DIAGNOSTIC INSTRUMENTATION AND ANALYSIS LABORATORY

POTASSIUM EMISSION ABSORPTION SYSTEM

TOPICAL REPORT

Leslie E. Bauman

Prepared for the United States
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Topical Report

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Leslie E. Bauman
Senior Research Scientist
and
Professor of Physics and Chemistry
Mississippi State University

Diagnostic Instrumentation and Analysis Laboratory
Mississippi State University
Mississippi State, Mississippi 39762

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NOMENCLATURE

Symbol	Name	Unit(s)
<i>Roman Alphabet</i>		
A	spectral line integrated absorptivity	$s^{-1}m^{-1}$
B	Planck blackbody function	
b	potassium density profile constant	dimensionless
C_2	Planck second constant, 1.43388×10^7 nm K	nm K
c	speed of light in a vacuum, 2.9979×10^8	$m \cdot s^{-1}$
e	electron charge, 1.43388×10^7 C	C
E	particle extinction-to-absorption ratio	dimensionless
E_i	ionization energy	eV
g_i	atomic partition function for level i	dimensionless
h	Planck's constant, 6.624×10^{-34} J·s	J·s
I	Light intensity, subscripts for lamp, L ; flame, F ; and lamp transmitted through a flame, $L+F$	arbitrary
f_i	emission line strength for atomic line i	dimensionless
J	Light intensity in-scattered by particles	arbitrary
k	Boltzmann's constant, 1.3805×10^{-23} J/K	J/K
L	optical path length	m
m	mass, subscripts for foreign atom, f ; and potassium atom, K	kg
m_e	electron mass, 9.108×10^{-31}	kg
N	thermal boundary layer profile exponent	dimensionless
N_j	mole fraction of specie j	dimensionless
n	number density, with subscripts for electron, e , neutral potassium, K , ion, i , and at standard temperature and pressure, s	number m^{-3}
P	Pressure, subscript for standard, s	atm
Q_d	electron-molecule collision transfer cross section	m^2
t	atomic excited state lifetime	s
τ	transmittivity, subscripts for detector- and lamp-side windows	dimensionless
T	temperature, subscripts for core flow, c ; lamp, ℓ ; gas, g ; standard, s ; wall, w ; and path position, x	K
x	optical path position	m
v	velocity	m/s
z	particle-to-gas Planck blackbody intensity ratio	dimensionless
<i>Greek Alphabet</i>		
α_λ	atomic resonance line absorption coefficient	per meter m^{-1}
δ	thermal boundary layer width	m

η	particle absorption coefficient	m^{-1}
λ	wavelength or subscript denoting wavelength dependence	nm
μ	mobility, with subscripts for electron, e , and ion, i	$\text{C}\cdot\text{s}\cdot\text{kg}^{-1}$
π	pi, 3.14159	
ν	collision frequency	s^{-1}
ν_t	total collision frequency	s^{-1}
σ	electrical conductivity	mhos/m
σ_i^2	collision cross section for line i	m^{-2}
τ	optical depth	dimensionless
Φ	gas-to-lamp Planck blackbody intensity ratio	dimensionless
Ω	albedo, with subscript p for particle cloud albedo	dimensionless

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Over the years several Mississippi State University students contributed to the development of the Sodium Line Reversal System, the pre-cursor instrument, and later to the Potassium Emission Absorption System through their masters thesis research.*

*Zhiliang Chen, 1990, "Far Wing Potassium Line Profiles in Combustion-Fired MHD Flows."

Xiangyang Ma, 1988, "Effects of Light Scattering by Particles on Gas Temperature Measurement using Line Reversal Method," co-directed with Russel K. Lengel of DIAL.

Hsueh-Tien Hung, 1988, "Lineshape Fitting for Gas Temperature and Potassium Number Density Measurements in a Particle-Laden Coal-Fired Magnetohydrodynamic Gas Flow."

Charles R. Campbell, 1983, "The Development of an Automatic Microprocessor-Based Sodium D-Line Reversal Instrument for Temperature Measurement on Simulated Coal-Fired Magnetohydrodynamic Gas Flows."

Adel Hasan Y. Hassounah, 1982, "Theoretical Application of Sodium-Line Reversal Technique for Temperature Measurements of Particle-Laden Gaseous Flame," co-directed with Hugh L. Coleman of Mechanical Engineering and DIAL.

ABSTRACT

The Potassium Emission Absorption System is one of the advanced optical diagnostics developed at Mississippi State University to provide support for the demonstration of prototype-scale coal-fired combustion magnetohydrodynamic (MHD) electrical power generation. Intended for application in the upstream of an MHD flow, the system directly measures gas temperature and neutral potassium atom number density through spectroscopic emission absorption techniques. From these measurements the electron density can be inferred from a statistical equilibrium calculation and the electron conductivity in the MHD channel found by use of an electron mobility model. The instrument has been utilized for field test measurements on MHD facilities for almost a decade and has been proven to provide useful measurements as designed for MHD nozzle, channel, and diffuser test sections. The theory of the measurements, a system description, its capabilities, and field test measurement results are reported here. During the development and application of the instrument several technical issues arose which when addressed advanced the state of the art in emission absorption measurement. Studies of these issues are also reported here and include: two-wavelength measurements for particle-laden flows, potassium D-line far wing absorption coefficient, bias in emission absorption measurements arising from dirty windows and misalignments, non-coincident multiwavelength emission absorption sampling errors, and lineshape fitting for boundary layer flow profile information. Although developed for MHD application, the instrument could be applied to any high temperature flow with a resonance line in the 300 to 800 nm range, for instance other types of flames, rocket plumes or low temperature plasmas.

PURPOSE

The PEAS instrument was developed for use as an nonintrusive, upstream MHD diagnostic with direct measurement of temperature and potassium atom density and indirect measurement of electron density and conductivity. The instrument was intended to provide experimental temperature measurements to support studies of heat transfer and combustor performance. The measurements of potassium density should assist studies of seed injection or seed regeneration. Measurement of electron density and conductivity are crucial for analysis of channel performance. The system was designed to provide time-resolved measurements in order to provide not only average values but also probability distributions for information on fluctuations in experimental parameters.

PERFORMANCE REQUIREMENTS

The Potassium Emission Absorption System was intended to provide as accurate as possible measurements of gas temperature and seed atom density in the upstream components of magnetohydrodynamic (MHD) facilities with a working fluid provided by seeded coal-fired combustion products. Temperature measurements using a modified line reversal technique can provide on a stable benchtop flame an accuracy traceable to NIST standards of better than 10 K with a similar precision. On a coal-fired MHD flow, inherent flow fluctuations, emission absorption and scattering of the ash/slag particle cloud, and the presence of cool boundary layers complicate the measurements. A better than 2% accuracy was desired for temperature measurements using the instrument. For most of the flows studied this translates to better than 50 K. The possible accuracy of the seed atom density measurement is limited by the knowledge of the emission line strength which is only known to within $\pm 10\%$. It was simply hoped that the precision of the density measurements would be good enough to support studies of seed atom density versus time and facility conditions.

INTRODUCTION

The purpose of this report is to draw together in a final report the description, capabilities and scientific background for the diagnostic instrument known as the Potassium Emission Absorption System (PEAS). And in the process, provide the reader with the knowledge as to how the instrument may be used to support the development of coal-fired MHD energy generation.

The Potassium Emission Absorption System (PEAS) is a multiwavelength emission absorption instrument developed for measurement of gas temperature and seed atom density measurements on large-scale, combustion-fired magnetohydrodynamic (MHD) flows. With the assumptions of 1) ionizational equilibrium and 2) a lack of other important sinks or sources of electrons, the instrumental results can also be used to calculate the electron density and combined with electron mobility model infer the electron conductivity. The instrument, although it could be used on any well characterized absorption line present in the flow, has been named for potassium, widely used for *seeding* high temperature flows with electrons because of its low cost and relatively low ionization energy.

By its nature, the instrument is based upon line-of-sight intensity measurements and so provides bulk results; however, measurements are made on the wings of the atomic absorption line to avoid cool boundary layer effects and yield measurements approximating that of the hot core of a flow. Measurements of a transmitted reference white light and the flame emission are made at two wavelengths to eliminate bias caused by particle emission/absorption or out-scattering, making the instrument applicable to particle-laden combustion systems, especially coal-fired systems. The two-wavelength method also significantly reduces problems with particle in-scattering, optical window fouling, and misalignments, problems that can be especially severe on large-scale, coal-fired combustion systems. With relatively simple calculations and with a tungsten lamp as the reference white light source, the instrument is robust enough for use as a monitor/process control instrument.

The Potassium Emission Absorption System has been a field ready instrument for almost a decade but was continually refined with experience gained from field testing. Example field test results are included through the Technical Issues and Performance Evaluation sections of this report. The instrument has demonstrated its capability to provide valuable experimental measurements for prototype MHD testing.

TECHNICAL APPROACH

Line reversal is a well known and much used technique for measuring very accurate flame temperatures.^{1,2} The spectroscopic technique falls in the general category of emission absorption. Typically used with a white light source at an atomic resonance line in the visible spectrum, emission absorption techniques provide easily implemented, accurate measurements of not only temperature but also the species concentration of the atomic emitter. Applied in its most general form and referred to as a modified line reversal method,³ the reference lamp temperature is held constant and the gas or flame temperature is found by recording the intensity of the pre-flame or reference lamp, the lamp transmitted across the flame, and the flame emission. The intensities are line-of-sight path integrals and hence the measured gas temperature is a spatial average. Even with the development of more sophisticated laser-based techniques which can provide spatial resolution, line reversal is still routinely used for verification of performance of other techniques because of its high accuracy.⁴

Emission absorption measurements may be either spectrally resolved or integrated over a resonance line. For flows with cool boundary layer, spectrally resolved measurements on the wings of an atomic line will give measurements that approach the values for the hot core of a boundary layer flow -- removing errors due to the cooler boundary layers. More complicated multiwavelength measurements can remove errors due to particle emission, absorption and outscattering and thereby make the techniques applicable to particle-laden flows such as coal combustion flows or solid rocket motors.

Opposed optical access is required, but with fiber optic light transmission and micro-lenses the required size of the optical port can be considerably reduced. With a white light source such as a tungsten lamp and non-cooled detector(s), the optical components are robust and long lived. In addition, the analysis is relatively simple and can be performed real-time; the combination of robustness and simple analysis makes the technique suitable for monitoring or controlling a process stream.

A Brief Theory of Line Reversal

Classical Line Reversal. Line reversal is based upon Kirchhoff's law, i.e., in local thermodynamic equilibrium the ratio of the emissivity of an object to its absorptivity is equal to the emissivity of a blackbody and so depends only on wavelength and the object temperature. For a gas at a temperature T_g a gas element of thickness dx and area dA will emit a flux into a unit solid angle $d\Omega$ and unit wavelength interval $d\lambda$ of $B_\lambda(T_g)dA\alpha_\lambda dx d\lambda d\Omega$, where α_λ is the gas absorption coefficient. A fraction of light of incident intensity I from the lamp at an effective blackbody temperature of T_ℓ falling on the gas will be absorbed according to $I_\lambda(T_\ell)A\alpha_\lambda dx d\lambda d\Omega$, so that the change in a light beam intensity across the gas element is

$dI_\lambda = (B_\lambda(T_g) - I_\lambda(T_\ell))\alpha_\lambda dx d\lambda$. Adjusting the lamp so that the change in intensity across the path is zero then fixes the effective blackbody temperature of the lamp to be the same as the gas and the flame temperature has been determined from knowledge of the reference lamp. This expression is valid for spectrally resolved or integrated intensities.

For an optical path length L across a flame, the transmitted lamp intensity is a path integral as

$$I_\lambda(L) = \int_0^L \alpha_\lambda B_\lambda(T_g) e^{-\tau_x} dx + e^{-\tau_L} I_\lambda(T_\ell), \quad (1)$$

where $\tau_x = \int_0^x \alpha_\lambda dx'$.

With constant properties across the path length through the flame, the integral is easily solved for the flame emission and the transmitted lamp intensities in terms of the lamp-only intensity as

$$I_{L+F} = B_\lambda(T_g)(1 - e^{-\alpha_\lambda L}) + I_\lambda(T_\ell)e^{-\alpha_\lambda L},$$

$$I_F = B_\lambda(T_g)(1 - e^{-\alpha_\lambda L}), \text{ and} \quad (2)$$

$$I_L = I_\lambda(T_\ell).$$

Here $\tau_L = \alpha_\lambda L$ is the total optical depth across the flow. At the reversal point the transmitted lamp intensity matches the lamp intensity without the flame and therefore the effective lamp temperature matches the gas temperature. The reversal point is illustrated in Fig. 1.

$$I_{L+F} = B_\lambda(T_g)(1 - e^{-\alpha_\lambda L}) + I_\lambda(T_\ell)e^{-\alpha_\lambda L} = I_\lambda(T_\ell) = I_L$$

$$\therefore B_\lambda(T_g) = I_\lambda(T_\ell) \text{ and } T_g = T_\ell. \quad (3)$$

Figure 1. An illustration of the reversal point, i.e., where the transmitted lamp signal is the same whether or not the flame is present. For this illustration the optical depth is 1 and 37% of the reference lamp is absorbed but balanced by an equal flame emission.

