a time longer than 6 sec to reach the reversal point of about 2000°K starting from the state that the source lamp has no brightness. If the temperature of the source is previously so as to be near the expected flame temperature, the apparatus follows temperature's variation of about 100°K in 2-3 sec.

The accuracy of this pyrometry depends on the emissivity of Na D line besides the electric noise. When E_{λ_1} and E_{λ_2} are the effective emissivities at 5890Å and 5885Å, respectively, the alternate current produced in the photomultiplier is due to the following quantity,

$$\Delta = \{E_{\lambda_1} B(\lambda_1, T_g) + (1 - E_{\lambda_1}) B(\lambda_2, T_0)\} - \{E_{\lambda_2} B(\lambda_2, T_g) + (1 - E_{\lambda_2}) B(\lambda_2, T_0)\}.$$

As $\lambda_1 \doteq \lambda_2$, $B(\lambda_1, T_g) \doteq B(\lambda_2, T_g)$ and $B(\lambda_1, T_0) \doteq B(\lambda_2, T_0)$, then,

$$\Delta = (E_{\lambda_1} - E_{\lambda_2}) \{B(\lambda_1, T_g) - B(\lambda_1, T_0)\}. \quad (10)$$

Referring to Fig. 5, $E_{\lambda_1} \gg E_{\lambda_2}$, and the minimum out-put signal to move the balancing motor is determined by the electric noise level at some amplification factor; in other words, unless Δ in Eq. (10) exceeds a certain constant value, $B(\lambda, T_g)$ is assumed to be equal to $B(\lambda, T_0)$ in the apparatus. Therefore, the larger the emissivity, the better the accuracy, and in this study, the emissivity is necessary to be larger than about 0.2. In the pyrometry of methane-air flames, the fluctuation of the observed reversal temperatures was about 30°K.

5. NON-BALANCING METHOD

Self-balancing method has an advantage of direct recording of the observed reversal temperature, but the response time of this method is not short enough and the accuracy is almost same as the visual method. In the present method, the intensity of emission or absorption of the gases containing sodium atoms to or from the continuous spectrum of the light source having a fixed brightness temperature, is measured, and the difference between the temperature of the gases and that of the light source is recorded.

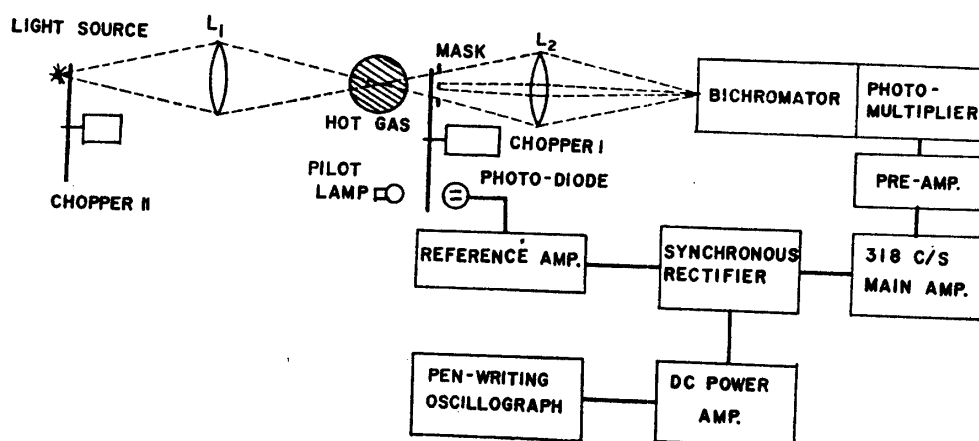


FIGURE 8. Block-diagram of non-balancing method.

Fig. 8 shows the main block-diagram of the apparatus. In this case, the chopper I of the bichromator interrupts the upper and lower light beams alternately at a rate of 318 c/s, so that the two monochromatic light beams enter the photomultiplier alternately every 1/318 sec. The signal produced is amplified by the main amplifier shown in Fig. 9, and the out-put is synchronously rectified by mixing the reference signal from the photoconductive cell, which receives the light chopped by the chopper I from the pilot lamp. This rectified signal is recorded on the pen-writing oscillograph.

