

FR-3319

UNCLASSIFIED

A PHOTOELECTRIC PYROMETER FOR THE MEASUREMENT OF LUMINOUS FLAME TEMPERATURES

J. A. Curcio and D. V. Estes

July 14, 1948

Distribution Unlimited

Approved for
Public Release

Approved by:

Dr. J. A. Sanderson, Head, Radiometry Section
Dr. E. O. Hulburt, Superintendent, Optics Division



NAVAL RESEARCH LABORATORY

CAPTAIN H. A. SCHADE, USN, DIRECTOR

WASHINGTON, D.C.

DISTRIBUTION

ONR (5)

RDB

Attn: Guided Missiles Committee (5)

AN-GM Mailing List

Parts A, C, DP, DG, DA, and DW (Copy Attached)

UNCLASSIFIED

CONTENTS

Abstract	iv
Problem Status	iv
Authorization	iv
INTRODUCTION	1
DERIVATION OF TEMPERATURE EQUATIONS	1
Optical Pyrometer	1
Photoelectric Pyrometer	4
PHOTOELECTRIC PYROMETER	6
Experimental Results	9
Accuracy of Results	10
Conclusion	11

ABSTRACT

A photoelectric pyrometer has been developed for the measurement of flame temperatures. By means of a photo-multiplier tube covered with an interference filter transmitting a spectral band at $5520\text{\AA}$, radiant intensities of luminous flames were measured first against a dark background and then with a mirror so placed behind the flame that radiation was redirected, thereby increasing the flame thickness. The photocell filter system was calibrated with radiation from a globar at known brightness temperatures. Application of Wien's and Kirchoff's radiation laws provided a relation between photocell currents and flame temperatures. Flame temperatures determined by this method were about 10 to 15 percent lower than temperatures obtained by sodium line reversal, presumably because the integrated optical paths contributing to observed radiant intensities were different in the two cases.

PROBLEM STATUS

This is an interim report on this problem.

AUTHORIZATION

NRL Problem Number N04-02R.

UNCLASSIFIED

A PHOTOELECTRIC PYROMETER FOR THE MEASUREMENT OF LUMINOUS FLAME TEMPERATURES

INTRODUCTION

This paper discusses a method for determining the temperature of smoky, luminous flames by means of two measurements of the intensity of light at a single wavelength, one intensity measurement being made on a single thickness of the flame and the second being made on a greater thickness through the same section of flame. This method has been used extensively by Hottel¹ and others employing optical pyrometers. It consists essentially of making two brightness temperature measurements with an optical pyrometer, one by sighting the pyrometer through the flame against a dark background, and the second by sighting the pyrometer through the same section of the flame with a plane mirror of known reflectivity as the background. By applying the Wien and Kirchhoff radiation laws, an equation has been derived which relates the true temperature of the flame to the two brightness temperatures, the emissivity of the flame having been eliminated in the derivation of the equation.

In the present work the optical pyrometer has been replaced by a photomultiplier tube and an interference filter. This photoelectric pyrometer is aimed at the flame with and without the mirror, and by noting the output ammeter deflections, which are proportional to spectral intensity, the true flame temperature may be easily obtained. The quantity which must be determined experimentally is a proportionality factor between output meter current and the spectral intensity. This quantity was determined by noting the output current with the photoelectric pyrometer aimed at a globar of known brightness temperature.

DERIVATION OF TEMPERATURE EQUATIONS

Optical Pyrometer

Wien's equation will be used to describe the spectral radiant intensity of the flame.

¹ H. C. Hottel and F. P. Broughton, Ind. Eng. Chem. Anal. Ed. 4, pp. 166-75 (1932).

$$J_{\lambda} = E_{\lambda} C_1 \lambda^{-5} e^{-C_2/\lambda T}, \quad (1)$$

where:

J_{λ} = spectral radiant intensity in watts/(2 π steradian cm²),

E_{λ} = spectral emissivity of the radiator,

C_1 = first radiation constant = 3.697×10^{-12} watts cm²,

λ = wavelength in cm,

C_2 = second radiation constant = 1.432 cm degrees, and

T = true temperature of the emitting body in degrees Kelvin.