Modified Line Reversal Measurements Fixing the lamp temperature and calculating the flame temperature from a series of intensity measurements is far easier to implement for automatic measurements than classical line reversal. The ratio between the Planck blackbody emissions for the gas and lamp can be found as

$$\Phi_{\lambda} = \frac{B_{\lambda}(T_g)}{I_{\lambda}(T_{\ell})} = \frac{I_F}{I_L - I_{L+F} + I_F} \quad (4)$$

Then using the Wien's law form of the blackbody radiation law

$$B_{\lambda}(T) = C_1 \lambda^{-5} e^{-C_2/kT}, \quad (5)$$

the gas temperature is related to the effective lamp temperature as

$$\frac{1}{T_g} = \frac{1}{T_{\ell}} - \frac{\lambda}{C_2} \ln(\Phi_{\lambda}). \quad (6)$$

The results are independent of the absorption coefficient, so the intensity measurements may either be spectrally resolved (monochromatic) or integrated. If spectrally resolved, this measurement of temperature is referred to as a single wavelength line reversal measurement.

Two-Wavelength Measurements of Temperature. Problems arise in applying emission absorption techniques to coal-fired combustion flows because of emission/absorption and scattering of the ash/slag particles. A two-wavelength method known as the Schmidt method had been previously used to determine gas temperatures in particle laden flows; however, this technique depended upon measurements at one of the wavelengths sufficiently off the resonance line to assume the measurement reflected only particle properties.⁵ The potassium D-lines are so broad in MHD flow as to practically prohibit signal collection at an off-line wavelength. Figure 2 on the next page shows a scan of the visible emissions from the CFFF diffuser illustrating the extreme breadth of the potassium D-line in an MHD flow. Here because of the cool boundary layer surrounding the hot flow, a dip is seen at the D-line centers at 766.5 and 769.9 nm.

A two wavelength technique minimizing the errors caused by the particles can be made with both wavelength positions on the resonance line but at different optical depths.⁶ The calculations are based upon the assumption that the particle effects are broad band relative to the width of the resonance line radiation.

Consider a parallel, axisymmetric source light passing through an emitting, absorbing, and scattering medium that is a hot gas at a temperature T_g containing particles at temperature T_p . The assumption is made of local thermodynamic equilibrium such that the transfer equation assuming axial symmetry can be written as⁷

$$\mu \frac{\partial I_{\lambda}(x, \mu)}{\partial x} = -(\alpha_{\lambda} + \eta_{\lambda} + \sigma_{\lambda}) I_{\lambda}(x, \mu) + \alpha_{\lambda} B_{\lambda}(T_g) + \eta_{\lambda} B_{\lambda}(T_p) + j_{\lambda} \quad (7)$$

where $I_{\lambda}(x, \mu)$ is the intensity at a position x and in a direction given by the direction cosine μ , α_{λ} is the absorption coefficient of the gas, η_{λ} is the absorption coefficient of the particles, σ_{λ} is the scattering coefficient of the particles, and the Planck spectral blackbody function at the temperature T is denoted by $B_{\lambda}(T)$. The term j_{λ} represents the specific in-scattering contribution of the particles as

$$j_{\lambda} = \frac{\sigma_{\lambda}}{2\pi} \int_{-1}^1 P(\mu, \mu') I_{\lambda}(x, \mu') d\mu' \quad (8)$$

where $P(\mu, \mu')$ is the probability of light scattering from direction μ' into direction μ and σ_λ is the wavelength specific scattering cross section. Assuming the in-scatter term to be negligible and setting $\mu = 1$ gives Thomas' model.³⁰

Figure 2. Emission spectrum from the CFFF diffuser.

For the case of constant properties, a simple expression results from the integration over a path length of L :

$$I_{L+F} = \frac{\alpha_\lambda + z\eta}{\alpha_\lambda + \eta E} B_\lambda(T_g) (1 - e^{-(\alpha_\lambda + z\eta)L}) + I_\lambda(T_\ell) e^{-(\alpha_\lambda + z\eta)L} + J_\lambda$$

$$I_F = \frac{\alpha_\lambda + z\eta}{\alpha_\lambda + \eta E} B_\lambda(T_g) (1 - e^{-(\alpha_\lambda + z\eta)L}) + J_\lambda \quad (9)$$

$$I_L = I_\lambda(T_\ell)$$

where $I_\lambda(T_L)$ is the incident lamp intensity at $x = 0$ and J_λ is the in-scatter term. Here the extinction-to-absorption ratio for the particles has been introduced as $E = (\eta + \sigma)/\eta$ and the explicit dependence on the particle temperature has been removed by using the ratio $z = B_\lambda(T_p)/B_\lambda(T_g)$. The wavelength subscripts on the particle parameters have been omitted here since they vary relatively slowly compared to the atomic absorption coefficient. More typically used for scattering problems is the albedo; the particle cloud albedo, Ω_p , is found as $\Omega_p = (E - 1)/E = \sigma/(\sigma + \eta)$ and the total albedo as $\Omega = \sigma/(\alpha_\lambda + \eta + \sigma)$. The total optical depth, τ_L , is found as

$$\tau_{\lambda} = (\alpha_{\lambda} + \eta E)L = \ell n \left(\frac{I_L}{I_{L+F} - I_F} \right) \quad (10)$$

includes the particle extinction through absorption and out-scatter. The term J_{λ} represents the in-scattered radiation exiting the out-going boundary of the medium and if the medium is enclosed by a hot wall at temperature T_w , radiation from the wall will enter into this term.

The calculation of gas temperature can be found as in Eq. 5 from measurements of the signals of lamp plus flame, flame only, and preflame lamp at two wavelengths as

$$\Phi_{2\lambda} = \frac{\tau_{\lambda_1} \Phi_{\lambda_1} - \tau_{\lambda_2} \Phi_{\lambda_2}}{\tau_{\lambda_1} - \tau_{\lambda_2}} \approx \frac{B_{\lambda_1}(T_g)}{I_{\lambda_1}(T_{\ell})} \quad (11)$$

where the Φ_{λ} 's are found as in Eq. 4. This equation will be referred to throughout this document as the two wavelength emission absorption measurement of gas temperature and it eliminates the errors due to emission/absorption and out-scatter of the particle cloud.

The two wavelength calculation assumes that the wavelengths are sufficiently close so that

$$\Phi_{\lambda_1} = \frac{B_{\lambda_1}(T_g)}{I_{\lambda_1}} \approx \frac{B_{\lambda_2}(T_g)}{I_{\lambda_2}} = \Phi_{\lambda_2} \quad (12)$$

If the wavelengths are widely separated, then this may not be the case as the reference lamp effective blackbody temperature is a function of wavelength through the emissivity of tungsten and transmission factors of the optical system. One can correct the calculation as

$$\frac{B_{\lambda_1}(T_g)}{I_{\lambda_1}(T_{\ell})} = \frac{\tau_{\lambda_1} \Phi_{\lambda_1} - \tau_{\lambda_2} \Phi_{\lambda_2} \exp \left(C_2 \left(\frac{1}{\lambda_2 T_{\ell}(\lambda_2)} - \frac{1}{\lambda_1 T_{\ell}(\lambda_1)} \right) \right)}{\tau_{\lambda_1} - \tau_{\lambda_2}}, \quad (13)$$

where $T_{\ell}(\lambda)$ refers to the effective lamp temperature at the wavelength λ .

The two-wavelength technique cannot account for the light in-scattered by the particles. The temperature measurement error from in-scatter can be expressed as

$$\Delta T_g \approx \frac{\lambda T_g^2}{C_2} \ln \left(1 + \frac{1}{\Phi_{2\lambda}} \frac{(\alpha_{\lambda_1} + \eta) J_{\lambda_1} - (\alpha_{\lambda_1} + \eta) J_{\lambda_1}}{\alpha_{\lambda_1} - \alpha_{\lambda_2}} \right). \quad (14)$$

This is considerably reduced from the error introduced into a one wavelength measurement which is

$$\Delta T_g \approx \frac{\lambda T_g^2}{C_2} \ln \left(\frac{\alpha_\lambda + z\eta}{\alpha_\lambda + \eta E} + \frac{J_\lambda}{\Phi_\lambda} \right). \quad (15)$$

Seed Atom Density Measurements

With these individual intensity measurements it is also possible to measure the emitter density given knowledge of the absorption line strength and shape. For a total optical path length across the flow of L , the atomic absorption coefficient is found as

$$\alpha_\lambda = \frac{\tau_\lambda}{L} = \frac{1}{L} \ln \left(\frac{I_L}{I_{L+F} - I_F} \right). \quad (16)$$

Classical Theory of Absorption Lineshapes. The total resonance line absorption coefficient is directly proportional to the atomic density as⁸

$$\int \alpha_\lambda d\lambda = \frac{\lambda_0^2}{8\pi} \frac{g_2}{g_1} \frac{n}{t} \left(1 - \frac{g_1}{g_2} \frac{n'}{n} \right) \approx \frac{\lambda_0^2}{8\pi} \frac{g_2}{g_1} \frac{n}{t} = \frac{\pi e^2}{m_e c} n f, \quad (17)$$

where g_i is the statistical weight of ground or excited state respectively, n is the density of ground state atoms and n' is the density of excited state atoms, t is the excited state lifetime, and λ_0 is the line center wavelength. For temperatures of interest in MHD flows, a negligible fraction of the potassium atoms will be excited and the approximate form can be used, which written in terms of the f -value or oscillator strength is shown as the right hand side of Eq. (17).

Line broadening mechanisms determine the shape of the absorption line: natural broadening due to the finite lifetime of the excited state, Doppler broadening due to the motions of the atoms and Lorentz broadening due to collisions with foreign gases. The width arising from the natural linewidth can be ignored at MHD flow conditions. The combination of Doppler and Lorentz broadening results in a Voigt profile

$$\alpha_{\lambda,V} = \alpha_0 \frac{a'}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2}}{a'^2 + (w-y)^2} dy \quad (18a)$$

where

$$\alpha_0 = \frac{2}{\Delta v_D} \sqrt{\frac{\ln 2}{\pi}} \frac{\pi e^2}{m_e c} n f, \quad (18b)$$

$$\Delta v_D = \frac{2\sqrt{2\ln 2}}{\lambda_0} \sqrt{\frac{kT}{m}}, \quad (18c)$$

$$\Delta v_L = \frac{2}{\pi} \sigma_L^2 n_f \sqrt{2\pi k t \left(\frac{1}{m} + \frac{1}{m_f} \right)}, \quad (18d)$$

$$w = \frac{2c}{\Delta v_D} \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right) \sqrt{\ln 2}, \quad (18e)$$

$$a' = \frac{\Delta v_L}{\Delta v_D} \sqrt{\ln 2}, \quad (18f)$$

and

$$y = \frac{2\delta}{\Delta v_D} \sqrt{\ln 2}. \quad (18g)$$

Here the subscript f refers to the foreign gas and the shift in line center by collisional broadening is small enough to be ignored. The integral can be evaluated numerically or found as a polynomial approximation.⁹ The potassium doublet is overlapped for MHD flow conditions and the total absorption coefficient must be found as a sum of the absorption coefficients for the individual lines:

$$\alpha_\lambda = \sum_{i=1}^2 \alpha_\lambda(i). \quad (19)$$

In the near wings the Voigt profile is essentially Lorentzian and can be approximated as¹⁰

$$\alpha_{\lambda,L} = \frac{n_K a_2 a_\lambda}{\sqrt{T}} \quad (20a)$$

where a_2 and a_λ depend upon the constituents of the flow through collision effects as

$$a_2 = \frac{e^2}{2m_e c^3} \sqrt{\frac{8k}{\pi} \left(\frac{1}{m_K} + \frac{1}{m_f} \right)} n_s T_s \frac{P}{P_s} \quad (20b)$$

and

$$a_\lambda = f \sigma^2 \left(\frac{1}{\lambda} - \frac{1}{\lambda_0} \right)^{-2}. \quad (20c)$$

The potassium D-line oscillator strengths and collisional cross sections can be found in tabulations by Radzig and Smirnov¹¹ and Hofmann and Kohn,¹² respectively. Appendix 1 lists the f -values for alkali atoms along with other atomic constants used in the PEAS data analysis.

