M.H.D. DIAGNOSTICS - GAS TEMPERATURE AND EMITTANCE

by

W. E. HILL

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GENERAL ELECTRIC

General Engineering Laboratory

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M.H.D. DIAGNOSTICS

GAS TEMPERATURE AND EMITTANCE

I. Introduction:

The expected operating conditions coupled with the physical requirements associated with the magnetohydrodynamic generation of electrical power present some unique challenges from the instrumentation viewpoint. Some of the instrumentation techniques developed in the allied field of combustion instrumentation can be expected to make valuable contributions in the area of diagnostics related to the development of a magnetohydrodynamic generator. Gas temperature and emittance are examples of significant parameters that are common to both combustion and anticipated M.H.D. instrumentation and developed measurement techniques are reviewed.

II. Gas Temperature:

The expected temperature range of 4000 to 6000°F is not high by our present standards, however it is above the limit that can be measured by conventional immersion type sensors. Such radiation methods as Line Reversal, Two Color Pyrometry, Self Reversal (Two Path Method) or the Population Method (relative intensities of spectral lines) are possibilities for temperature determination. Let us review the basic theory of these methods and describe developed systems that have made them useful engineering tools.

A. Line Reversal:

Figure 1 shows the Classical Line Reversal Method. (Slide #1 Classical Line Reversal Method).

When light from a background source which emits a continuous spectrum is passed through a sodium colored gas and viewed in a spectroscope, the sodium D line doublet will appear either as bright (emission) lines or as dark (absorption) lines depending upon whether the brightness temperature of the background source is higher or lower than the gas temperature. When the brightness temperature of the background source matches the gas temperature, the D lines are invisible against the continuum and defining gas temperature is only a matter of establishing the temperature of the background source. The Classical Method incorporated an adjustable temperature source and an imaged optical system which limited the temperature range and the optical path length that could be accommodated.

Figure 2 shows a Parallel Beam Line Reversal System. (Slide #2 Parallel Beam Line Reversal System).

The background source and the slit of the spectroscope are each at the principal focus of a lens with a parallel beam between the two lenses. The background source is the positive crater of a D.C. carbon arc which is maintained at a constant brightness temperature of 6200°F. The reversal or matching condition is obtained by varying the radiant energy from the source to the flame by means of a calibrated variable transmission rotating sector disc. Such a system has been operated with optical path lengths in excess of 100 feet.

B. Self Reversal or Two Path Method:

(Slide #3 Planck's and Wien's Blackbody Equations and Wien's Non-Blackbody Equation).

Planck's law expresses the relation of the radiant intensity, J, of a blackbody as a function of wavelength, λ, and absolute temperature, T.

$$J_\lambda = \frac{C_1 \lambda^{-5}}{e^{\frac{C_2}{\lambda T}} - 1}$$ where C_1 and C_2 are constants.

For values of the product λT less than 3000 micron degrees K, Planck's equation can be replaced by Wien's equation which gives the spectral energy distribution with an error of less than 1%.

$$J_\lambda = C_1 \lambda^{-5} \quad e^{-\frac{C_2}{\lambda T}}$$

Wien's equation can be used to calculate the temperature of a non-blackbody if the spectral emissivity is known.

$$J_\lambda = E_\lambda J_{\lambda B}$$

Measured values of J_λ and E_λ may then be used to calculate temperature. One method of determining the emittance of a flame is to determine the ratio of the flame intensity when viewed against a mirror (intensity plus non-absorbed reflected intensity) to the flame intensity viewed against a non-reflecting background.

At an isolated wavelength, this may be expressed as

$$E_\lambda = \frac{1}{\mathcal{R}}\left(1 + \mathcal{R} - \frac{J_M}{J_F}\right)$$

where E_λ = emittance @ wavelength λ

$\mathcal{R}$ = reflectance of mirror

J_M = intensity viewed against mirror

J_F = intensity viewed against non-reflecting background

Figure 3 shows the Classical Two Path Method. (Slide #4 Classical Two Path Method and Equation).