Equation (1) is simpler than the Planck equation, and is accurate to within one percent when λT is less than 0.3 cm degrees, which is true throughout the range of wavelengths and temperatures dealt with here.

Let J_{λ}^i represent the spectral radiant intensity viewed by the optical pyrometer when aimed at the flame against the dark background, and let T^i be the brightness temperature measured. Equation (1) is written

$$J_{\lambda}^i = K_1 e^{-K_2/T^i} \quad (2)$$

where

$$K_1 = C_1 \lambda^{-5},$$

and

$$K_2 = C_2 / \lambda.$$

It is required to associate Equation (2) with the radiative properties of the flame. Let ϵ_{λ} be the emissivity per cm³ and α_{λ} the absorption coefficient of the flame. The spectral radiant intensity per cm² emerging from a column of the flame of thickness t cm is given by

$$\begin{aligned} J_{\lambda}^i &= \int_0^t \epsilon_{\lambda} \alpha_{\lambda} e^{-\alpha_{\lambda} t} \\ &= \frac{\epsilon_{\lambda}}{\alpha_{\lambda}} (1 - e^{-\alpha_{\lambda} t}). \end{aligned} \quad (3)$$

It is assumed that the measurement is to be made at a wavelength λ where there are no band systems and where thermodynamic equilibrium exists so that Kirchoff's radiation law can be applied. That is, $\epsilon_{\lambda}/\alpha_{\lambda}$ is equal to the radiant intensity of a black body at the same true temperature as the flame. Then it follows that $(1 - e^{-\alpha_{\lambda} t})$ is the integrated emission coefficient

E_f of the entire flame thickness. Therefore, in terms of Wien's radiation law,

$$J_{\lambda}' = K_1 e^{-K_2/T'} = K_1 e^{-K_2/T} (1 - e^{-\alpha t}), \quad (4)$$

in which T' is the brightness temperature and T the true temperature of the flame. It will be recognized that E_{λ} of Equation (1) is equal to $(1 - e^{-\alpha t})$.

Now, let J_{λ}'' represent the spectral radiant intensity viewed by the optical pyrometer when aimed at the flame with a mirror behind the flame, and let T'' be the second brightness temperature measured. Then

$$J_{\lambda}'' = K_1 e^{-K_2/T''} \quad (5)$$

The spectral intensity J_{λ}'' is also given by

$$J_{\lambda}'' = \frac{\epsilon_{\lambda}}{\alpha_{\lambda}} (1 - e^{-\alpha_{\lambda} t}) + \frac{\epsilon_{\lambda}}{\alpha_{\lambda}} (1 - e^{-\alpha_{\lambda} t}) R e^{-\alpha_{\lambda} t} \quad (6)$$

where the first term on the right hand side of Equation (6) is the radiation received from the flame directly, and the second term represents the radiation emitted toward the mirror multiplied by the reflectivity of the mirror R and the transmission of the flame $e^{-\alpha_{\lambda} t}$. Applying Kirchhoff's law to Equation (6) and equating to Equation (5),

$$J_{\lambda}'' = K_1 e^{-K_2/T} (1 - e^{-\alpha_{\lambda} t}) (1 + R e^{-\alpha_{\lambda} t}) = K_1 e^{-K_2/T''} \quad (7)$$

From Equation (4),

$$(1 - e^{-\alpha_{\lambda} t}) = e^{K_2 \left(\frac{1}{T} - \frac{1}{T'} \right)}, \text{ and}$$

$$e^{-\alpha_{\lambda} t} = 1 - e^{K_2 \left(\frac{1}{T} - \frac{1}{T'} \right)}.$$

Making these substitutions in Equation (7) and simplifying,

$$e^{-K_2/T''} = (1 + R) e^{-K_2/T} - R e^{K_2 \left(\frac{1}{T} - \frac{1}{T'} \right)} \quad (8)$$

A further simplification is made by dividing both sides by $e^{-K_2/T'}$.

$$e^{K_2 \left(\frac{1}{T'} - \frac{1}{T''} \right)} = (1 + R) - R e^{K_2 \left(\frac{1}{T} - \frac{1}{T'} \right)} \quad (9)$$

Equation (9) is the derived equation relating the true temperature of the flame T to the two brightness temperatures T' and T'' measured with the optical pyrometer.