Two-Wavelength Measurements of Atomic Density. A two-wavelength emission absorption measurement can measure the atomic density in particle-laden flows by canceling particle extinction effects. With the assumption that the particle extinction effects are broad band relative to the width of the resonance line, a difference in optical depths depends only upon the atomic density: $\tau_{\lambda_1} - \tau_{\lambda_2} = (\alpha_{\lambda_1} + \eta E)L - (\alpha_{\lambda_2} + \eta E)L = (\alpha_{\lambda_1} - \alpha_{\lambda_2})L$. The atomic density is found as

$$n_K = \frac{\tau_{\lambda_1} - \tau_{\lambda_2}}{a_2(a_{\lambda_1} - a_{\lambda_2})L} \sqrt{T_g}. \quad (21)$$

A single wavelength emission absorption measurement of the atomic density is absolutely not valid for particle-laden flows because of the particle extinction contribution to the optical depth.

Integrated Line Measurements. Typical application of the PEAS instrument for seed atom number density measurement in MHD flows relies upon a model for the absolute optical depth at a particular wavelength on the line wing. This measurement scheme demands that the optical system fully resolve the wing of the atomic line. This is relatively easily accomplished for the typically observed seed atom emission lines due to high loadings and long path lengths. However, on shorter path length benchtop flames or with weaker lines or lower loadings the atomic emission lines may be too narrow to resolve and then this scheme cannot be used for atomic density measurements. For such situations, measurements can still be made by analyzing the spectrally integrated line absorption.

Absorption measurements of an unresolved atomic line can be used to provide a measure of the atomic density.⁸ The integrated absorptivity is given by

$$A = \int_{\Delta\nu} (1 - e^{-\alpha_\lambda L}) d\nu = \frac{\int_{\Delta\nu} I_L d\nu - \int_{\Delta\nu} I_{L+F} d\nu + \int_{\Delta\nu} I_F d\nu}{\int_{\Delta\nu} I_L d\nu}, \quad (22)$$

where the total atomic absorption coefficient is given by Eq. (17) on page 10. The unresolved measurements of lamp, lamp plus flame, and flame-alone intensities are represented by the integrals of I 's. The atomic absorption coefficient is a linear function with atomic number density with a shape given by a Voigt profile, so a numerical integration coupled with an iterative adjustment of a guessed number density can be used to find the atomic number density. This is acceptable for a limited number of measurements. Look-up tables for various temperature and pressures would provide a faster scheme if such measurements were ever desired for field tests. Figure 3 illustrates the total potassium D-line absorptivity for variations in temperature and potassium number density.

Figure 3. Integrated potassium D-line absorptivity versus atomic density for a pressure of 1 atm and temperatures ranging from 1800 to 2800 K in increments of 200 K.

Electron Density and Conductivity Measurements

The conductivity of the MHD working fluid conductivity is a crucial parameter for analyzing MHD channel performance. Potassium seed is the primary source of free electrons in the flow through thermal ionization as $K \leftrightarrow K^+ + e^-$, therefore an indirect measure of the electron density can be made from emission absorption measurements of temperature and seed atom density with the assumption of ionization equilibrium. Additionally, the electron density with an electron mobility model gives an estimate of the electron conductivity. The following is an excerpt from a previously published report.¹³

Brief Theory of Plasma Conductivity. Considering a plasma to be an ionized gas, we can view it as being composed of electrons, positively charged ions, and neutral atoms or molecules. In a direct current electric field, the electrons and ions will, in opposite directions, repetitively accelerate until suffering a collision, and then accelerate again. This results in a drift velocity for the motion of the charged particles that provides a conductivity

$$\sigma = -n_e e \mu_e + n_i e \mu_i, \quad (23)$$

where n_e is the electron density, $-e$ is the electron charge, μ_e is the electron mobility, and n_i is the ion density and μ_i is the ion mobility. The electron mobility depends upon particle charge, mass and collision frequency as

$$\mu_e = \frac{e}{m_e \nu}, \quad (24)$$

where m_e is the electron mass and ν is the collision frequency. A similar expression could be written for the ions in the plasma. Because of the ratio of masses, the mobility of the ions will be negligibly small compared to that of the electrons; we can, for a very good approximation, consider the conductivity to arise solely from the electrons.

Collisions will occur between the various particles and at different impact velocities, depending upon the temperature of the plasma. The important velocity changing collisions will occur between the electrons and the heavy particles in the plasma. For the seeded MHD flows, the neutral particles vastly exceed the number of ions. In this case, the collision frequency is primarily the electron neutral collision frequency averaged over the electron velocities and the neutral species. The velocity average is denoted by an overbar and the conductivity of a weakly ionized gas can be written as

$$\sigma = \frac{n_e e^2}{m_e \bar{\nu}}. \quad (25)$$

Thus, a measurement of the electron density and collision frequency will provide a measure of the plasma conductivity.

Saha Calculation of Electron Density. With the assumption of ionization equilibrium the electron density can be inferred from measures of temperature and neutral seed atom density by application of the Saha equation:^{14,15}

$$\frac{n_e n_i}{n_K} = \frac{(2\pi m_e kT)^{3/2}}{h^3} \frac{2g_i}{g_0} \exp\left(-\frac{E_i}{kT}\right), \quad (26)$$

where g_i/g_0 is 1/2 for the alkali metals. The ionization energy for potassium is 4.340 eV (See Appendix A for the ionization energy of other alkali atoms). Ionization equilibrium should be easily established at the temperature, pressure and flow velocity of typical MHD flows.

The seed ion number density is usually assumed to be equal to the electron density for the Saha computation, although chemical equilibrium computations predict as much as a 10% deviation from equality because of formation of CO_2^- and OH^- ions. Phosphorus has been proposed as a possible sink of electrons in a coal-fired MHD flow but studies showed only a small effect.^{16,17} Chemical equilibrium calculations are only accurate to within 10 to 20%, and the accuracy of the emission absorption measurements of potassium is less than 10% for potassium, due to the uncertainty in the absolute absorption coefficient from the oscillator strength^{11,18} so the simplifying assumption of equality in ion and electron densities seems justified.

The measurement uncertainty for determining the electron number density through a Saha calculation is given by

$$\frac{\delta n_e}{n_e} = \left[\left(\frac{1}{2} \frac{\delta n_K}{n_K} \right)^2 + \left(\left(\frac{3}{4} + \frac{E_i}{kT} \right) \frac{\delta T}{T} \right)^2 \right]^{\frac{1}{2}}. \quad (27)$$

The electron density depends exponentially on temperature and the temperature is easily measured to an accuracy of better than 2% with line reversal. At a temperature of 2500 K with measurement uncertainties of 25% in the seed atom density and 50 K in temperature, the electron density measurement uncertainty is about 20%.

Electron Mobility Model. Chemical equilibrium calculations of the composition of the MHD working fluid, coupled with an electron mobility model can be used to calculate the electron collision frequency in order to estimate the conductivity from the electron density measurement. The electron collision frequency was modeled by the method presented by Frost.¹⁹ The expression for mobility is an integral over electron velocities as

$$\mu_e = \frac{4\pi e}{3m_e} \int F(v) \frac{d}{dv} \frac{v^3}{v_t} dv, \quad (28)$$

where $F(v)$ is a Maxwellian velocity distribution which should be applicable for MHD flow conditions and v_t is the total collision frequency at a particular electron velocity. This expression is valid for no magnetic field or in the direction of the field; in the perpendicular direction the mobility is reduced by electron cyclotron effects by approximately $\mu_{\perp}/\mu = (1 + B^2 \mu^2)^{-1}$. The only conductivity measurements made with the PEAS instrument on prototype MHD facilities were in the aerodynamic duct at the CFFF without the presence of a magnetic field.

The total collision frequency is the sum of the collision frequency with neutral molecules, v_0 , and the collision frequency with ions, v_i . The v_0 is found as a sum over the species in the flame

$$v_0 = \sum_j v N_j Q_d(j), \quad (29)$$

where N_j is the j -th species mole fraction (excluding ions and electrons) and $Q_d(j)$ is the species specific electron-molecule momentum collision transfer cross section.

The electron-ion collision frequency is found as an analytic expression,

$$v_i = 0.476 K \eta^{-1}, \quad (30)$$

where η is the dimensionless electron energy variable $1/2 m_e v^2 / kT$ and

$$K = \frac{2\pi m_e e^2 \ln \Lambda}{(4\pi\epsilon_0)^2} \left(\frac{2e}{m_e} \right)^{\frac{1}{2}} \left(\frac{kT}{e} \right)^{-\frac{3}{2}}, \text{ where } \Lambda = \frac{3}{(2\pi n_e)^{\frac{1}{2}}} \left(\frac{4\pi\epsilon_0 kT}{e^2} \right)^{\frac{3}{2}}. \quad (31)$$

Model mobility calculations for conditions representative of the CFFF aerodynamic duct at a pressure of 2 atm are shown in Fig. 4 for various seed loadings. These model results were used in the conductivity measurements shown in Fig. 46 on page 60.

Figure 4. Electron mobility calculations for the CFFF aerodynamic duct at a pressure of 2 atm.

SYSTEM DESCRIPTION

Fundamental to the design of any emission absorption instrument is the separation scheme for obtaining the transmitted lamp and the flame-one emission signals. With a very stable source and detector, the reference lamp signal can be obtained before or after the test. Additional design considerations for an emission absorption instrument for prototype-scale coal-fired MHD flows, include 1) moderate spectral resolution to resolve the potassium D-lines and avoid error due to the cool boundary layer of the flow with line wing measurements; 2) multi-wavelength detection in order to remove broadband particle effects; while also obtaining 3) a fast time response because of the rapid fluctuations in the MHD flow properties.

A decision was made to satisfy these design considerations by using a medium size monochromator (0.25 m to 0.5 m focal length) with a vidicon detector operated as a multichannel analyzer. Vidicon detectors are area detectors which were state of the art at that time for simultaneous multiwavelength detection. With an area detector, the two signal can be separated vertically on the detector surface while the horizontal axis is used for spectral separation. Both spatial and temporal separation schemes were studied and the final system design incorporated synchronized optical choppers for temporal separation of the line reversal signals. The original design of the instrument included fibers for light transmission from the lamp to the MHD flow as well as from the flow to the detector components²⁰ as was used in a previously design sodium line reversal instrument.²¹ The lamp-side fiber was abandoned in order to achieve high effective lamp temperatures at the potassium wavelengths.

Beyond the above design considerations, it was desired to keep the instrument as compact and lightweight as possible for transporting to MHD facilities for field tests. The PEAS hardware and software are described below followed by a brief description of standard operating procedures for the instrument.

System Hardware.

The essential system components are a tungsten strip lamp for a reference light source, lenses and an optical fiber for light transmission, a system of synchronized optical choppers and an optical shutter for temporal separation of the transmitted lamp and flame emission signals, a monochromator for spectral separation, an optical multichannel detector, and a computer for instrumentation control, data collection and analysis. Figure 5 diagrams the instrument hardware diagram. Not shown in the diagram are two beam blocks, one at the detector and one at the lamp. Also carried with the instrument but not shown in the diagram is a 8 mm tape drive for archiving test data.

Figure 5. System diagram for the Potassium Emission Absorption System.

The components have been packaged for relatively easy transport with all but the computer and remote components in a single electronics enclosure. The optics surrounding the MHD flow are mounted on optical rails for easy benchtop alignment and positioning in the field. The monochromator/detector and optics are mounted on an optical breadboard which sits upon the electronics cabinet. The rails are positioned on the breadboard for transport. All of the components are of a size and weight that the system can be shipped by air to remote test sites. Figure 6 shows the major components as packaged.

The reference lamp is crucial to accurate line reversal measurement and the reader should refer to Appendix 2 for details concerning the lamp and determining its effective blackbody temperature for use as a line reversal source. Long time (>24 hours) studies of the lamp and detector were performed to verify their stability and justify using pre-test lamp signals for the line reversal signals. The lamp and detector were found to be very stable but to be doubly cautious, a monitor of the lamp power supply current is brought into the OMA and digitized and stored with each data set on the computer.

The lamp and associated optics on optical rails are either mounted to the MHD test train or positioned on adjacent tables. The lamp is imaged in the center of the flow or in some cases a collimated beam is transmitted across the flow. An iris diaphragm is positioned at the lamp-side lens image on the detector-side to exclude light from areas of the flow that have not been illuminated by the white light -- this point is critical for accurate line reversal temperature measurements. The light is imaged on the tip of an 1 mm diameter quartz optical fiber²² and transmitted to the detector system. At the detector-side components, a 40 mm focal length achromat lens and a 40 mm focal length cylindrical lens provide a strip of light to nearly match the height of the

monochromator slit. Two openings on the chopper blade illumine the upper and lower halves of the detector with the two line reversal signals. Except for the cylindrical lens, achromat doublet lenses²³ are used throughout the system to facilitate optical alignment, since the eye is not sensitive to the potassium D-line wavelength region. The change in effective focal length for these lenses is less than 0.3% from yellow to the potassium D-line wavelengths.