The optical system of the Classical Two Path Method consists of two nearly coincident paths through the flame. One views the flame against a mirror and the other against a black surface. This system requires no source of known temperature but requires two detectors and offers considerable experimental difficulty in effecting and maintaining critical optical alignment.

C. Two Color Pyrometry:

The Two Color Pyrometer determines temperature from the ratio of the intensities at two wavelengths. This method is applicable if the emissivities at the isolated wavelengths are equal.

D. Population Method:

Relative Intensity of Two Spectral Lines

The intensity of a spectral line is a function of the population of the energy levels which give rise to the line. If the excitation is thermal, then according to Boltzmann Statistics, the intensities of two spectral lines from the same element are given by:

(Slide #7 Population Method Equations)

$$I_1 = N_o\, g_1\, e^{-\frac{E_1}{KT}} A_1\, hf_1$$

$$I_2 = N_o\, g_2\, e^{-\frac{E_2}{KT}} A_2\, hf_2$$

Where I = intensity

N_o = population of ground state

g = statistical weight

E = excitation energy

K = Boltzmann constant

T = absolute temperature

A = transition probability

h = Planck's constant

f = frequency of line

and dividing gives:

$$\frac{I_1}{I_2} = \frac{A_1\, g_1\, f_1}{A_2\, g_2\, f_2}\; e^{\frac{E_2 - E_1}{KT}}$$

$\frac{I_1}{I_2}$ is determined by spectrographic means. A_1 and g_1 may be calculated by quantum mechanics or preferably determined experimentally. For selected lines the intensity ratio may be plotted against temperature as a working curve.

III. Gas Emittance:

The gas emittance is significant from the design and material viewpoints since, for a given operating temperature, the radiant heat transfer to the walls is directly proportional to gas emittance. A similar situation is encountered in gas turbine type combustion systems.

Kirchhoff's law is usually the basis for determining the emittance of gases and flames. This law states that for a thermal radiator of any kind and for any wavelength the emissivity is equal to the absorptivity. Therefore a measurement of the absorption at a chosen wavelength by the gas of radiation passing through it gives a measure of absorptance and this value is equal to the emittance at that wavelength. Experimenters in the field have used various methods to determine the spectral emittance values of gases by measuring the absorptance from a suitable source through the gas. The Schmidt Method has been used by such recognized authorities as: Silverman, Saunders, Hornbeck, and Tourin (see references). The essentials of this method are shown in Figure 4. (Slide #8 Schmidt Emittance Method).

A source of continuous radiation (such as a silicon carbide globar) is placed on one side of the flame and a spectrometer on the opposite side. The spectrometer is capable of isolating a very narrow wavelength band that can for all practical purposes be considered monochromatic. At a chosen wavelength it is then possible to obtain the following indications:

1. The intensity of the flame alone (blank the globar).
2. The intensity of the globar source alone (turn off flame).
3. The combined intensity from the flame and globar.

From these indications the monochromatic emittance may be calculated.

If a flame could be held stable for a long enough period of time, it would be possible to determine the spectral emittance at closely spaced wavelength intervals and arrive at total emittance which is the integral of spectral emissivity over the wavelength interval of zero to infinity.

A more direct approach to determining total emittance is:

1. Measure the total radiated energy by means of a radiometer.
2. Measure the gas temperature.
3. Calculate the absorptance which is equal to the emittance.

This approach has been used to determine the radiant heat transfer on such related problems as:

1. A 10 inch diameter laboratory combustor to facilitate predicting radiant heat transfer from larger combustors.
2. Jet engine afterburner operating on high energy fuels.
3. Jet engine main combustor operating on hydrocarbon fuel.

(Slide #9 - Emittance Results)

Some of the results of these tests are summarized below.