The chopper II, which is located in front of the light source, interrupts the light from the source at a rate of 10 c/s, and so the light from the source passing through the gas and that from only the gaseous body enter the bichromator alternately every 0.1 sec.

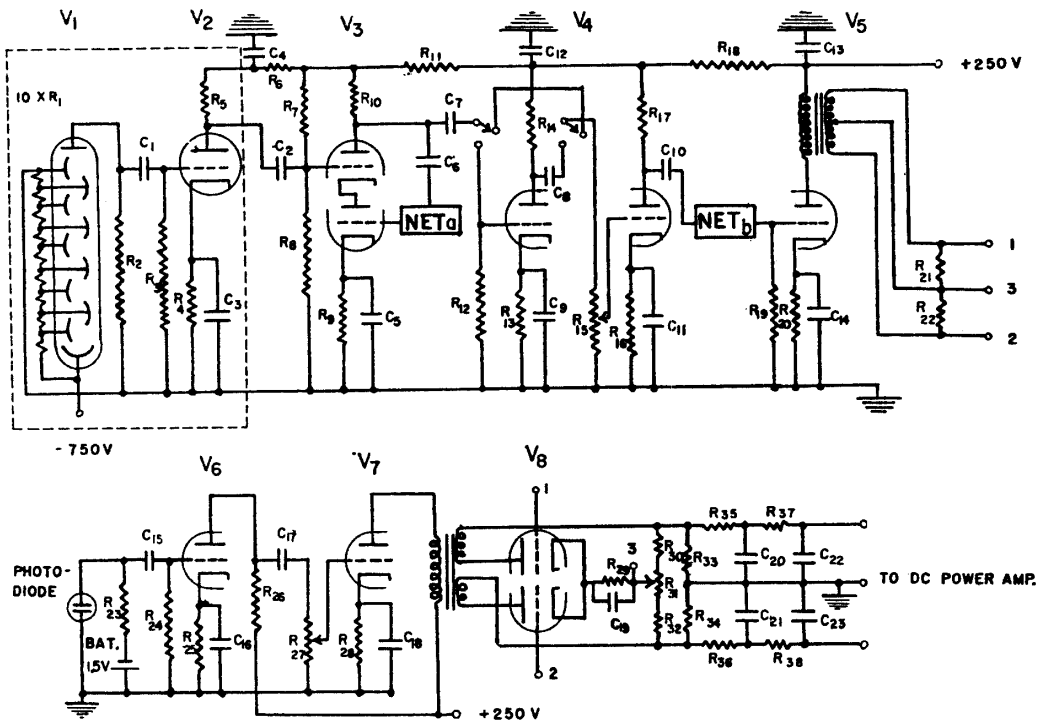


FIGURE 9. Amplifier used in non-balancing method.

- V_1 : 1P22 V_2 : 6J4 V_3 : 12AT7 V_4 : 12AX7 V_5 : 1/2 12AU7
 V_6 : 12AX7 V_7 : 1/2 12AU7 V_8 : 12AU7
 NET a: 318 c/s twin T net, NET b: 50 c/s twin T net.

The two Littrow mirrors of the bichromator are set so that the wave-lengths of two alternate light beams emitted from the exit slit may be 5890\AA ($=\lambda_1$), which is one of the Na D doublet lines, and 5865\AA ($=\lambda_2$), whose spectrum line does not contaminate Na D line. In the case of pyrometry of high temperature gas, intensities of the two alternate light beams at λ_1 and λ_2 are as follows:

$$\left. \begin{aligned} \lambda_1: I_1 &= \{E_{\lambda_1} B(\lambda_1, T_g) + (1 - E_{\lambda_1}) B(\lambda_1, T_0)\} \Delta \bar{\lambda} \Delta \Omega \Delta s, \\ \lambda_2: I_2 &= B(\lambda_2, T_0) \Delta \bar{\lambda} \Delta \Omega \Delta s, \end{aligned} \right\} \quad (11)$$

where the spectral slit-width and the brightness temperature of the source are assumed to be same at wave-length λ_1 and λ_2 , since $\lambda_1 \approx \lambda_2$.