Figure 6. Potassium emission absorption system (PEAS) hardware photograph.

The monochromator is an HR-320 from Instruments SA with focal length of 0.32 m and a choice of 600, 1200, 1800 or 2400 groove/mm gratings.²⁴ Depending upon the grating size the monochromator has a $f\#$ of 4.2 or 5.0. With the 1200 groove/mm grating the dispersion is 2.4 nm/mm. A stepper motor was added to the adjustable entrance slit for computer control of the slit width, one step adjustment corresponds to 1 microns in slit width. In addition, the manufacturer supplied wavelength drive was replaced with a computer controlled stepper motor as the original drive was unreliable under field test conditions. With a 1200 groove/mm grating 100 steps corresponds to 1 nm.

The detector is a Princeton Applied Research model 1254E red enhanced silicon intensified target (SIT) vidicon detector with a model 1216 multichannel detector controller referred to collectively as an optical multichannel analyzer (OMA).²⁵ The detector sensitivity is approximately 2 detected photon per count. The target is masked to a 12.5 mm square area of 512x512 pixels. The crosstalk between channels is approximately 3 channels for half maximum signal. With a 1200 groove/mm grating the monochromator/detector resolution is approximately 0.2 nm.

The detector scan geometry and timing are software selectable on the LSI and sent over a 16-bit parallel output interface to the 1216 controller. The vidicon data is collected by the computer over a 16-bit parallel input. The 1216 input/output board was modified to invert the logic of the signal lines for easier computer control. This entailed replacing the three DM8097 chips with DM8098 chips. The computer parallel interface board was modified by stretching the 400 nm OMA new data ready pulse to a 20 μ s pulse.

Design considerations for the PEAS timing included 1) exposure of the detector only one during a time interval required to read the OMA (30 ms or more) and 2) a time resolution of less than 5 ms to hopefully resolve the MHD flow fluctuations. The synchronized optical choppers system provides the spatial separation of the transmitted lamp and flame emission-only signals with near temporal coincidence. The choppers are Laser Precision model CTX-534.²⁶ The lamp-side chopper uses a 6-slot blade and is operated at a 300 Hz chopping frequency. The 1" circular opening in the chopper head case was replaced with a 5° aperture so that the lamp is fully open and fully closed for intervals of approximately 1.4 ms with transitions of about 0.28 ms. An emitter-detector pair on the lamp-side chopper blade provides an external clock signal for synchronously driving the detector-side chopper. The detector-side chopper blade is a custom blade with 12 clock holes and so is rotated at 25 Hz, i.e., providing a 40 ms period. This blade has two 5° openings separated by 10° as shown in Fig. 7. The openings are offset radially to expose the upper and lower halves of the vidicon detector with the transmitted lamp and flame emission-only signal, respectively. The openings correspond to approximately 0.5 ms exposures separated by 1 ms. The jitter in the optical chopping is specified to be less than 0.01 radians $\times$ slots for speeds above one quarter of the maximum and 0.05 radians $\times$ slots for lower speeds. The worst case jitter then is 0.032 ms for the lamp-side chopper and 0.32 ms for the detector-side chopper. The combined jitter is low enough to be assured that the lamp is either fully open or fully closed for the exposures. This was verified by experimentation with fast photodiode detectors.

Figure 7. Sketch of the detector-side chopper blade.

The instrument timing is illustrated in Fig. 8. The emitter-detector pair on the detector-side chopper head was moved to a radial position just out from the clock emitter-detector pair and is 180° away from the exposure position. A single sync hole provides the output signal to the computer for synchronized data collection. The time to read the signal from the vidicon is generally greater than the 40 ms between exposures so in addition to the choppers a Uniblitz SD-10 optical shutter is used.²⁷ The computer detects the synchronization signal which occurs just prior to the exposures and software determines when to open the shutter for 40 ms in order to obtain a single exposure. The shutter is closed while the data is read from the detector. Several reads of the vidicon detector are necessary to extract the complete signal. A study of the vidicon signal versus frame time revealed that a total channel read time of 200 ms is sufficient. Typically parameters used are channel times of 60 ms with 3 or more scans. With full track scans then the total read time is 0.18 s or more for each frame of data.

Figure 8. Timing diagram for the PEAS instrument synchronized choppers.

The computer is an LSI-11/73 computer configured for general purpose data collection. The interface boards used by the PEAS instrument include: a 16-bit parallel I/O configured for the OMA, a second 16-bit parallel I/O used for control of the wavelength and slit stepper motors as well as the two beam blocks, and a real-time clock board for accurate timing. The lamp power supply signal is brought in through the OMA COMP line so that no analog-to-digital converter is needed for the system.

System Software.

The software for the PEAS instrument is primarily written in FORTRAN 77. For speed, some of the data collection and computer display routines have been written in Macro-11.²⁸ The data and results files created by operation of the PEAS instrument are listed in Table 1. The DAT:WAVCAL.DAT file stores the state of the monochromator: current wavelength, dispersion and entrance slit width. This file is updated whenever a program changes the settings.

The software can be grouped into general purpose routines, diagnostic routines and the emission absorption routines. Table 2 describes the routines. For ease, operation of the instru-

ment can be started with menu screens: DMENU for diagnostic routines, GPMENU for general purpose routines, and MENU for the emission absorption routines. A library of commonly used subroutines is used in creation of each of the routines.

Table 1. PEAS computer data and results file types.

Type	File Description
Stored on the DAT: disk unit:	
*.CTL	OMA scan pattern and timing control file in ASCII format.
*.INT	OMA intensity file. Front end is a duplicate of the *.CTL file used for data collection, then data and if requested background data. in ASCII format. Several general purpose programs store the last data set as TEMPOR.INT.
*.LMP	Pyrometer measurements and calculation results for the tungsten lamp calibration.
*.RSP	OMA response file with the same format as *.INT files. The relative system response is stored in integer format as ratio*1000.
*.PLU	Potassium emission absorption file as unformatted binary data.
Stored on the RES: disk unit	
*.SUM	Emission absorption results in file by file format of average, standard deviation and sample size for 10 parameters.
*.CAL	Line reversal results for an individual scans in a *.PLU file.
*.TBL	Table listing of *.SUM results suitable for importing into a spreadsheet program for plotting.
*.PLT	File of HP plotter commands for plotting line reversal results.

System Operation

Prior to a field test the operator must determine the desired monochromator dispersion and configuration for the optical rails as optical alignments are more easily performed in the laboratory rather than the field. The expected flow temperature, optical path length across the flow, seed loading, and pressure will allow an estimate of the potassium D-line spectra and help select the grating. The 600 groove/mm grating was used for field test on the CFFF and CDIF diffuser, while the 1200 groove/mm grating was used for field tests on the CFFF aerodynamic duct. The 1800 groove/mm grating would only be used for very low seed loading, such as the experiments at the CDIF post-nozzle location for testing without seed injection.

Achromat lenses are used throughout the system as the eye is not sensitive to the potassium wavelengths for alignment purposes. Lens focal lengths from 60 mm to 1000 mm are available. Over longer path lengths a collimated optical arrangement may be used. Proper alignment of the rails is best checked with a HeNe laser for centering and backlighting with a white light through the fiber to verify that the fiber/iris combination does not view any space not illuminated by the tungsten lamp. A proper breadboard alignment will give nicely separate dual tracks on the center of the OMA.

Table 2. Names and description of the PEAS software routines.

Name	Description
Emission Absorption Routines:	
CALIB	Finds system response for a particular OMA scan pattern, stores in *.RSP.
EFFLMP	Calculates the tungsten lamp effective temperature for operator input of pyrometer measurements. Stores results in *.LMP file
LMPSTR	Stores the average reference tungsten lamp spectrum in a *.INT file.
LRCALC	Emission absorption calculation on *.PLU files. Options include selection of wavelengths for analysis, automatic selection, or integrated line analysis.
LREXPT	Emission absorption experiment including data collection, display, calculation, and storage in *.PLU and *.SUM files.
CTSTOR	Stores emission absorption data in *.PLU files.
TKETBL	Creates a table file of results from a stored *.SUM file.
General Purpose Routines:	
AVGINT	Displays and stores signal averaged spectroscopic data from the OMA.
BTIMST	Sets the clock/calendar.
CTWAVE	Storage of OMA spectral data in *.PLU format with wavelength increments.
DMAAVG	Direct Memory Access (DMA) version of AVGINT.
DMARTS	DMA version of RTSCAN.
EXIT	Restores default terminal characteristics after running PEAS routines.
HPPLOT	Drives the HP 7475 plotter.
LMPCAL	Specific wavelength scans for calibrating the instrument response.
PARAMS	Routine for setting up a OMA scan patterns, stores in a *.CTL file.
PLTFIL	Generates an ASCII file for plotting from a *.INT file.
RESET	Power-up reset of the OMA and reset of the system clock.
RSTORE	Reads from a stored *.INT file and displays the spectra.
RTSCAN	Real-time scan of the OMA, including wavelength and slit control
SDRIVE	Sets the monochromator slit width.
STORE	Stores the TEMPOR.INT file under an entered name.
WDRIVE	Sets the wavelength of the monochromator.
Diagnostic Routines:	
BITTST	Displays OMA data bits and the relative time intervals between them.
BLOCK	Toggles the selected light beam blockage device.
CLCKGO	Starts the real-time clock counting again after battery failure.
DMATST	Displays the incoming data from the OMA on the DMA interface.
IOLOOP	Repetitively writes data words to the OMA output port.
IOTEST	Loop back test of the parallel board attached to the OMA.
NOISE	Calculates OMA noise standard deviation for adjustments of the vidicon.
RTCTST	Simple test of the counting operation of the real-time clock board.
SETBIT	Sets selected bits on the output port of the misc. parallel interface board.
SHUTST	Test of shutter/chopper synchronized data collection.

Just prior to the test, the operator should 1) choose OMA scan pattern to match the OMA illumination, 2) calibrate the system wavelength with a potassium spectral lamp, 3) calibrate the OMA response with the CALIB routine, choose a lamp current setting to approximately match the expected flow temperature and finally 4) run the EFFLMP and LMPSTR routines for saving the pre-flame reference lamp and spectra. During the CALIB routine the operator must remove the lamp-side chopper in order to illuminate both of the chopper openings, i.e., both OMA tracks.

During the test the operator can choose to only store data for post-test analysis with the CTSTOR routine or can choose to store and analyze the data with the LREXPT routine. For full spectral information the CTSTOR routine operators at 1 spectrum per second while the LREXPT routine operates at 1 spectrum every 2 seconds. If the experiment is expected to last over several hours, the operator should copy the WAVCAL.DAT, *.CTL, *.INT, and *.RSP files to each of the three available disk units. Two of the disk units can store data for about six hours, the other is slightly smaller. For longer tests, the operator must break data collection and archive the disk units to tape. During the test the operator should periodically check to see that the windows are clean and that the optics are still aligned, but the data collection routines run unattended.

Following the test, the operator should repeat the pyrometer measurements and the CALIB and LMPSTR routines in case of problems during the test.

The data is analyzed post-test with the LRCALC routine, creating *.SUM and *.CAL files. The *.SUM files are converted to tabular form with the TKETBL routine. Many early routines were written for output of the data on an HP 7475 plotter. This has been replaced with a serial line transfer of the *.SUM file to a PC and output of the data using a spreadsheet program.

TECHNICAL ISSUES

Error in Multiwavelength Emission Absorption Techniques

Cool Boundary Layers. Figure 9 illustrates the three signals for a modified line reversal calculation on a model boundary layer flow at the sodium D-line wavelengths. The cool boundary layer absorbs with a more narrow linewidth the light emitted in the hot core of the flow producing the effect of a dip at the line centers. On the line wings, a spectrally resolved modified line reversal measurement will yield a temperature approaching that of the core of the flow.

Figure 9. Illustration of emission absorption spectra for a boundary layer flow at the sodium D-lines.

The effect of cool boundary layers on emission absorption measurements of temperature has been well studied.²⁹⁻³³ The reader should especially refer to the article by Onda et al. for a treatment of error in the atomic density determination as well as temperature.¹⁰ The boundary layers will bias the measured temperature to lower temperatures and will bias the seed atom density to higher values as shown below, with the biases increasing with optical depth, i.e., towards line center.

Referring back to the radiative transfer integral, Eq. 1, and using the boundary layer temperature model along with the Lorentz form of the atomic absorption coefficient, one can find by numerical integration the error caused by the cooler boundary layers if the boundary layer profile is known. The error can be minimized by measurements in the line wing where the optical depth is low.