10" Diameter Combustion Chamber

Type Fuel	Flame Temperature °F	Emittance
Bunker "C"	2500	0.48
Bunker "C"	2375	0.47
Diesel	2400	0.25

Main Combustor - Aircraft Gas Turbine

Type Fuel	Flame Temperature °F	Emittance
JP-6	2510	0.13
JP-6	2790	0.17
JP-6	2870	0.25

The relatively high emittance values obtained on the Bunker "C" flame can be partly attributed to the fact that the mixture was purposely adjusted to fuel rich conditions to obtain the highest possible emittance which would present the most severe design problem. Since associated with fuel rich conditions is a lower gas temperature, these conditions are not expected in proposed M.H.D. channels.

The major difference between the expected flames and those encountered in other combustion systems arises from the addition of seed material. Since the alkali metals have the lowest ionization potential, they are the potential seed materials. Previous observations of sodium seeded flames such as the exhaust of rocket engines have not revealed any appreciable continuous radiation. Spectrograms obtained in the laboratory from flames seeded heavily with potassium carbonate show nine spectral lines from the excited states of potassium and three lines from the excited states of singly ionized potassium. These spectral lines were superimposed on a rather weak continuous background. This is evidence that the continuous radiation resulting from single ionization of only one kind of atom is rather insignificant from the radiant heat transfer viewpoint.

IV. Bibliography

1. Flames, Their Structure Radiation and Temperature
   Gaydon and Wolfhard - Chapman & Hall Ltd. 1953
2. Physical Measurements in Gas Dynamics and Combustion
   Vol. IX High Speed Aerodynamics and Jet Propulsion -
   Princeton Univ. Press 1954

3. Combustion, Flames and Explosions of Gases - Lewis & Van Elbe - Academic Press Inc., New York

4. Experimental Temperature Measurement in Flames & Hot Gases - Volume II of Temperature, It's Measurement and Control in Science and Industry - Reinhold Pub. Corp. 1955 - H.P. Broida

5. Spectroscopy and Combustion Theory - A.G. Gaydon 2nd Edition - Chapman & Hall

6. Optical Methods for the Determination of Flame Temperatures - S.S. Penner - American Journal of Physics, Vol. 17, 1946B

7. A Method for Measurement of Gas Temperatures by Means of Infrared Radiation - Air Force Technical Report #6004, May 1950 - Grossman, Tandler and Tourin

8. Emission and Absorption Studies of Jet Engine Hydrocarbon Combustion Products - WADC Technical Report 57-516 Geo. A. Hornbeck and Lief O. Olsen

9. Effects of Temperature Gradients of Self-Absorption of Infrared Radiation in Hot Gases - AFCRC-TN-58-462 R.H. Tourin

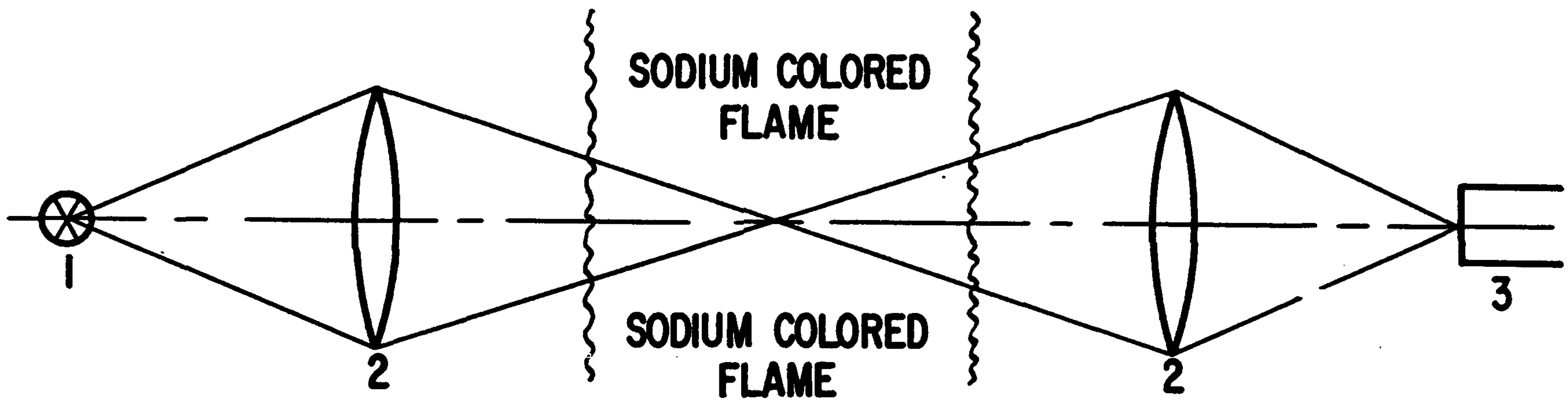
10. Some Studies of Radiating Flames in a Small Gas Turbine Type Combustion Chamber - D.J. Weeks, O.A. Saunders, British Journal Fuels.