A difference between I_1 and I_2 causes the 318 c/s alternate out-put from the photomultiplier, and the rectified signal v is proportional to the above difference, because the main amplifier and the synchronous rectifier have good linearity. When the phase of the synchronous rectifier is adjusted so as to obtain the positively rectified voltage at $I_1 > I_2$, as shown in Fig. 10, then

$$v \propto \beta_1 I_1 - \beta_2 I_2, \quad (12)$$

where β_1 and β_2 are sensitivities of the photomultiplier at wave-lengths λ_1 and λ_2 , respectively. In the following cases, the rectified signal v is written as;

(i) when the light source only illuminates the bichromator,

$$v_0 \propto \beta_1 B(\lambda_1, T_0) - \beta_2 B(\lambda_2, T_0) = 0, \quad (13)$$

(ii) when the light from the high temperature gas enter the bichromator, the

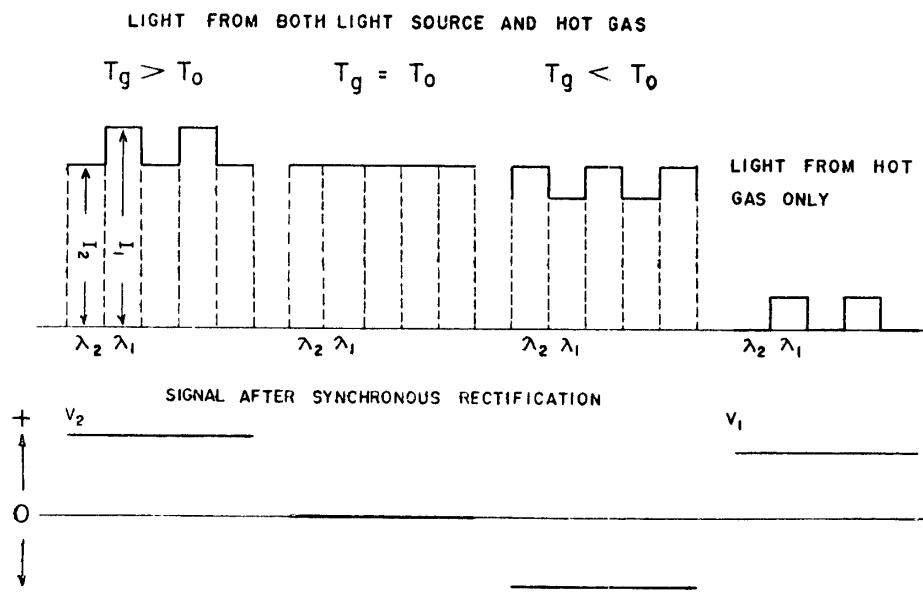


FIGURE 10. Schematic diagram of 318 c/s alternate in-put to photomultiplier and signal after synchronous rectification in various cases.

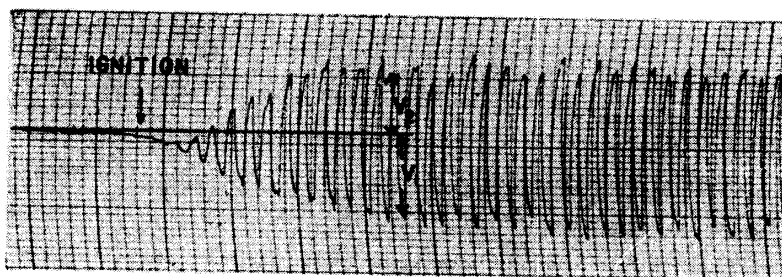


FIGURE 11. An example of record on pen-oscillograph. This was obtained at the pyrometry of the solid propellant's flame.

chopper II interrupts the light beam from the source,

$$v_1 \propto \beta_1 E_{\lambda_1} B(\lambda_1, T_g), \quad (14)$$

(iii) when the light from the light source through the high temperature gas enter the bichromator, the chopper II does not interrupts the light beam from the source,

$$v_2 \propto \beta_1 E_{\lambda_1} \{B(\lambda_1, T_g) - B(\lambda_1, T_0)\} + \{\beta_1 B(\lambda_1, T_0) - \beta_2 B(\lambda_2, T_0)\}. \quad (15)$$

Fig. 8 shows the relation of the rectified voltage v and the 318 c/s alternate output from the photomultiplier in the case (iii), when the temperature of the light source is larger or smaller than that of the gas.