To demonstrate that for measurements in the optically thin region on the wing of a resonance line the error approaches a constant value, consider a simplistic boundary layer flow with two layers of constant properties as shown in Fig. 10. The emitted intensity can be written as

$$I_F = B(T_w)(1 - e^{-\tau_w})e^{-\tau_c} + B(T_c)(1 - e^{-\tau_c})e^{-\tau_w} + B(T_w)(1 - e^{-\tau_w}), \quad (32a)$$

where

$$\tau_w = \alpha_w \delta \text{ and } \tau_c = \alpha_c (L - 2\delta). \quad (32b)$$

Solving for Φ according to Eq. 4, expressing the result as an expansion in τ_w and keeping only first term, then assuming small optical depths with the absorption coefficient given by Eq. 20 shows

$$\Phi \approx \frac{B(T_c)}{I(0)} \left(1 - \frac{B(T_c) - B(T_w)}{B(T_c)} \frac{n_{K,w}}{n_{K,c}} \frac{2\delta}{L - 2\delta} \frac{\sqrt{T_c}}{\sqrt{T_w}} \right). \quad (33)$$

Here the wavelength dependence in the optical depth cancels out with the assumption of optical thinness. If the boundary layer temperature is lower than the core flow temperature then the error is negative, i.e., line reversal will underestimate the core flow temperature.

Figure 10. Illustration of the temperature profile across a model boundary layer flow.

Now, consider the measurement of atomic density. Solving for the atomic absorption coefficient according to Eq. 16 assuming that the measured temperature is close to the core temperature gives

$$\alpha = \frac{\alpha_c (L - 2\delta) + \alpha_w 2\delta}{L} \therefore n_K = n_{K,c} \left[1 + \frac{2\delta}{L} \left(\frac{n_{K,w} \sqrt{T_c}}{n_{K,c} \sqrt{T_w}} - 1 \right) \right]. \quad (34)$$

If there is negligible atomic density in the boundary layer of the flow then the error is negative and is purely due to overestimating the optical path length of the flow. If the flow can be described as frozen chemistry then the atomic depth in the boundary layer will be close to that in the core of the flow and a measurement will overestimate the atomic density in a cooler boundary layer flow. More typically, the atomic density will be exponential with temperature due to chemical equilibrium so that the error will be negative.

Particle Cloud Effects. The following is partially an excerpt from a published paper demonstrating the advantages of two wavelength emission absorption measurements of temperature and atomic density in coal-fired MHD flows.³⁴

Given here are model radiative transfer calculations for coal-fired flows as well as experimental results for a simulated coal-fired flow which support the model calculations and demonstrates the utility of the two wavelength emission absorption measurements of temperature and seed atom density. A numerical solution was found for the radiative transfer problem of a parallel, axisymmetric source light passing through an emitting, absorbing, and scattering medium which contains a hot potassium laden gas at a temperature T_g and particles at temperature T_p . The hot gas is assumed to be described by an infinite slab geometry and enclosed by a hot wall at temperature T_w . Only single scattering was considered. A Voigt profile was used to model the potassium atom absorption coefficient and calculations were done for an atomic mass fraction of 0.002 with the foreign constituent being nitrogen molecules for the purpose of computing the collisional broadening of the D-lines. Calculations were performed for a pressure of 0.95 atmospheres and temperatures of $T_g = T_p = 2500$ K, a lamp temperature of 2500 K, a wall temperature of 1900 K, and a path length of 20 cm.

The particle absorption and scattering coefficients were found from Mie theory using the complex index of refraction found by Goodwin.³⁵ The Sauter mean diameter of the particles was taken to be 1 micron and an upper limit distribution function was used as described in previous work.³⁶ Five cases were run for number density of particles from 1×10^5 to 5×10^5 /cm³ to span the estimated range of interest for coal-fired MHD flows.

Figure 11 shows profiles of the blue wing of the 766.5 nm potassium line as well as the transmitted lamp profiles for the five different particle loadings. It was found that out-scattering and in-scattering by the particle cloud are of the same order of magnitude and this is exhibited by the only slight change in the potassium profiles with increasing particle loading. However the transmitted lamp profile does show decreasing signal away from line center due to increased scattering at higher loading. Figure 12 shows the optical depth versus wavelength for the five cases. The optical depth increases linearly with increasing particle loading. Calculations were begun on the blue side of the lines at 760 nm and at this wavelength the optical depth at the heaviest loading is double that of the clean flow, i.e. that due to the atomic line alone.

Figure 11. Model potassium D-lines spectral profiles for five different particle loadings at lamp and gas temperatures of 2500 K. The upper trace shows a transmitted lamp profile for a particle free flow as "a". Increasing particle densities, 1×10^5 , 2×10^5 , 3×10^5 , 4×10^5 , and 5×10^5 per cm^3 , cause decreasing radiances and are shown as traces b-f. The emission profiles for all cases show only slight increases in radiance with increasing particle density and are marked collectively as g.

Figure 12. Calculated optical depths for the five particle laden flows illustrated in Fig. 11. The optical depth increase with particle loading is significant on the edge of the spectral line.

Figure 13 shows the calculations of the gas temperature via the classical line reversal solution method and via the two-wavelength method. The classical method requires only emission absorption measurements at a single wavelength and the wavelength is shown on the abscissa. The classical method seriously underestimates the gas temperature with increasing particle density. The two-wavelength calculation using radiances at 760 nm and at the wavelength shown as the abscissa is reasonably independent of wavelength. The two-wavelength method only slightly overestimates the gas temperature with increasing particle density. Insignificant changes result from varying the first wavelength for this modeled data; for experimental data the two wavelengths should be chosen to give significantly different optical depths for signal to noise considerations. The classical method clearly underestimates the temperature on the wings of the line and approaches the input value toward line center at high optical depths. The error in the two-wavelength method is nearly independent of wavelength and causes a slight overestimation of the temperature. The error in the two-wavelength method arises because of differences in the in-scatter term at the two wavelengths as discussed above. The error increases when the two wavelengths are similar in optical depth -- a situation which can easily be avoided.

Figure 13. Calculations of gas temperature via the two-wavelength method (a-e) and the classical method (f-j).

Both techniques are influenced by boundary layer effects and this was not included in the model treatment. Cooler boundary layers cause an underestimation of the temperature which tends to cancel the error in the two-wavelength method and increase the error in the classical method. A good rule of thumb is to work at wavelengths where the optical depth is less than unity²⁹ in order to minimize the error, which for this case is satisfied at wavelengths less than about 764 nm. A reasonable value is generally taken to be an optical depth of 0.5, and for the worst case the classical method underestimates the gas temperature by 50 K and the two-wavelength method overestimates the gas temperature by 15 K. Very careful choice of the wave-

length to maximize the temperature measured with the classical method will minimize the error; however, this is impractical for most flows where fluctuations in optical depth are rapid and large. The lower error in the two-wavelength method as well as its insensitivity to wavelength, i.e. optical depth, make the method clearly superior to the classical method for temperature measurements of particle laden flows.

The applicability of the atomic density calculation is argued from the results shown in Figure 14 which show that this two-wavelength method is a dramatic improvement to the classical technique. The classical method uses radiances at a single wavelength and shows a strong wavelength dependence, seriously overestimating the atomic potassium number density with increasing particle density. The classical results do approach the model value towards line center where the optical depth is large, however as stated previously this region must be avoided due to boundary layer effects. At an optical depth of 0.5, the classical method result is 20% high for the highest particle loading. The two-wavelength calculation, using radiances at 760 nm and at the wavelength shown on the abscissa, is in error only slightly due to the very slight error in temperature and due to the approximation used for the Voigt profile. The model matches the assumptions in the two-wavelength atomic density calculation and the only slight error arises from the error in temperature, reduced by the square root relationship, and a the slight error introduced by the approximate form used for the Voigt profile. An exact calculation of the Voigt could have easily been used if necessary.

In contrast, the two wavelength method shows only a very slight overestimation of atomic density and the results are independent of wavelength. Not shown is the effect of varying the second wavelength, however, calculations over a matrix of wavelengths showed only a weak variations. Of course, the uncertainty increases with closely spaced wavelengths.

Figure 14. Calculations of potassium number density via the two-wavelength method (a-e) and the classical method (f-j).

Application of the two-wavelength method for gas temperature and seed atom density on the Mississippi State University (MSU) Combustion Test Facility are shown in Figures 15-17. These measurements were made on a simulated coal-fired MHD flow created by burning a slurry of #2 fuel oil, coal fly ash, and K_2SO_4 with preheated air. The optical path length is 20.3 cm. Figure 15 shows the emission-only and transmitted lamp profiles for the potassium doublet and clearly illustrates the effect of self-reversal with the center dips at the line centers. The differences between the classical and two wavelength determinations of temperature are shown as a function of wavelength in Fig. 16. The increased measurement uncertainty due to a small difference in optical depth is seen in the wings; the first wavelength was chosen to be 760 nm and the second is shown on the abscissa.

Figure 15. Potassium D-line emission absorption spectrum recorded on the MSU Test Facility. The pre-flame lamp and transmitted lamp signals are shown as traces *a* and *b*, respectively. The flame emission and background signals are shown as traces *c* and *d*.

Although the differences in temperature are only slight because of the short path length, the differences are still significant in the determination of atomic density, as shown in Fig. 17. The measurements on the line wings corroborate the numerical results, showing a serious overestimation of potassium atom density with a single wavelength determination. The calculated mole fraction is doubled over a 2 nm change in wavelength on the wings of the line using a single wavelength measurement. Both methods do rely upon the assumption of a Voigt profile which is not valid for the far wings of the broad self-reversed potassium lines so the measurements are only reported in the near wing.³⁷

Figure 16. Two wavelength and classical calculations of gas temperature versus wavelength from the data presented in Fig. 15.

Measurements by both methods are strongly affected by the cool boundary layers of the flow near line center. The thermal profile of the flow in the MSU test stand has been studied by coherent anti-Stokes Raman spectroscopy³⁸ and by lineshape fitting,³⁹ with both results indicating about 1 cm boundary layer that follows a 9th power law between an approximate wall temperature of 1800 K and a core temperature of 2500 K. Using this profile and an ideal gas relationship for the variation of potassium density in the boundary layer, i.e., ignoring chemical equilibrium effects, a length correction factor for the number density according to the method of Onda is 0.7 cm. This correction would raise the estimates of number density by only about 3%. To put things in perspective, this adjustment for boundary layer effects is negligible compared to the effort in the single wavelength results caused by particle effects.

Figure 17. Two wavelength and classical calculations of atomic potassium mole fraction versus wavelength from the data presented in Fig. 15.

The single wavelength determination of seed density does not show a plateau where both the particle and boundary layer errors are minimized. A spectra region of at most 0.1 nm does give roughly similar results for the two methods, within 10%. This position is roughly that of the intensity maximum, a spectral region which will shift nearly linearly with density. Calculations with this thermal profile show that a 25% drop in atomic density will shift the maximum by almost 0.2 nm.⁴⁰ Our experience has been that during tests when problems occur with the seed feed, densities can change by an order of magnitude. With changes such as this, a fixed single wavelength measurement cannot make accurate temperature or seed atom density measurements in coal-fired flows. However, the two wavelength method is independent enough of the chosen wavelengths to provide an accurate measure of seed density with changing conditions.

Similar results were seen for sodium line reversal measurements on the Argonne National Laboratory AMPEL facility as shown in Figures 18-20. Here the sodium is a trace quantity from the coal and the lines are considerably narrower than for the potassium seed atom doublet at MHD conditions. The spectral information was recorded with the Sodium Line Reversal System operating as a scanning monochromator so the lineshape shows noise due to fluctuations in flow conditions during the scan. The path length on the AMPEL facility is 56 cm and the pressure was 1 atm. At the longer path length, the particle errors are increased dramatically.

Figure 18. Sodium D-line emission absorption spectrum recorded on the AMPEL Test Facility. The upper trace is the transmitted lamp signal while the lower trace is the emission-only signal.

In summary, the numerical calculations and experimental results shown here demonstrate the accuracy of two-wavelength emission absorption for measurements of temperature and seed atom density at coal-fired MHD flow conditions. Knowledge of the loading, temperature and optical properties of the particles is not required. The method requires measurement of the preflame lamp, transmitted lamp and flame emission at two significantly different optical depths, i.e., two different wavelengths, on an instrumentally resolved atomic resonance line. The basic

assumption is that the particle effects are independent of wavelength over the width of the resonance line.

Figure 19. Temperature calculations for the emission absorption data shown in Fig. 18: upper trace is the two-wavelength calculation with the first wavelength at 588 nm and the lower trace is the one-wavelength calculation.