Photoelectric Pyrometer

The optical pyrometer is now replaced by a photo-multiplier tube, an interference filter, and an auxiliary optical setup for focussing an image of the flame, with and without the mirror as background on a slit placed in front of the photo-multiplier tube. The photoelectric current produced is proportional to the spectral intensity J_λ , λ being the wavelength of maximum transmission of the interference filter. Thus, without the mirror in place

$$D_1 = C' K_1 e^{-K_2/T'} \quad (10)$$

where

D_1 = photo-multiplier output current which is proportional to J_λ ,

C' = proportionality constant, and

$K_1 = C_1/\lambda^5$ (constant).

Let C' and K_1 be combined so that

$$D_1 = C e^{-K_2/T'} \quad (11)$$

where C is the instrumental constant which is determined experimentally. Similarly, the photocell response with the mirror in place may be written as

$$D_2 = C e^{-K_2/T''} \quad (12)$$

From Equations (9), (11) and (12) one obtains

$$\frac{D_2}{D_1} = 1 + R - \frac{R D_1}{C e^{-K_2/T}} \quad (13)$$

which is written

$$\ln \left[\frac{1 + R - D_2/D_1}{R D_1} \right] + \ln C = \frac{K_2}{T} \quad (14)$$

Hence, when the instrumental constant, $\ln C$, is known, true flame temperatures can be easily had from the photoelectric responses to spectral intensities with and without the mirror.

The multiplier pyrometer constant, $\ln C$, was determined by focussing the image of a globar at known brightness temperatures on the photo-multiplier

arrangement and reading meter deflections as a function of brightness temperature for eleven temperatures between 1278°K and 1648°K. By using Wien's Equation in the form of Equation (11) or (12), where D is the meter deflection, in 10^{-7} amperes, observed when the brightness temperature of the globar was T°K,

$$\ln C = \ln D + K_2/T. \quad (15)$$

Quantities observed in determining $\ln C$ are shown in Table I. The average deviation in $\ln C$ was 0.23 percent, and values determined at these various temperatures showed no trend with temperature which would result from the use of an inadequately narrow wavelength band.

Table I

Globar Temperatures (T°K)	Meter Deflections D, 10^{-7} amp	$\ln C$
1278	1.2	20.4182
1308	2.1	20.5752
1348	3.5	20.4976
1378	5.5	20.5306
1421	9.7	20.5283
1456	13.4	20.4125
1493	20.5	20.3961
1498	22.5	20.4313
1548	41.2	20.4768
1588	58.7	20.4087
1648	103.7	20.3830

$$\ln C = \ln D + \frac{K_2}{T} \quad (15)$$

$$K_2 = \frac{C_2}{\lambda} = \frac{1.432}{5520 \times 10^{-4}} = 2.5942 \times 10^4$$

$$\text{average } \ln C = 20.4568$$

$$\text{average deviation} = .04686$$

$$\text{percent deviation} = 0.23 \text{ percent}$$

Many flames of high emissivity emit continuous radiation in the visible spectrum permitting the observations required by Equation (14) to be made by photocells covered with interference filters,^{2,3}. These exist in sufficient variety to permit a choice of spectral region within the visible region and with bandwidths approaching those obtainable with monochromators. The flames on which the present exploratory measurements were made were vigorous, luminous gas-oxygen, air-acetylene and candle flames. The emissivity of these flames was usually greater than 0.10.