From Eqs. (13), (14) and (15),

$$(v_2 - v_0)/v_1 = 1 - \{B(\lambda_1, T_0)/B(\lambda_1, T_g)\}, \quad (16)$$

and when $B(\lambda, T)$ is replaced by Wien's equation of thermal radiation,

$$1/T_g = (1/T_0) + (\lambda_1/c_2) \ln \{1 - (v_2 - v_0)/v_1\}, \quad (17)$$

where c_2 is hc/k . Here, v_0 , v_1 and v_2 are recorded on the oscillograph, and so the value of temperature T_g can be calculated from Eq. (17).

Heidmann et al and Millar et al observed the intensity of light at wave-length

λ_1 in the cases same as aforementioned, using a monochromator or a filter, and derived the similar equation. Their equations are derived as follows:

in the case (i),

$$D_0 \propto B(\lambda_1, T_0) \Delta \bar{\lambda} \Delta \Omega \Delta s,$$

in the case (ii),

$$D_1 \propto E_{\lambda_1} B(\lambda_1, T_g) \Delta \bar{\lambda} \Delta \Omega \Delta s,$$

in the case (iii)

$$D_2 \propto \{E_{\lambda_1} B(\lambda_1, T_g) + (1 - E_{\lambda_1}) B(\lambda_1, T_0)\} \Delta \bar{\lambda} \Delta \Omega \Delta s,$$

where D 's show the photo-electric signals proportional to the intensity of the light at wave-length λ_1 . Then,

$$(D_2 - D_0) / D_1 = 1 - \{B(\lambda_1, T_0) / B(\lambda_1, T_g)\}. \quad (18)$$

Eqs. (18) and (16) have an equal form, but in the present case, v_0 is nearly zero and v_2 corresponds to $(D_2 - D_0)$ in Heidmann or Millar's case. The present method is characterized by the fact that the intensity of Na D spectrum line's emission or absorption to or from the continuous back-ground spectrum of the light source is amplified.

In general, the emissivity of the gaseous body having several cm in diameter cannot exceed about 0.2 to avoid the disturbance of the true temperature due to the contamination of sodium vapor, and therefore D_2 or D_0 is about fivefold larger than D_1 . On the other hand, v_1 can be larger than v_2 or v_0 in the present method, and so the accuracy of a measured quantity, $1 - \{B(\lambda_1, T_0) / B(\lambda_1, T_g)\}$, is improved by about a factor of five than Heidmann et al or Millar et al's method. The present method can be used, even when the emissivity is smaller than 0.2. The accuracy measured is about 10°K at 2000°K of the gas temperature.

Since v_1 and v_2 are recorded alternately every 0.1 sec by the chopper II, the response time of the pyrometer is 0.1 sec, which can be shortened by rotating the chopper II more rapidly. However, in the present method, the chopper I must rotate about ten fold faster than the chopper II, and it is difficult to chop a light beam faster than an order of 10^{-3} sec. In the present method, the response time cannot be made shorter than an order of 10^{-2} sec, but it can be an order of 10^{-3} sec in Heidmann et al or Millar et al's method. Curcio investigated the pyrometry at the response time of 10^{-4} sec [10]. The present apparatus is going to be remodelled in order to obtain a pyrometer having a very short response time.

6. BRIGHTNESS TEMPERATURE OF LIGHT SOURCE

Brightness temperature T_0 of a non-black body at a wave-length λ is defined as follows:

$$B(\lambda, T_0) = E_\lambda B(\lambda, T_t), \quad (19)$$

where T_t is true temperature of the body and E_λ is emissivity of the body at a wave-length λ . Therefore, the brightness temperature can be obtained by comparing the intensity of light from the body with that of the black body.