Figure 20. Atomic mole fraction found for the emission absorption data shown in Fig. 18: lower trace is the two-wavelength calculation with the first wavelength at 588 nm, upper trace is the one-wavelength calculation.

A major advantage of the two-wavelength technique is that the results are reasonably independent of the choice of wavelengths. Changing conditions on prototype-scale MHD systems can lead to significant changes in seed atom emission linewidths such that a technique that is independent of the wavelength is desirable for automatic measurements. The method requires only limited spectral information and computations, so it is suitable for real-time monitoring of seed atom density in coal-fired flows. In addition, by providing accurate measurements of temperature and neutral seed atom density, the technique can also be used as an indirect monitor of the electron density in MHD flows using the Saha equation.

Broadband Errors in Emission Absorption

Presented here is an analysis of the bias and uncertainty arising from two major, and usually unavoidable, problems in applying emission absorption methods to large-scale combustion systems: 1) keeping the windows clean and 2) maintaining the optical alignment. The impetus for the study was an anomalous large temperature measurement uncertainty for potassium D-line measurements in a coal-fired magnetohydrodynamic (MHD) flow during the 89-CFC-15 test at the CDIF on August 10, 1990. The large uncertainty is explained by a rapid oscillatory misalignment. The oscillatory misalignment biases the measured temperature in the same manner as for a fouled lamp-side window and expressions for the biases for fouled optical windows are presented. Expressions are developed for the bias and uncertainty caused by a harmonic misalignment, which provide a consistent explanation of the test results. The robustness of a two-wavelength method for atomic density measurements is demonstrated. The trade-off for reduced measurement bias is an increased measurement uncertainty. The analysis and results reported here were previously published.⁴¹

Typical test results on large-scale MHD facilities, i.e. the Component Development and Integration Facility (CDIF) and Coal Fired Flow Facility, (CFFF) reveal bias in single wavelength methods caused by coal ash/seed particles to be greater than 100K in temperature and 100% in number density. A trade-off to the reduced particle bias in the two wavelength method is an increased measurement uncertainty, which for temperature is typically double that for a single wavelength measurement. On a well-controlled laboratory burner the measurement uncertainty is on the order of 15 to 20K and for CDIF and CFFF tests uncertainties have typically been 40 to 50K, 20 to 30K of which is most likely due to real fluctuations.⁴² One test at the CDIF however yielded extraordinarily large temperature measurement uncertainties. The analysis of the system performance on that test resulted in a demonstration of the robustness of two wavelength emission absorption measurement of temperature and atomic number density.

Figures 21 and 22 show respectively the measured gas temperature and potassium atom number density for the 89-CFC-15 test. Measurements were made at the middle ports of the triple port, diffuser test section -- downstream from the MHD channel. Relevant test log notes are shown in Table 3. The second half of the recorded data during which time the magnetic field was energized appears typical for PEAS measurements; prior to channel operation is when the temperature results are anomalous. The potassium number density results appear typical throughout the measurement period. The test continued for several hours after fouling of the optical windows became too severe to continue diagnostic measurements.

Figure 21. Two-wavelength potassium emission absorption measurements of gas temperature versus time for the 89-CFC-15 test.

Figure 22. Two-wavelength potassium emission absorption measurements of potassium atom number density versus time for the 89-CFC-15 test.

Two questions arise from this test. What is the cause of the extreme temperature uncertainties in the first half of the test and why do the number density results not show similar large uncertainties? And secondly, are the variations in potassium number real? The results reveal a generally higher value during magnet operation and also a sudden drop that occurs at the same time as the window fouling about 14:42. An analysis of the effect of loss of window

transmission given below implies that the seed atom density drop is real. This drop does occur before the test log indicates problems with the seed flow system.

Table 3. Notes for the 10-Aug-89 CDIF CFC-15 Test.

Time	Note
13:14:29	Coal-Fired Combustor (CFC) ignition
13:18:29	Seed Flow initiated
13:58:00	Invertor on-line
14:00:02	Starting magnet, gradual power up
14:15:25	Magnet at 4000 Amps
14:16:50	Begin increasing magnet and invertor
14:26:54	Magnet at full power (2.92 Tesla)
14:54:00	Seed System in manual
15:10:00	Seed flow steadily dropping, trying to restore
15:15:00	Seed system in auto

The anomalous temperature measurement uncertainty on the CDIF which disappears with extraction of power from the MHD channel is puzzling. A look at the raw data reveals that the transmitted lamp signal has very large uncertainties that drop with power extraction but the emission-only signal has a relatively constant signal-to-noise ratio for the span of measurements. This disparity cannot then be explained by a change in temperature or number density fluctuations in the gas flow so the source of the uncertainty would seem to be due to a rapidly fluctuating misalignment of the reference lamp beam. This misalignment could arise from vibrations of the optical mounts which are fixed on rails to the diffuser. The change in aerodynamic noise from the channel when power is extracted could explain the reduction in vibrations. However, we have not experienced such problems with operation of the PEAS previously. A more likely cause is beam steering in the flow. Velocity measurements for the same test indicate that before power is extracted there are large recirculation regions in the diffuser that rapidly shift from one wall to the other. Beam steering caused by pressure gradients in the flow could very well explain the anomalous results and presented here is an analysis of the effect of a harmonic optical misalignment on emission absorption measurements that is consistent with the test results.

Window Fouling. The worst source of bias in emission absorption measurements on large-scale combustion flows is the fouling of the optical windows. Depending upon the optical port design and the flow patterns, the fouling could occur on one or both windows. Introducing t_d and t_ℓ as the detector and lamp-side window transmissivities, respectively, the intensity measurements can be written as

$$\begin{aligned}
 M_{L+F} &= K_1 t_d \left[\frac{\alpha_1 + z\eta}{\alpha_1 + \eta E} B_1(T_g) (1 - e^{-\tau_1}) + J_1 \right] + K_1 t_d t_\ell I_1(0) e^{-\tau_1} \\
 M_F &= K_1 t_d \left[\frac{\alpha_1 + z\eta}{\alpha_1 + \eta E} B_1(T_g) (1 - e^{-\tau_1}) + J_1 \right]
 \end{aligned}
 \tag{35}$$

The transmission losses will not be a function of wavelength except perhaps for the most unusual case of deposition of an selectively absorbing material on the window, so no wavelength subscript is indicated for t_d and t_ℓ . Solving for the measured blackbody ratios and optical depths allows for inspection of the introduced error:

$$\Phi_1^m = \Phi_1 t_d \frac{1 - e^{-\tau_1}}{1 - t_\ell t_d e^{-\tau_1}}, \quad (36)$$

$$\tau_1^m = \tau_1 - \ln(t_\ell t_d), \quad (37)$$

and

$$\Phi_{1,2}^m = \frac{\tau_1^m \Phi_1^m - \tau_2^m \Phi_2^m}{\tau_1^m - \tau_2^m}. \quad (38)$$

The window transmissivities, t_d and t_ℓ , will vary individually from one down to zero as the window fouls becoming opaque, so as one or both of the windows foul the optical depth will increase and the single wavelength blackbody ratio will decrease. Fouling of the detector-side and lamp-side windows will each cause errors in the same direction for the single wavelength measurement of temperature that are additive. The error is greater for a transmission loss of the detector-side window but either gives a measured gas temperature that undervalues the true gas temperature as shown in Fig. 23 for $\tau_1 = 0.8$ and $\tau_2 = 0.2$.

Figure 23. Bias in Planck blackbody ratios for emission absorption measurements as a function of lamp- and detector-side window fouling.

In contrast the errors are in opposite directions for the two wavelength method; the two wavelength blackbody ratio will overvalue the gas temperature if the lamp-side window fouls and undervalue the temperature with fouling of the detector-side window. If both windows are fouled the error for the two wavelength technique lies somewhere between the two extremes

shown in Fig. 23. The error for both windows fouling is shown in Fig. 24. The two wavelength technique remains reasonably well-behaved down to 20% transmission, i.e. only 45% transmission through each window. The single wavelength technique shows significant error even at small transmission losses. The specific results depend upon the optical depth at the two chosen wavelengths.

Figure 24. Error contours in determining a Planck ratio of unity versus the transmissivities of the detector- and lamp-side windows for (a) one-wavelength measurement and (b) two-wavelength measurement.

Observations by this author over several years indicate that the most severe window fouling occurs during the combustor ignition. If the optical ports can be shuttered during these time periods, the fouling of windows is minimal. If the windows cannot be shuttered and the fouling occurs during the ignition, then simply recording post-test the effective blackbody lamp temperature through the fouled lamp-side window and the lamp signal through both fouled windows and using these in the calculations will essentially eliminate the error in either measurement method. This presumes that transmission is not reduced so as to seriously reduce the signal-to-noise ratio. The advantage of the two wavelength method arises when the fouling occurs throughout the test. In this case the systematic error from the indeterminate transmission losses is reduced by using the two wavelength method. One can put a limit on the error involved by measuring the window transmissivities after the test.

Figure 24 illustrates the effect of window fouling for the optical depths that are typically of measurements made in the laboratory or on the 20 cm diameter Mississippi State University test facility, $\tau_1 = 0.8$ and $\tau_2 = 0.2$. Measurements at the CDIF with heavy ash carryover and on the CFFF with a longer path length give significantly larger continuum optical depths so that error from a fouled lamp window is reduced for the single wavelength method. However, it is such particle-laden conditions that cause considerable error in the single wavelength temperature and number density methods and make the two wavelength methods preferable.

The increase in the measured optical depth with window fouling will directly introduce error in the single wavelength measurement of emitter number density; this technique requires an absolute measure of optical depth at a particular wavelength on the resonance line. In contrast, the two-wavelength method will cancel the broadband error in the optical depth, leaving only the error that arises in the temperature measurement and even this bias is reduced by the square root relationship. As long as there is some lamp light transmitted across the flow, window fouling will not introduce bias into the two wavelength measurement of emitter atom number density.

Optical Misalignments. Emission absorption measurements require collection of a transmitted lamp signal eliminating light collection from any section of the flame that has not been transilluminated by the lamp. Problems in maintaining an optical alignment over long path lengths and on sometimes severely vibrating facilities can be considerable. On large-scale combustion facilities slowly varying shifts in alignment will have an insignificant effect on the emission signal but potentially will cause a loss of transmitted lamp signal affecting the emission absorption measurements in just the same way as lamp-side window fouling does. Careful selection of the optical elements and mounts can reduce this problem and if access to the optics is available during testing, such shifts can be corrected for as they occur and for this author such problems have been minimal. However, the problem of rapidly fluctuating misalignment of the lamp image seems to have arisen in the CDIF CFC-15 Test and presented here is an analysis of how a harmonic alignment problem effects bias and uncertainty in emission absorption measurements. If lamp misalignment occurs through beam steering caused by rapid pressure fluctuations in the flow or by vibration of the optical mounts then a harmonic oscillator treatment would be an appropriate model for analysis of the problem.

The analysis here is specific for the optical elements of the PEAS instrument but the treatment could be generalized to other optical configurations. A tungsten lamp with a 2 mm wide strip filament is used as the reference lamp and on the opposite side of the hot flow a 1 mm core diameter fiber is used for light collection and transmission back to a monochromator and detector, in this case a vidicon detector. The fiber tip is carefully centered on the lamp image, leaving 0.5 mm of the lamp image on either side of the fiber tip for 'grace' and this optical arrangement has been used successfully for many tests. Fig. 25 shows how the effective lamp signal collection efficiency is reduced by displacement of the lamp image and also how the measured optical depth would increase due to the loss of lamp signal.

Using the results of Fig. 25 and time-averaging over the harmonic displacement cycle reveals how the misalignment will affect measurements. Figure 26 shows how the time averaged lamp collection efficiency factor changes with vibration amplitude along with the standard deviation for averaging time-resolved measurements. Also shown is the average and standard deviation for the bias in the measured optical depth due to the vibration induced misalignment.

Figure 25. Lamp collection efficiency factor and optical depth increase versus misalignment between a 1-mm-diameter optical fiber and a 2-mm-wide lamp filament image.

Figure 26. Time-averages and standard deviations for lamp collection efficiency factor and optical depth increase versus harmonic amplitude of misalignment.

The PEAS has a time resolution for illumination of the lamp and emission signals of about 0.25 ms with a separation of 0.5 ms so that knowledge of the misalignment frequency would be required to determine whether the results would be described as time averaged or resolved. All of the spectral information is collected for the same time intervals. If the detection system time-resolves the vibration, which seems to be indicated, then a large population of individual measurements of collection efficiency and optical depth bias would yield average and standard deviations as shown in Fig. 26.