PHOTOELECTRIC PYROMETER

A schematic diagram of the photoelectric pyrometer is shown in Figure 1. The multiplier phototube was an RCA 1-P22 with high sensitivity at 5500 Angstroms. Suitable neutral filters were used so that the output from the multiplier tube was less than 2.0 microamperes in all cases. The filter F was an interference filter transmitting 39 percent at 5520 Angstroms. The half-width of the transmitted band was 140 Angstroms. The transmission curve of the filter⁴ is shown in Figure 2. The lens L was 5.6 cm in diameter and 60 cm in focal length. The mirror was silvered on the back surface and reflected 0.90 of the incident light at λ 5520Å and 0.80 at λ 6650Å. It was placed about 10 cm behind the flame, while lens L of the pyrometer was about 170 cm in front of the flame. The lens formed the image of the flame at 92.7 cm and the image of the mirror image of the flame at 87.7 cm. The multiplier was placed at 90 cm from the lens, the out-of-focus point where the two images of the flame were the same size. A vertical slit, 2 mm x 6 mm, immediately in front of the multiplier tube, limited the portion of the flame seen by the cathode.

It should be noted that the photoelectric pyrometer is not limited to flames which are at distances used in these experiments. The optical arrangement can be so adjusted that the photoelectric pyrometer can be used at any reasonable distance. For, if the solid angle subtended by the multiplier tube is filled with radiation from the calibrating globar or tungsten strip, the pyrometer can be used at any distance so long as the same solid angle is filled with light. Thus, all that is necessary is a proper choice of stops and slit size in order that the solid angle may be completely filled with light when the flames are at various distances.

This photoelectric pyrometer has been used only in preliminary laboratory measurements on propane-oxygen flames, on smoky air-acetylene flames, and on a candle flame. The propane gas was burned in an ordinary gas laboratory torch which was adjusted to produce a sooty luminous flame about 2 cm in diameter and 40 cm high. The measurements on the flames consisted of observing the output meter deflections D_1 without the mirror and then immediately observing D_2 with the mirror in place.

² J. A. Sanderson and R. L. Ueberall, "German Interference Filters," NRL Report H-2731 (5 January 1946)

³ L. N. Hadley and D. M. Dennison, *J. Opt. Soc. Am.* 37, pp. 451-465 (June 1947)

⁴ These filters are available from Baird Associates, Cambridge, Mass., and The Farrand Optical Co., E. 238 St. and Bronx Blvd., New York.

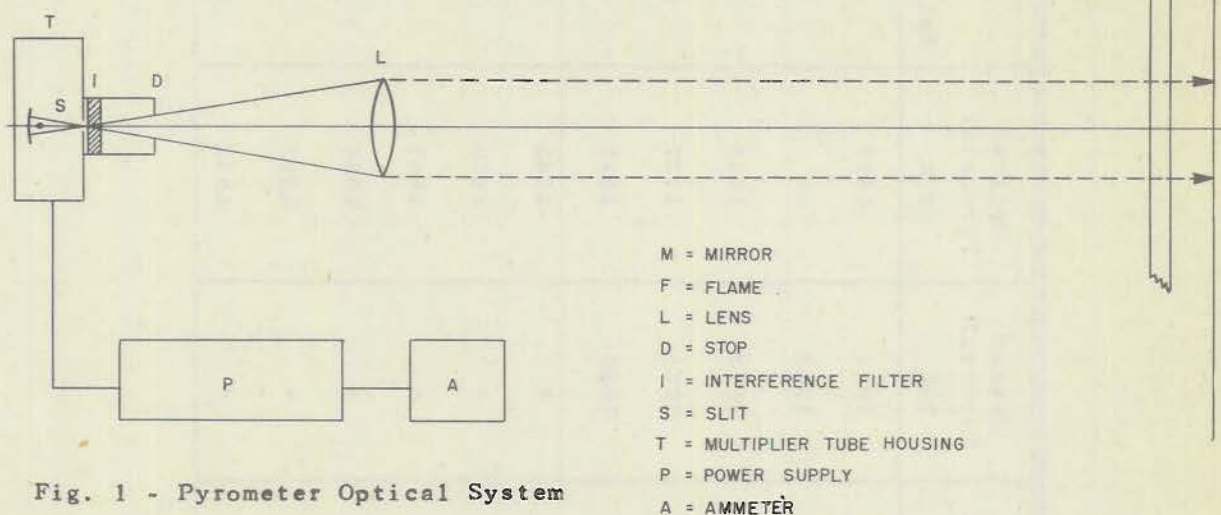


Fig. 1 - Pyrometer Optical System

In each case the flame temperatures were also determined by the use of an optical pyrometer in place of the photoelectric pyrometer, and by the sodium line reversal method⁵ in some cases.