In the reversal method, the light source is usually a tungsten ribbon lamp, but its brightness temperature cannot be raised higher than 2400°K and a time required to change the temperature is longer than a filament type lamp. For these reasons, the 200W projector lamp of coiled filament type is used as a light source. The brightness temperature is measured by the Yokokawa's optical pyrometer in relation to the lamp current. As the optical pyrometer gives the brightness temperature at wave-length of 650 m μ , the value obtained must be calibrated to give the value at wave-length of 589 m μ . From Eq. (19),

$$\begin{aligned} (1/T_t) - \{1/T_0(\lambda')\} &= (\lambda'/c_2) \ln E_{\lambda'} , \\ (1/T_t) - \{1/T_0(\lambda)\} &= (\lambda/c_2) \ln E_{\lambda} , \end{aligned}$$

then,

$$1/T_0(\lambda) = \{1/T_0(\lambda')\} + (\lambda'/c_2) \ln E_{\lambda'} - (\lambda/c_2) \ln E_{\lambda} , \quad (20)$$

where λ and λ' are wave-lengths 589 m μ and 650 m μ , respectively and E_{λ} and $E_{\lambda'}$ are emissivities of tungsten at corresponding wave-lengths. There have been many investigations about the emissivity of tungsten; here Larrabee's data are adopted [14]. He derived the following experimental equation about the emissivity of tungsten,

$$\begin{aligned} \text{at } 450 \text{ m}\mu - 680 \text{ m}\mu: E_{\lambda T} &= 0.4655 + 0.01558\lambda + 0.2675 \times 10^{-4}T \\ &\quad - 0.7305 \times 10^{-4}\lambda T , \end{aligned} \quad (21)$$

where T and λ are expressed in terms of °K and μ , respectively.

Since the absorption of light by the lens L_1 in Fig. 1 lowers the brightness temperature of the source, the resulting calibration must be done. When the transmittancy of L_1 is κ ,

$$1/T_0'(\lambda) = \{1/T_0(\lambda)\} - (\lambda/c_2) \ln \kappa , \quad (22)$$

where $T_0'(\lambda)$ is calibrated value.

Thus, using the optical pyrometer the brightness temperature of the filament lamp can be obtained, but this calibration might have some uncertainty, because it is difficult to measure a correct temperature of fine filament by the optical pyrometer. Besides, the emissivity of tungsten ribbon or strip has been reported, and it is possible that the emissivity of coiled filament tungsten would have some different value.

In order to obtain more reliable value of the brightness temperature, the gas-filled tungsten ribbon lamp, which has brightness temperature of 2042°K at 659 m μ when the lamp current is 14.88 A*, is used as a primary standard. Then, the relative intensity of light from the filament lamp at wave-length 589 m μ is measured with the bichromator used as a monochromator; the intensity $I(i)$ at a certain lamp current i is compared with that of the primary standard lamp. From Wien's equation,

$$I(i)/I_0 = \exp [-(c_2/\lambda)\{(1/T_0(i)) - (1/T_0)\}] , \quad (23)$$

where $T_0(i)$ is brightness temperature of the filament lamp at lamp current i , and

* The author is indebted to Mr. M. Suzuki of The Electrotechnical Laboratory for his precise measurement of brightness temperature.

T_0 is that of the primary standard lamp. As a result, the brightness temperature of the filament lamp is obtained without using the optical pyrometer, as shown in Fig. 12, and it is ascertained that the calibrated values by the optical pyrometer are almost correct. These calibration makes it possible to use a filament lamp as a secondary standard of brightness temperature.