Writing the lamp collection efficiency factor as F , the time averaged transmitted lamp signal can be written in terms of the average of F and its standard deviation (averages are shown with overbars and standard deviations with δ)

$$\overline{M}_{L+F} = \frac{\alpha_1 + \eta}{\alpha_1 + \eta E} B_1(T_g) (1 - e^{-\tau_1}) + J_1 + (\overline{F} + \delta F) I_1(0) e^{-\tau_1} \quad (39)$$

and the expressions for measured optical depth and blackbody ratio can be written as

$$\tau_1^m = \tau_1 - \ln(\overline{F} \pm \delta F) \approx \tau_1 - \ln(\overline{F}) \pm \frac{\delta F}{\overline{F}} \quad \text{for } \frac{\delta F}{\overline{F}} \ll 1 \quad (40)$$

and

$$\Phi_1^m = \Phi_1 \frac{1 - e^{-\tau_1}}{1 - (\overline{F} \pm \delta F) e^{-\tau_1}} \quad (41)$$

Writing $\Phi_{1,2}^m$ in terms of these expressions allows for inspection of bias caused by the fluctuating misalignment in the two wavelength calculation of temperature. The optical depths are overestimated and Φ_1 and Φ_2 are underestimated with greater error at smaller optical depths, so that the two wavelength method overestimates the gas temperature as occurs with fouling of the lamp-side window.

The optical depth difference used in the number density calculation is

$$\tau_1^m - \tau_2^m = \tau_1 - \ln(\overline{F} \pm \delta F)_1 - \tau_2 - \ln(\overline{F} \pm \delta F)_2 \quad (42)$$

and will be reasonably accurate in spite of the oscillating misalignment if the transmitted lamp signals for the two wavelengths are collected over the same time interval.

The averages of a large set of time-resolved measurements are as follows for optical depth and blackbody ratio:

$$\tau_1^m = \tau_1 - \overline{\ln(F)} \pm \delta[\ln(F)] \quad (43)$$

and

$$\Phi_1^m = \Phi_1 (1 - e^{-\tau_1}) \left[\frac{1}{1 - \overline{F} e^{-\tau_1}} \pm \delta \left(\frac{1}{1 - \overline{F} e^{-\tau_1}} \right) \right] \quad (44)$$

These expressions also predict that the optical depths are overestimated and Φ_1 and Φ_2 are underestimated with greater error at smaller optical depths. Single wavelength measurements, then would underestimate the gas temperature and overestimate the emitter atom

number density. In contrast, the two wavelength $\Phi_{1,2}^m$ will measure high as shown earlier for fouling of the lamp-side window.

The optical depth difference for the two wavelength number density calculation is then

$$\tau_1^m - \tau_2^m = \tau_1 \pm \delta[\ln(F)]_1 - \tau_2 \mp \delta[\ln(F)]_2 . \quad (45)$$

If the transmitted lamp signals for the two wavelengths are collected over the same time interval, then the number density calculation will be accurate in spite of the oscillating misalignment and with no appreciable increase in uncertainty. This is the case for the PEAS instrument measurements since all of the transmitted lamp spectra is collected as multiwavelength data from the same time exposure.

CDIF 89-CFC-15 Results. Figure 27 plots as a function of time the optical depth at the on-line wavelength and the number of valid two-wavelength temperature calculations from a set of 50. When the magnet is energized, the optical depth decreases by about 0.6 and the number of valid measurements increases to typical numbers of 47-49. Both of these trends are consistent with a harmonic misalignment of the lamp beam that disappears with MHD operation of the channel. The preceding harmonic vibration analysis revealed that the uncertainty in optical depth bias is nearly the same as the average bias. So if the bias is about 0.6 then the uncertainty is on the same order and many of the data sets would be invalid since the typical optical depth difference used for selection of wavelengths is 0.5. Some of the data sets before this time show low optical depths and large sample sizes indicating perhaps no misalignment problem and a good measure of the gas temperature prior to energizing the magnet.

Figure 27. On-line optical depth and samples versus time for the CDIF 89-CFC-15 test.

Figure 28 shows the measurements of gas temperature versus time. If the bias is indeed caused by misalignment that bias the temperatures high, then the lowest averages recorded represent the best estimate of the true gas temperature. Indeed, reanalysis of the test data

discarding data sets where the off-line lamp transmission is less than 10% yields temperatures around 2350 ± 50 K during this non-MHD portion of the test. After power extraction begins, the measured temperatures drop to around 2300 ± 30 K. A heat transfer calculation predicts a gas temperature of 2350 K at this location in the diffuser during the MHD power extraction.⁴³

Figure 28. Measured average temperature versus time for the CDIF 89-CFC-15 test.

The optical depth after energizing the magnet is nearly as low as that observed at the beginning of the test, which suggests that there has been little fouling of the windows. The gradual climb in optical depth during MHD operation appears to be associated with an increase in potassium number density as argued below. At the end of the measurement span, the sudden increase in optical depth associated with a drop in samples indicates windows fouling.

Figure 29 shows the average temperature versus measured on-line optical depth for the MHD portion of the test. Looking first at optical depths below 2.2, temperatures calculated with the one wavelength method show a 50 K drop as the optical depth varies from 2.1 to 1.7. This trend is consistent with error introduced by the particle emission, absorption, and scattering effects that cause the one wavelength method to underestimate the gas temperature with greater error at lower optical depth. Avoiding this bias is the reason for using the two wavelength method on particle laden flows. The two wavelength results show greater spread corresponding to an increased measurement uncertainty but are independent of optical depth as expected. From this plot it is apparent that window fouling has not occurred before the last three data sets and therefore the trends observed with the two wavelength temperature and number density measurements reflect true changes in the flow. While the trends in the single wavelength results also include particle bias and so are more difficult to interpret, the emitter number density increase during this time span causes the one wavelength method to over predict the temperature rise.

Figure 29. Temperature versus optical depth during MHD power extraction of the CDIF 89-CFC-15 test.

Measured optical depths greater than 2.2 all occur at the end of the measurement span and are consistent with the window fouling analysis presented in this paper. At the greatest optical depth, which is for the last recorded measurement, the one wavelength temperature has dropped by over 150 K nearly twice that for the two wavelength calculation. This is consistent with fouling of the detector-side window.

Now to address the anomalous temperature fluctuations before power extraction. Figure 30 plots the measured temperatures as a function of the off-line optical depth for the non-MHD portion of the test. The data sets for optical depths of 1.5 and below are measurements at the start of the test and appear unaffected by lamp misalignment. For the remaining sets, the single wavelength temperature results show a decrease of about 100 K in temperature with an increase in optical depth of about 2.0. The measured two wavelength temperatures show an increased uncertainty with the higher optical depths and a trend toward higher temperatures. The temperature increase is at least 200 K; however, the sets with high measured optical depths correspond to small sample sizes, so the trend in temperature is difficult to quantify. These general trends are consistent though with a fluctuating lamp misalignment, a consequent bias in the measured optical depths and temperatures, and indicate a fairly large vibration amplitude.

Figure 31 shows the calculated potassium atom mole fraction for the one and two wavelength diagnostic methods. The consistent offset between the two results is the bias introduced into the single wavelength measurements by particle cloud absorption, leading to an overestimation in mole fraction of about 0.004. For the period before energizing the magnet, the single wavelength results are predicted by the harmonic misalignment analysis to be even higher because of the bias in the optical depth and indeed this is reflected in the large mole fraction which drops as the magnet is energized. Indeed the lack of appreciable change in the standard deviation of the two wavelength atomic density as shown in Fig. 22 is consistent with time resolving the fluctuating misalignment.

Figure 30. Temperatures versus optical depth during the non-MHD portion of the CDIF 89-CFC-15 test.

Figure 31. Measured average potassium number density versus time for the CDIF 89-CFC-15 test.

At the end of the measurement period, as the windows are fouling, the one wavelength calculation of density is near constant while the two wavelength measurement shows a steep decrease. This is consistent with bias in the one wavelength method offsetting a true decrease in the atomic density as shown by the two wavelength results. The drop in seed density begins in advance of the log note stating that the seed flow was in manual mode and the later note that the seed flow was steadily dropping. It is not inconceivable that changes in control of the facility that led to manual seed control were what caused the fouling of the windows.

In contrast and based upon the analysis presented here, the trends in the two wavelength calculations should be real since the method is unaffected by either problem since the measurement technique depends upon differences in optical depth canceling out window transmissivity and misalignment induced biases. The results show a near steady value at a mole fraction of 0.004 that gradually doubles during the MHD generator operation before dropping at the end of the measurement period. Chemical equilibrium calculations predict a mole fraction of 0.0043 at a temperature of 2350 K for recorded test conditions at a time of 14:40 during generator operation while at that time emission absorption measurements yielded a potassium mole fraction of 0.0067 ± 0.0017 and a temperature of 2295 ± 31 K.

The anomalous two wavelength temperature measurements on this test have been explained by a rapidly fluctuating misalignment of the lamp image on the collection optics. A harmonic oscillator model was used to analyze the bias and uncertainty that arises from such a misalignment, although the source of the misalignment has not been identified. The very large temperature uncertainty in the two wavelength method arises because of the form of the equation that depends upon the difference in optical depths at the two wavelengths. The one wavelength method suffers bias but not the dramatically increased uncertainty. The one wavelength method could be considered preferable because of the smaller uncertainty, but using such a method there would have been no indication of the misalignment problem -- the observed lower temperatures and higher densities would have been presumed to be real.

Also presented was an analysis of the bias introduced by window fouling into the temperature and number density methods. The analysis reveals that the observed drop in potassium number density at the end of the measurement period is real. The misalignment fluctuations do not affect the two wavelength measurement of number density and the measured variations in number density for the test are presumably valid.

On particle-laden combustion flows where window fouling is a problem or on large-scale systems where vibrations and long path lengths exacerbate alignment problems, two wavelength time-resolved emission absorption techniques can provide accurate diagnostic measurements of atomic density. Such line-of-sight measurements because of their low-cost, reliable instrumentation and simple analysis, can provide robust monitoring of large-scale combustion flows.

Potassium Far Wing Absorption Profile.

The following is an excerpt from a journal article reporting on the experimental determination of the potassium D-line far wing absorption coefficient.⁴⁴ On small scale facilities, potassium emission absorption measurements can be made near line center where the absorption is well represented by a classical Voigt profile. However, the high seed loading, high particle density, and long optical path length of prototype scale experimental MHD facilities render the potassium D-line opaque near line centers and force emission absorption measurements to the far wing. Previous studies have shown that the alkali D-line far wings deviate from a Voigt profile for a variety of collisional partners.⁴⁵ Theoretical quasi-static models for far wing broadening have typically been at low pressures for alkali-rare gas systems.^{46,47} At this time, a theoretical model for potassium D-line broadening under MHD

conditions would be intractable because of the many collisional partners and the lack of accurate interaction potential curves and therefore such a model is best determined experimentally.

Vasileva, Deputatova, and Nefedov studied potassium emission in a torch as well as in the 20 cm diameter U-02 MHD facility.⁴⁸ They did not observe resonance broadening and concluded that the wings could be fit with power law profiles, the blue wing beyond 765 nm with an exponent -1.3 and the red wing with an exponent of -1. Goodwin and Mitchner studied the red wing in light of heat transfer effects and concluded that the absorption coefficient is a function of temperature and found an exponent in the far red wing of -1.5.³⁵ Im and Ahluwalia also studied the potassium D-line absorption coefficient determined by Vasileva, et al. and proposed a model profile to use for calculating radiant heat transfer in MHD facilities.⁴⁹

In light of the need for a model including wavelength and temperature dependencies that would be suitable for automatic seed atom density measurements and the desire to work in the blue wing where there are no interfering lines and detector responses are better, we have reinvestigated the potassium D-line far blue wing. A requirement for a suitable model is a relationship between the absolute absorption at particular wavelengths and temperature. The previous work has fairly well defined the shape of the profile, but the work by Goodwin and Mitchner suggests a strong temperature dependence for the red wing.

The general method used to develop the model exponent is very similar to that used by Vasileva et al.; however, a regression fit to an intensity model including self-absorption and blackbody effects was used (rather than their iterative method). The regression fit also included adjustments of the wavelength for matching the power-law profile to a Voigt profile. The model was tested with good results by application to profiles on larger scale MHD experimental facilities: measured number densities using the profile agree well with chemical equilibrium calculations. The model combined with time-resolved multiwavelength emission absorption measurements should allow for the first time accurate monitoring of MHD seed-atom loading on large-scale facilities through a nonintrusive diagnostic technique.

Using a power law matched to a Voigt profile in the near wing to model the potassium D-line blue wing, the model absorption coefficient is expressed as

$$\alpha_{\lambda,P} = \frac{(1/\lambda - 1/\lambda_0)^m}{(1/\lambda_m - 1/\lambda_0)^m} \alpha_{\lambda_m,L} \quad (46)$$

Here m is the power law exponent and λ_m is wavelength at which the Voigt and power law profiles match and λ_0 is the line center wavelength. This model predicts that the temperature dependence of the absorption coefficient per atom at a particular wavelength will vary as one over the square root of temperature. For temperatures of interest in an MHD channel or diffuser, 2300 to 2800 K, this corresponds to a nearly constant behavior with temperature.