For the sodium reversal method, sodium was introduced into the flame by burning a small bit of rocksalt on the lower edge of the flame. A tungsten filament lamp was placed behind the flame, and both the flame and the lamp were viewed in a spectroscope, thus superimposing the D lines of sodium on the continuum of the tungsten lamp. When the flame was cooler than the tungsten filament, the sodium lines appeared dark as in absorption; and when the flame was hotter than the filament, the lines were bright as in emission. The current through the lamp was varied until the sodium lines blended

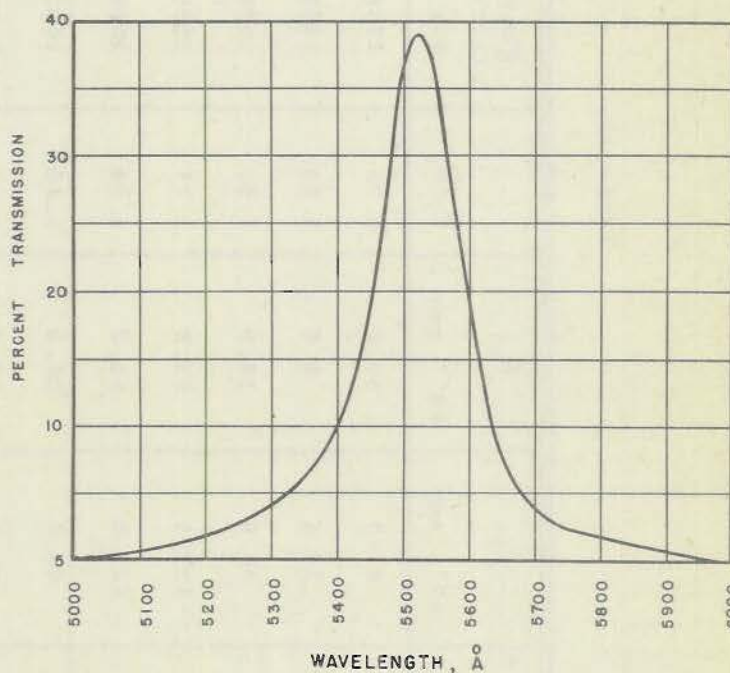


Fig. 2 - Transmission of Interference Filter

⁵ "Temperature - its measurement and control in science and industry," Am. Inst. Phys., p. 708, Reinhold (1941).

Table II

No.	Flame	D_2 10 ⁻⁷ amp	D_1 10 ⁻⁷ amp	D_2/D_1	Photo- electric T°K	Sodium Reversal T°K	Optical Pyrometer T°K	Emissivity
1	Oxy-propane	87.5	50.0	1.75	1758	1945	1656	0.17
2	Oxy-propane	14.6	9.6	1.53	1498	1753	*	0.41
3	Oxy-propane	30.4	18.9	1.60	1579	1893	1635	0.33
4	Oxy-propane	112.5	63.8	1.77	1800	1975	1737	0.14
5	Oxy-propane	115.0	61.2	1.88	2069	1959	1615	0.02
6	Oxy-propane	45.0	25.5	1.76	1697	*	1740	0.16
7	Oxy-propane	24.1	12.3	1.80	1647	*	1670	0.11
8	Oxy-propane	13.7	7.4	1.85	1670	*	1562	0.06
9	Candle	20.2	12.5	1.61	1544	*	1586	0.32
10	Air-acetylene	36.8	23.2	1.59	1596	*	1593	0.34
11	Air-acetylene	43.9	28.0	1.57	1609	*	1642	0.35

* Not measured.

with the tungsten continuum and were not discernable. Then the optical pyrometer measurement of the brightness temperature of the tungsten filament gave a value for the true temperature of the flame.