11. Fundamental Studies High Temperature Instrumentation W.E. Hill & A.I. Dahl - General Electric Co. Report No. 57GL331

12. Temperature Measurements - High Temperature Physics A.I. Dahl & W.E. Hill - General Electric Co. Report No. 58GL6

13. Applications of Two Color Pyrometry - W.E. Hill General Electric Co. Report No. 58GL257

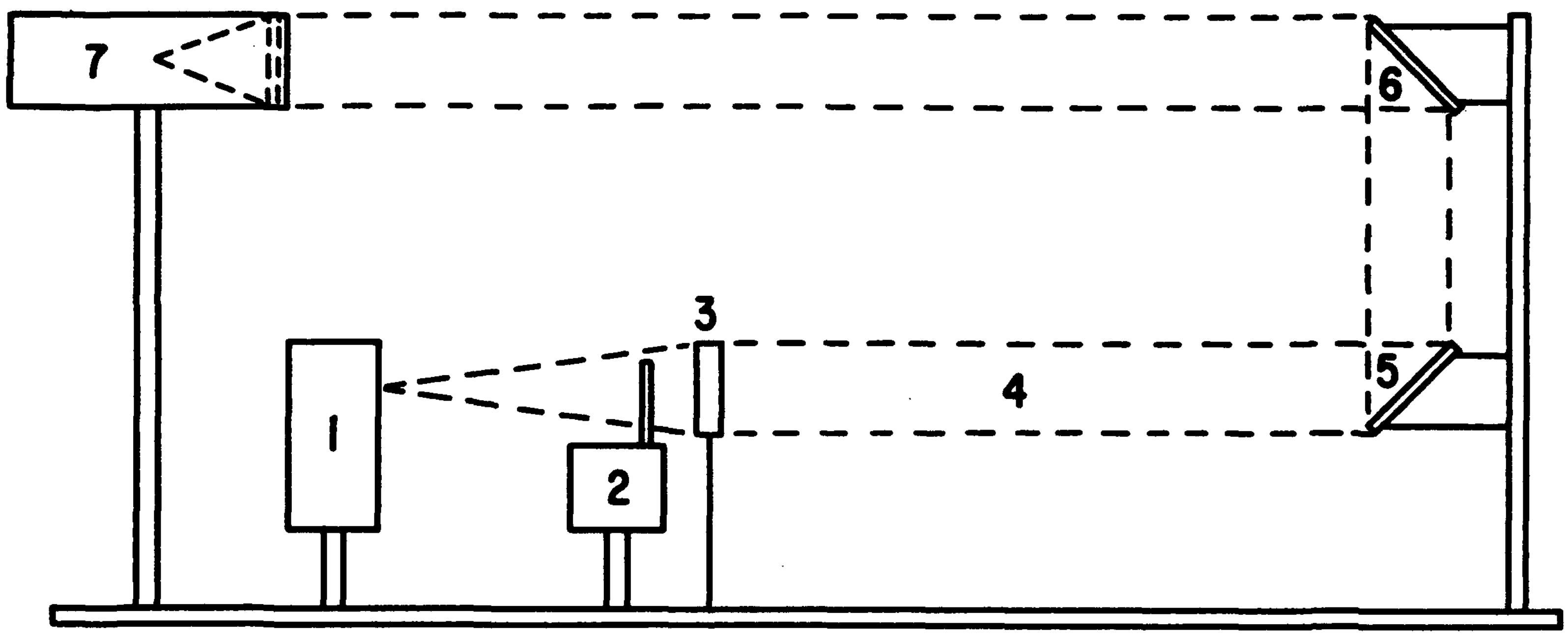
CLASSICAL LINE REVERSAL METHOD



1. REFERENCE SOURCE
2. LENS
3. SPECTROMETER

Figure 1

PARALLEL BEAM SODIUM D-LINE REVERSAL SYSTEM



1 - SOURCE
2 - ROTATING SECTOR DISC
3 - LENS
4 - FLAME
5 - MIRROR
6 - MIRROR
7 - LENS AND SPECTROSCOPE ASSEMB[illegible]