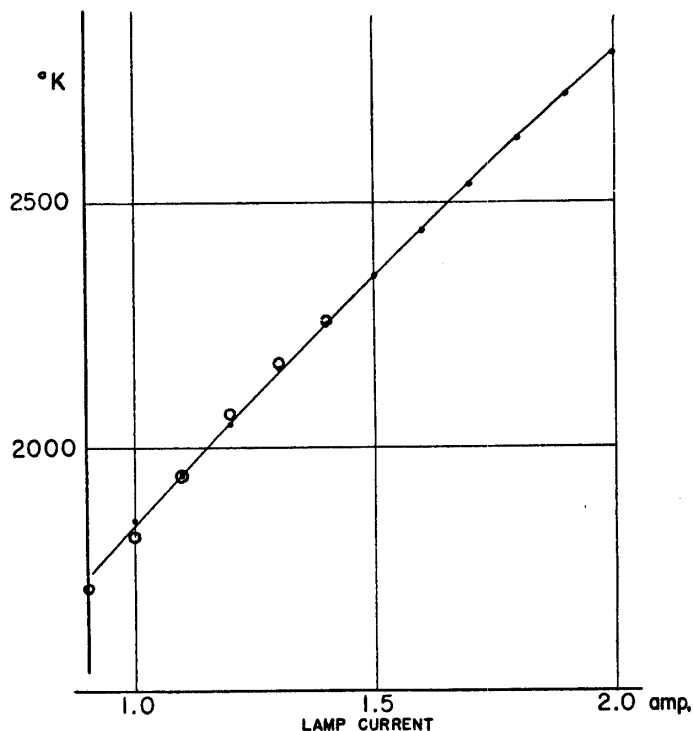


FIGURE 12. Brightness temperature of the 200W coiled filament lamp;
 ●: determined by the comparison with the primary standard lamp,
 ○: determined by the optical pyrometer.

The temperature range of pyrometry by the Na D line reversal method is limited by the weakness of thermal emission of Na D line in lower temperature side and by the brightness temperature of the light source in higher side. The maximum temperature of tungsten filament lamp is 2800°K, and therefore in non-balancing method the temperature up to 3000°K is measurable, beyond which another light source must be used.

Gaydon and Wolfhard used the carbon arc as a light source, and measured its brightness temperature to be 3590°K at 5180Å and 3710°K at 3750Å [9]. The author measured the brightness temperature of 150W Xenon arc lamp as follows:

at 5890Å, 2924°K with 7.5 A of arc current.

The pyrometry of higher than 4000°K by the Na D line reversal method may be difficult owing to the lackness of a suitable light source, but in the ultra-violet region, the hydrogen or mercury discharge tube has a very intense spectrum, so that some higher temperature can be measured if a spectrum line in the ultra-violet region is adopted. Model' measured the temperature higher than 5000°K in the strong shock wave using the sun as a standard light source, which had the temperature of 5500°K, though his method was not reversal type [15].

7. RESULTS OF MEASUREMENT BY THE PYROMETER

7.1. Temperature of Methane-Air Flame (Self-balancing method)

There have been many studies on the measurement of flame temperatures by the Na D line reversal method. Here, the temperature of methane-air flame has been observed in order to compare the present pyrometer with the usual visual method. The burner used was of a flat flame type, and had a diameter of 6 cm. To obtain Na D line from the flame, the fine dust of sodium carbonate was introduced in two ways; first into the center part of the flame and the other into the total flame. The significant difference of the reversal temperature between two ways was not recognized. However, Kavelar and Lewis observed that the reversal temperature of the flame totally colored by sodium atoms was lower than that of the flame partially colored, using the Mecker burner of 7/8" in diameter [16].

The reversal temperature measured by the self-balancing method agreed fairly well with that by the visual method, as shown in Fig. 13.

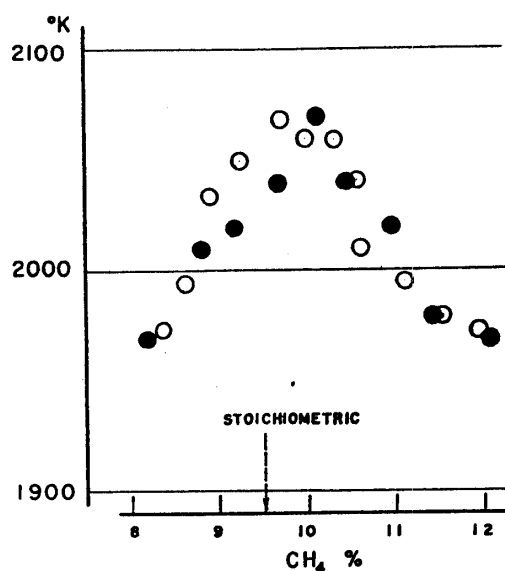


FIGURE 13. Temperature of methane-air flame;
○: measured by self-balancing method,
●: measured by visual method.