Experimental Results

Results of a number of measurements are given in Table II. Meter deflections are indicated by D_2 and D_1 with and without the mirror respectively, while D_2/D_1 is the ratio of the two deflections. Check temperatures of the same flames by sodium reversal and by optical pyrometer methods are recorded as indicated.

Temperatures determined with the photo-cell and the optical pyrometer show an average difference of 3.5 percent. Since the optical arrangements were identical, the differences shown in Table II represent the sum of instrumental errors of both instruments, together with the effect of any fluctuations of the flames. Temperatures obtained by sodium D line reversal were about 15 percent higher than those obtained with the optical pyrometer. The flames were unquestionably non-uniform. A platinum wire placed in the flame was cooler at the center than near the flame edges. Since the integrated optical paths of the radiation may be different for the two methods, it cannot be said how closely any of the results of Table II approach the true "average" temperatures that would be recorded by a minute thermometer.

Figure 3 shows spectra obtained with a 2-meter, 15,000 line-per-inch grating spectrograph of the continuum spectrum produced by the flames under investigation (middle spectrum), of the portion of this spectrum transmitted by the interference filter (top), and of the Swan bands of C_2 (bottom) in a clean burning blue flame. While there is no evidence of the band system in the continuous spectrum, a better choice of filters could be made in order to avoid regions of band systems. However, it appears from work of G. H. Dieke, The Johns Hopkins University,

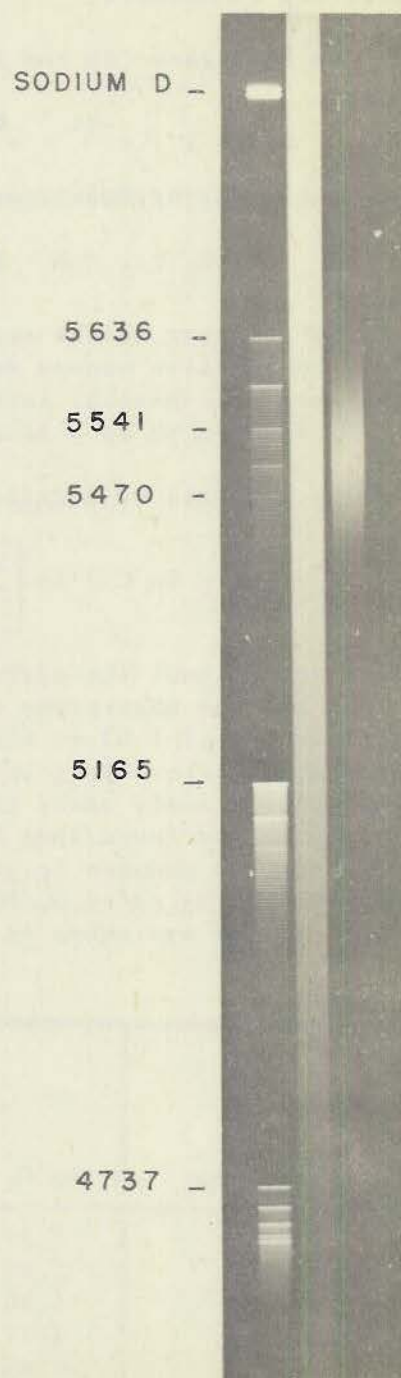


Fig. 3 - Flame Spectra

on the determination of flame temperatures from measurements of rotational line intensities that the band systems are in equilibrium with the flame. This is not true in arc spectra where the molecules may acquire excess rotational energy.

Accuracy of Results

In Equations (3) and (4) it was shown that

$$E = 1 - e^{-\alpha t} = e^{K_2 \left(\frac{1}{T} - \frac{1}{T'} \right)}$$

From which using Equations (9), (11) and (12) one obtains

$$D_2/D_1 = 1 + R - ER. \quad (16)$$

This shows that as the emissivity E approaches unity, the observed spectral intensities become equal and that as E becomes smaller the ratio of the observed spectral intensities approaches $(1 + R)$. Further, the ratio D_2/D_1 is seen to be a linear function of emissivity.