Figure 2

TYPICAL TWO PATH SYSTEM

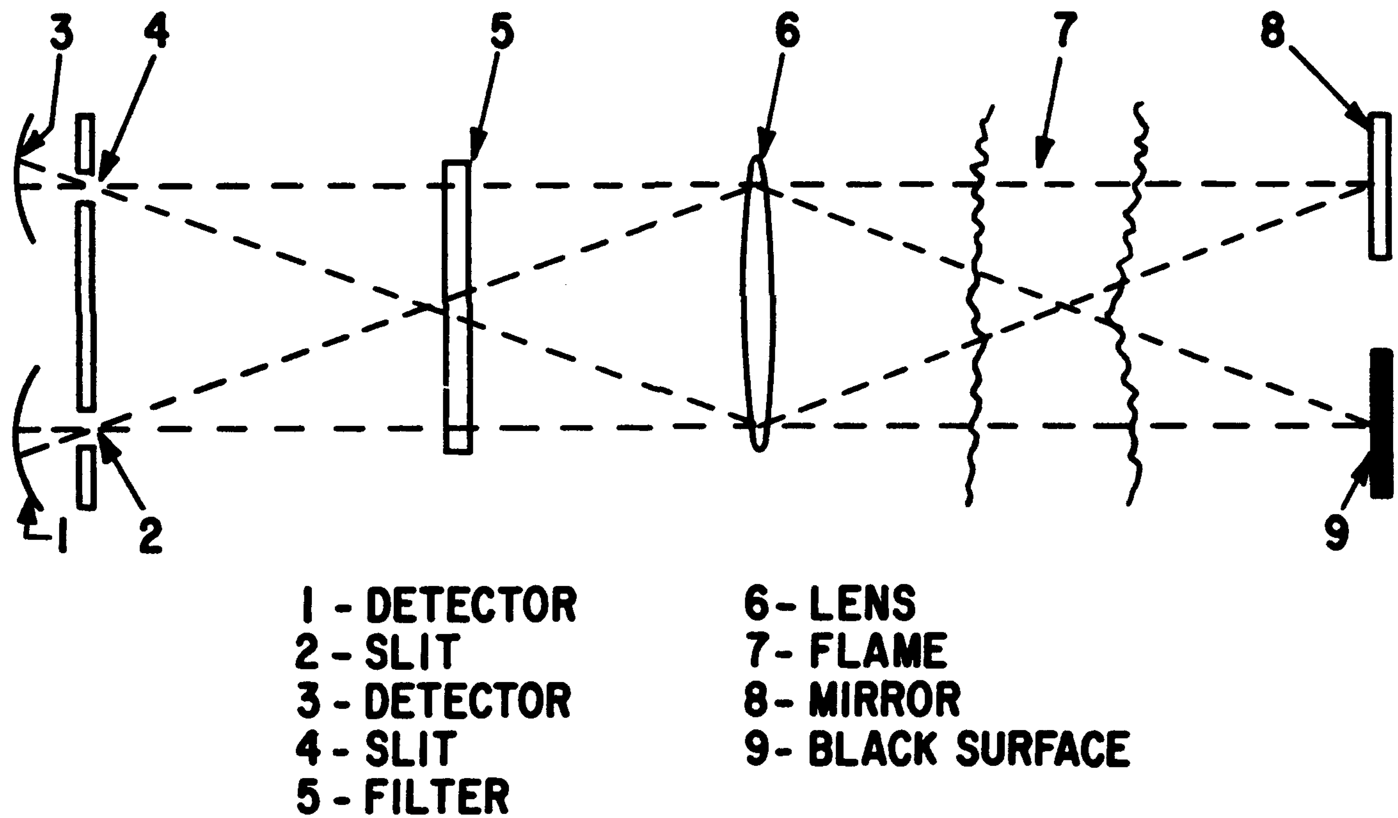
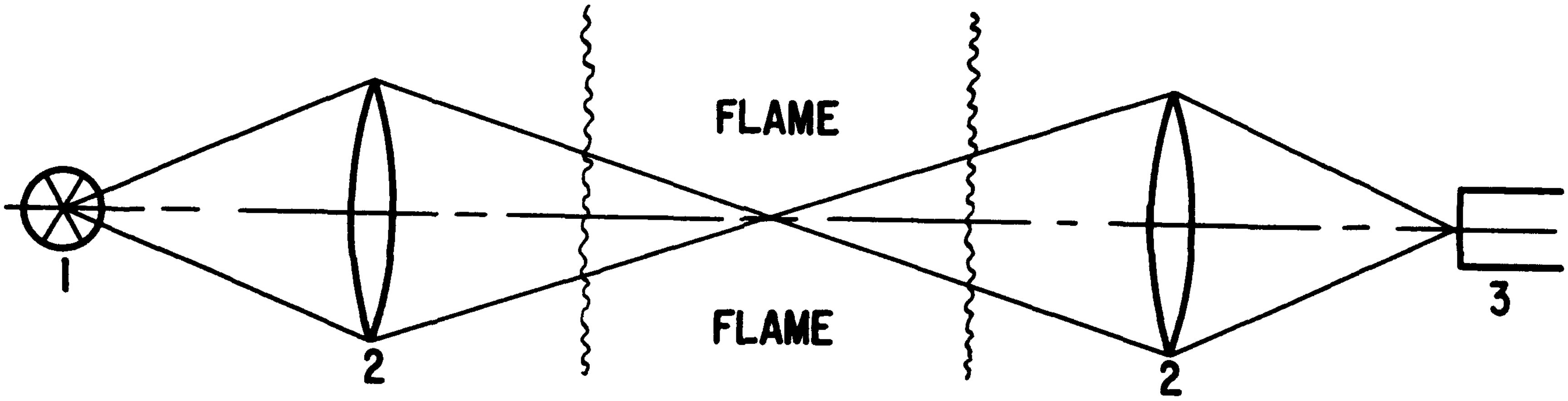


Figure 3

SCHMIDT FLAME EMITTANCE METHOD



1. GLOBAR SOURCE
2. LENS
3. SPECTROMETER

Figure 4

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ABSTRACT

Gas temperature and emittance are examples of significant parameters that are common to both combustion and anticipated M.H.D. instrumentation.

Such developed radiation techniques for temperature measurement as Line Reversal, Two Path, Two Color and Population method are reviewed. The Schmidt method

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~~CONCLUSIONS~~

Abstract continued:

for determining gas emittance is discussed and specific results are included.

(This was a paper presented at AIEE Conference on Engineering Aspects of Magnetohydrodynamics at the University of Pennsylvania on February 18-19, 1960.)

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