7.2. Temperature of Rocket Exhaust Jet (Non-balancing method)

The main purpose of constructing the present apparatus is the pyrometry of the working gases in the rocket engine, as mentioned in Section 1. First, the exhaust temperature of the JP-4-Nitric acid rocket having 100 kg of thrust was measured. The results obtained are shown in Fig. 14 together with the calculated theoretical temperatures, and it has been estimated that the present nozzle flow took place with the chemical equilibria neither shifting nor frozen, and that the relaxation of the chemical equilibria occurred. These discussions will be reported in the other paper [17]. The same observation about the exhaust temperature of the rocket engine was obtained by Simmons and DeBell [18].

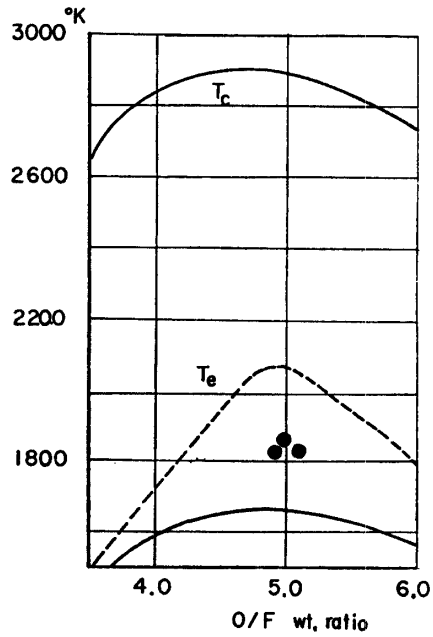


FIGURE 14. Temperature in the combustion chamber T_c and that in the exhaust jet T_e , with correction due to heat loss in the chamber $0.05 \text{ kcal/cm}^2 \cdot \text{sec.}$, and in the nozzle $0.084 \text{ kcal/cm}^2 \cdot \text{sec.}$;
 — and ---: with chemical equilibria frozen and shifting, respectively,
 ●: experimental value.

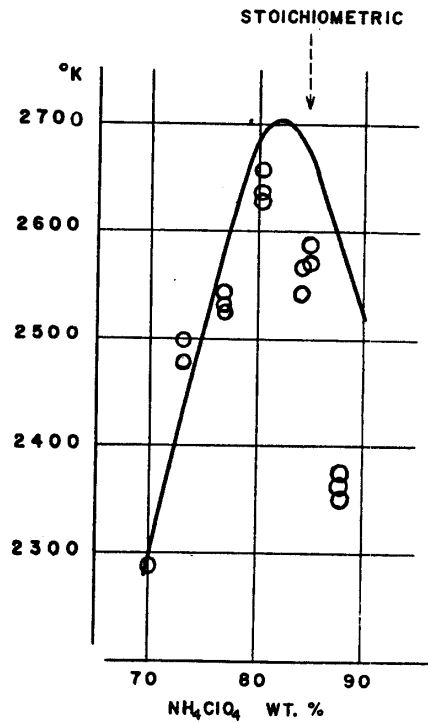


FIGURE 15. Flame temperature of ammonium perchlorate-polyester resin propellant;
 ○: experimental value,
 —: theoretical temperature.

7.3. Flame Temperature of Solid Propellant (Non-balancing method)

In the rocket engine of a certain propellant system, it is desired to obtain a maximum efficiency which is given theoretically. In order to satisfy the above requirement, it is necessary that the propellant reacts in the combustion chamber to reach a thermodynamically equilibrium state, and that the gas produced expands through the nozzle keeping the thermodynamic and chemical equilibria. The temperature of gas can be a parameter which describes its thermodynamic state; in other words, the comparison of the measured temperature with the theoretical temperature gives some information about whether the propellant completely reacts or not. As a first step of the study about the solid propellant rocket, the flame temperature has been measured at the atmospheric pressure.