An analysis of Equation (14),

$$\frac{K_2}{T} = \ln C + \ln \left[\frac{1 + R - D_2/D_1}{R D_1} \right], \text{ shows that the ratio of the intensities,}$$

with and without the mirror, is a critical factor, especially when the flame has low absorption (emissivity). For when the ratio D_2/D_1 gets larger, approaching $(1 + R)$ as the limit, the numerator becomes smaller and approaches zero. Since in this region the logarithms change rapidly, it is seen that a small error in D_2/D_1 produces a large error in T . From repeated trials it was found that D_2/D_1 could be determined with an accuracy of ± 2 percent. The changes in true temperatures corresponding to a change of ± 2 percent in the ratio D_2/D_1 have been computed for the first five flames of Table II and are shown in Table III:

Table III

Flame No.	D_2/D_1	Photo (T °K)	Error in T (°C) due to ± 2 percent error in D_2/D_1	Emissivity
1	1.75	1758	± 22	0.17
2	1.53	1498	± 6	0.41
3	1.60	1579	± 10	0.33
4	1.77	1800	± 35	0.14
5	1.88	2069	-140	0.02

Thus, in flame No. 4 the ratio was 1.77 and the error in T was ± 35 degrees C, while in flame No. 3, the ratio was 1.60 and the error was ± 10 degrees C, demonstrating this increase in possible error as the ratio D_2/D_1 is increased. Or, stated another way, the possible error is less when measuring flames of high emissivity because then the absorption loss is greater, and, consequently, the ratio D_2/D_1 is smaller. When the emissivity of the flame is 0.14 or higher, the percentage error in T arising from ± 2 percent error in D_2/D_1 is 2 percent, or less.

This does not imply that temperatures so determined represent true flame temperature within 2 percent; it means only that they should be repeatable within 2 percent. If the flame were uniform in temperature and absorption coefficient throughout, the measurements by this method or the sodium reversal method would give true temperature. In the case of non-uniform flames, which are more usual, results obtained by the present method and the sodium reversal method must of necessity differ, because the integrated optical paths of the radiation emerging from the flame are different in the two cases. "True flame temperature" is a meaningless term in such a case. Whether sodium reversal or the reflection method is more accurate in any case depends upon the particular nature of the inhomogeneities of the flame. In Table II, temperatures determined by the sodium reversal method were about 15 percent higher than those determined by the optical pyrometer, while the latter were within ± 3.5 percent of results with the analogous photoelectric pyrometer. The accuracy with which instrumental settings could be made was about equal in all methods. Hence, the results indicate no superiority of one method over the other but only the variations in indicated temperature which may be expected between the two methods.

Conclusion

The accuracy with which the experimental calibration constant, $\ln C$, of the photocell interference filter system could be determined indicates that the width of the spectral band transmitted by these filters is adequately narrow to permit the use of such a system as a precision pyrometer. If the system were used to measure the temperature of an unknown tungsten lamp, for example, the value of $\ln C = 20,4568 \pm 0.23$ percent in the pyrometer described above would lead to an error of ± 0.32 percent in lamp temperature. This precision is adequate for many flame temperature measurements on rocket motors and other flames where, in any case, the flames are not uniform throughout. Therefore, any optical method depending upon the measurement of radiation traversing a considerable layer of the flame may be in error. Furthermore, the use of photoelectric cells affords a method of following the variations in temperature of rapidly pulsating flames by presentation of photoelectric currents on a cathode ray oscilloscope screen. Pulsating flames were not investigated in the present work, but it is thought that for use in such a problem, a double optical photoelectric system could readily be constructed permitting one photocell to view a dark background through the flame while at the same time the other system views the mirror through the flame.

It is customary to maintain frequent calibration of photoelectric cells against a known source of radiation, such as a ribbon filament tungsten lamp, to insure that slowly changing photoelectric characteristics may not introduce instrumental errors.

* * *