The propellant strand (10×10 mm) composed of ammonium perchlorate-polyester resin, in which 0.3 wt. % of sodium carbonate was mixed, was burned in the atmosphere. The results are given in Fig. 15, and the theoretical flame temperature calculated here agrees with the observed temperature about the propellant having less than 80 wt. % of ammonium perchlorate. The disagreement between the theoretical and observed flame temperature of the propellant having more than 80 wt. % of ammonium perchlorate, might be caused by the incomplete combustion of the propellant. More detailed studies on the flame of the solid propellant are now in progress.

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REFERENCES

- [1] B. Lewis and G. von Elbe: *Combustion, Flames and Explosions of Gases*. Chap. XIV, Academic Press; N.Y., 1951.
- [2] P.J. Dyne and S.S. Penner: *Optical Methods for the Determination of Combustion Temperature*. *J. Am. Rocket Soc.*, 23, 165 (1953).
- [3] F.P. Bundy and H.M. Strong: *Measurement of Flame Temperature, Pressure, and Velocity*. *Physical Measurement in Gas Dynamics and Combustion, Section I*, edited by B. Lewis, R.N. Pease and H.S. Taylor, Princeton Univ. Press, Princeton, 1954.
- [4] D. Buchele: *A Self-Balancing Line-Reversal Pyrometer*. NACA Tech. Note 3656 (1956).
- [5] W.M. Brobeck, R.E. Clemenser and W.E. Voreck: *A Recording Sodium-Line Reversal Pyrometer*. *Jet Propulsion*, 28, 249 (1958).

- [6] M.F. Heidmann and R.J. Priem: A Modified Sodium-Line Reversible Technique for the Measurement of Combustion Temperature in Rocket Engines. *J. Am. Rocket Soc.*, 23, 248 (1953).
- [7] G.H. Millar, J.G. Winans, O.A. Uyehara and P.S. Myers: A Fast, Electro-Optical, Hot-Gas Pyrometer. *J. Opt. Soc. Am.*, 43, 609 (1953).
- [8] G.W. Bauserman, C.H. Prien and T. Zandstra: Determination of Transient Flame Temperature. *Rev. Sci. Instrument*, 25, 640 (1954).
- [9] A.G. Gaydon and H.G. Wolfhard: Spectroscopic study of low-pressure flames V. Evidence for abnormally high electronic excitation. *Proc. Roy. Soc. (London)*, A, 205, 118 (1951).
- [10] J.A. Curcio, H.S. Stewart and C.C. Petty: A Method for the Determination of Flame Temperature from Emission in the Ultraviolet OH Bands. *J. Opt. Soc. Am.*, 41, 173 (1951).
- [11] S. Silverman: The Determination of Flame Temperatures by Infra-Red Radiation. *J. Opt. Soc. Am.*, 39, 275 (1949).
- [12] A.G. Gaydon and I.R. Hurlé: Temperature measurement of shock waves by spectrum-line reversal method II. A double-beam method. *Proc. Roy. Soc. (London)*, A, 262, 143 (1959).
- [13] H.H. Strong, F.P. Bundy and D.A. Larson: Temperature Measurement on Complex Flames by Sodium Line-Reversal and Sodium D-Line Intensity Contour. 3rd. Symposium on Combustion (1949) p. 641.
- [14] R.D. Larrabee: Spectral Emissivity of Tungsten. *J. Opt. Soc. Am.*, 49, 619 (1959).
- [15] I. Sh. Model': Measurement of High Temperatures in Strong Shock waves in Gases. *Soviet Phys. JETP*, 5, 589 (1957).
- [16] H.H. Kaveler and B. Lewis: Flame Temperatures and Vertical Gradient in Natural Gas Flames. *Chem. Rev.*, 21, 421 (1937).
- [17] S. Tsuchiya: Studies on the Chemical Equilibrium Lag during the Rapid Expansion through the Rocket Nozzle. *Bull. Chem. Soc. Japan*, to be published.
- [18] F.S. Simmons and A.G. DeBell: Photographic Pyrometry of Rocket Exhaust Jets. *Aircraft Engineering*, 31, 144 (1959).