Figure 32 shows how various power law exponents affect the model shape of the potassium "blue" wing absorption coefficient.

Figure 32. Potassium D-line far wing absorption coefficient for model power laws.

Figure 33 shows the potassium D-line profiles recorded on the MSU test facility with oil-fired combustion seeded at 0.5 and 1% potassium by weight.^{39,50} The flow diameter was 20 cm and the pressure about 1.1 atm. This combination of size and loading fortuitously provided D-line profiles that were strong enough to study the far wing while still not opaque in the near wing. A spectral scan of a potassium lamp showed that the instrument resolution was about 0.1 nm, adequate for this study.

Figure 33. Atomic potassium emission profiles from seeded oil-fired combustion products. The flow diameter was 20 cm and the seed loadings correspond to 0.5 and 1% potassium by weight.

The profiles generally resemble those observed by Vasileva et al.⁴⁸ and in the red wing the observations of Goodwin and Mitchner.³⁵ Later experiments at higher temperatures, using a different combustor to provide oxygen enrichment, yielded more exaggerated wings. A

reanalysis indicates that all the experimental lineshapes can be fit reasonably with a single profile, adding for the later anomalous experiments a background luminosity. A spectral scan of the flame without seed loading at the start of the two experiments shown in Fig. 33 showed no significant background.

Figure 34 illustrates the model profile for the 1% seed loading case as shown in Fig. 33. This model was found by first least squares fitting the central line region (765-767 nm) to a Voigt profile integrated over a model boundary layer flow.²⁹ Such a method has been suggested by Hommert and Viskanta^{51,52} to be accurate to within 3% for determining gas temperature. Secondly, the core gas temperature found by fitting was corrected for the boundary layer effects using the method of Onda¹⁰ to provide an average gas temperature for an accurate Voigt profile for the near wings. For the 6 lb/hr case the corrected gas temperature was 2295 K. Finally, a regression analysis was used to fit the far-wings to a power-law profile matched to the Voigt profile at a position on the near wings.

Figure 34. Blue wing potassium D-line emission from the MSU test facility (6 lb/h case) and model profiles: a Voigt profile (lower line) and a power-law profile of exponent - 1.07 matched to the Voigt profile at 764.6 nm (smooth line through the experimental data).

Table 4 gives the results for the two cases shown in Fig. 33 and shows the reasonable agreement between the fitting results and chemical equilibrium calculations. Also the close agreement in the regression fit between the two seed loadings implies that self-broadening is not important; although, two seed loading is not a valid test, this confirmed to our satisfaction the results of Vasileva, Deputatova, and Nefedov who studied the profiles over three orders of magnitude.⁵³

Table 4. Lineshape fitting results compared to chemical equilibrium calculation predictions.

Test condition	Test Seed 1A	Test Seed 1B
Seed loading, lb/h	3	6
Boundary layer model results for line center		
Core Temperature, K	2295	2314
Wall Temperature, K	1922	1882
Boundary width, cm	1.7	1.2
Profile exponent	2	2
K mole fraction	0.0046	0.0090
Chemical equilibrium calculations		
K mole fraction	0.0059	0.0118
Regression fit of far wing, 740-760 nm		
Exponent, m	-1.086 ± 0.04	-1.063 ± 0.015
Match point, λ_m	764.60 ± 0.14	764.40 ± 0.06

The absorption coefficient model was determined for temperatures around 2300 K. By matching the far wing model to a Voigt profile, the model predicts a slowly decreasing absorption cross section per atom, α_λ/n_K , with increasing temperature. An excellent comparison is found for the model absorption cross section at 759.5 nm and the measurement at 2050 K by Vasileva et al.⁴⁸

To validate the absorption coefficient model, emission absorption measurements of temperature and atomic number density were made on larger scale flows and the results compared to chemical equilibrium calculations. Various emission absorption techniques have been utilized for nonintrusive measurements of seed atom density in MHD flows, including such methods as integrated emission intensities,⁵⁴ width of the self-reversed line center dip,³⁷ single wavelength, wing emission absorption,¹⁰ and two wavelength, wing emission absorption.³⁴ On large scale facilities the potassium D-line is too broad to effectively utilize integrated measurements without interference from other lines as shown in Fig. 33. Without knowledge of the thermal profile across the optical path length, wing reversal emission absorption methods are the most generally applicable and on particle-laden, coal-fired flows, two wavelength measurement are necessary to account for broadband absorption of the particles.³⁴

With a Voigt model for the absorption coefficient, the potassium number density can be found from measurement of the optical depth at a particular wavelength, τ_λ , as

$$n_K = \frac{\tau_\lambda \sqrt{T_g}}{a_2 a_\lambda L} . \quad (47)$$

On coal-fired combustion flows considerable error is introduced into such a single wavelength measurement by the particles in the flow (See below under particle-laden combustion). Spectrally resolved two wavelength measurements can eliminate the broadband

absorption and the out-scattering and considerable cancel the in-scatter error.⁵⁵ The equation then involves differences in both measured optical depth and the absorption coefficient,

$$\alpha_{\lambda_1} = \frac{\tau_{\lambda_1} - \tau_{\lambda_2}}{\left(\frac{\alpha_{\lambda_1}}{\alpha_{\lambda_1}} - \frac{\alpha_{\lambda_2}}{\alpha_{\lambda_1}} \right) L} \quad (48)$$

This is a measurement technique which has been used successfully on smaller scale MHD test facilities.³⁴ The error introduced into an absorption measurement of emitter density by a Voigt analysis is illustrated in Fig. 35 for various exponents of a power law. Also illustrated is the larger error for a single wavelength measurement. The potassium D-line on large-scale coal-fired MHD flows is nearly opaque out to 760 nm so a Voigt analysis on a non-Voigt shape will measure high by at least a factor of 2 and possibly more.

Figure 35. Multiplicative error introduced into the determination of potassium number density by applying a Voigt analysis to a non-Voigt lineshape.

Figure 36 illustrates the potassium D-line emission absorption profiles recorded on the U. S. Department of Energy Component Development and Integration Facility (CDIF) at the middle optical port of the diffuser test section. The optical path length at this position was 33 cm and the facility was burning Montana Rosebud coal with nominally 1.59% by weight potassium as a seed during the time in which this data was taken.

Figure 36. Potassium emission absorption spectrum from the diffuser of the CDIF.

Figure 37 shows calculation of the potassium number density from the data presented in Fig. 36 for two different methods: a two wavelength analysis using a Voigt profile, and a two wavelength analysis with the proposed power law model for the far wings. The optical depths used for the calculations were found at wavelengths of 740 nm and the wavelength shown on the abscissa. The choice of the first wavelength has a negligible effect on the results. Calculations with a single wavelength method (not shown) yield even greater number density values due to broadband particle effects.

Figure 37. Comparison of methods for calculating seed-atom number density from the CDIF emission absorption spectrum shown in Fig. 36.

The wavelength independence of the power law profile results is indicative of the accuracy of this model for the blue potassium far wing. The results do show decreased number

density at wavelengths longer than about 758 nm; however, this is due to boundary layer error. In the wings, the emission profile is very nearly that due to the hot core flow of a boundary layer flow, but at larger optical depths (i.e. nearer line center) the calculated results are averages across the flow.

Similar results are seen for the U. S. Department of Energy Coal-Fired Flow Facility (CFFF) as shown in Figs. 38 and 39. The optical path length in the diffuser where the measurements were made was 76 cm, double that of the CDIF, and the facility was burning Illinois #6 coal with potassium 0.83% by weight.

Figure 38. Potassium D-line emission absorption spectrum from the diffuser of the CFFF.

Figure 39. Comparison of methods for calculating seed-atom number density from the CFFF emission absorption spectrum shown in Fig. 38.

Table 5 shows that the for these two measurements, the agreement between the power law model results and chemical equilibrium calculations is very reasonable, within the ± 10 to 20% for such calculations. The pressures were taken from the facility reports and the temperature were found with the Potassium Emission Absorption System. The listed densities are the average and standard deviation of the results shown in Fig. 37 and 39 over the wavelength region 750 to 760 nm. The potassium far wing lineshape model seems to fit the observed spectra from the two prototype MHD facilities quite well and was programmed into the PEAS for automatic data analysis.

Table 5. Comparison between chemical equilibrium calculations and measured neutral potassium atom number density using a power-law profile for the far wing.

	CDIF	CFFF
Test condition		
Diameter, cm	33	76
Pressure, atm	0.885	0.95
Seeding, by mass	1.59%	0.83%
Emission absorption measurements		
Temperature, K	2540	2600
K mole fraction	0.0067 ± 0.001	0.0043 ± 0.0012
Chemical equilibrium calculations		
K mole fraction	0.0061	0.0035

Noncoincident Measurement Error

The multiwavelength potassium emission absorption system was successfully employed for measurements of temperature, seed atom density during numerous field tests in the subsonic diffuser test sections of two coal-fired MHD facilities, the Coal-Fired Flow Facility (CFFF) at the University of Tennessee Space Institute and the Component Development and Integration Facility (CDIF) in Butte, Montana.⁵⁶ The diffuser test sections provide the transition between the supersonic MHD channel and the radiant boiler. With optical access provided to the aerodynamic duct of the CFFF, a test section designed to simulate an MHD channel, for the first time emission absorption measurements have been made in the upstream of an MHD facility.⁵⁷ With large fluctuations in the flow properties at this location, it provides an extreme challenge for nonintrusive diagnostic measurements.

Three basic signals are needed for emission absorption measurements: emission, transmitted lamp, and a reference lamp. The reference lamp signal can be collected prior to the test; separating the other two signals is challenging and the method employed determines the system performance. Basic schemes depend upon either temporal or spatial separation. Previous reported techniques from other researchers with the potential of high speed time resolution include a knife wedge method⁵⁸ and a light polarization technique.⁵⁹ Both methods are impractical for measurements on large scale facilities as both require careful optical alignment and are especially sensitive to any vibration that may move the knife wedge or the polarizer.

Spatially-Resolved, Temporally Coincident Emission Absorption. Standard operation of the PEAS instrument relies upon temporal separation of the transmitted lamp and emission-only signals. Large standard deviations in the measurement uncertainties at this location led to the design and construction of a two-beam, spatially separated optical scheme for the instrument. The new scheme provided much improved measurements. This section excerpted from a published paper briefly compares the two different signal separation schemes, presents typical field test results, and demonstrates the ability to provide accurate measurements on high speed, turbulent flows.⁶⁰

In its typical configuration, the system uses a system of synchronized optical choppers and a vidicon multichannel detector to provide quasi-time resolved, spatially coincident emission absorption signals. The typical optical setup is diagrammed in Fig. 5 on page 18. The emission absorption signals are recorded on separate tracks of the vidicon detector -- a track consists of 500 channels of data. Each signal is an exposure of 0.5 ms and the signals are separated by 1 ms. It is important that the instrument provides time resolved spectra because of the nonlinear relationship between the intensities and the atomic density. With a temporal separation scheme, there is always a time delay between the emission signal and the transmitted lamp signal. For the emission absorption calculations the flame emission terms in these two signals are assumed to be the same and realistically they should be very close for the calculations to be valid.

Figure 40 plots typical emission absorption measurements in the CFFF diffuser using temporal separation of the signals. Lines showing plus and minus one measurement standard deviation are shown dotted while the solid line shows the average values. The standard deviations represent the instrument uncertainty combined with the true fluctuations in the flow. The standard deviations are about double that for the best instrument uncertainty as found experimentally on a stable benchtop flame. This indicates a reasonably small and acceptable instrument uncertainty for measurements in the diffuser.

Measurements in the optical test section of the aerodynamic duct shown below are from the LMF5 series tests on CFFF facility with Rosebud coal and a nominal primary stoichiometry of 0.85. The flow diameter is 12 cm and the measurement port is approximately 3 pipe diameters down from the coal-fired combustor. The flow pressure is estimated to be about 2 atm at the optical port location and the flow velocity is quite high (>1000 m/s). The flow is expected to be much more turbulent and to show greater fluctuations at this location closer to the coal-fired combustor as compared to the diffuser.

At the aerodynamic duct the optical access is limited to 1" windows with a large $f\#$ of 9. This limited access combined with a limited space for optics on rails in front of the windows, led to the choice of a collimated optical arrangement for the first measurements on the aerodynamic duct as shown in Fig. 41. Figure 42 shows measurements at the CFFF aerodynamic duct for temporal signal separation.

In spite of the noisy measurement results in the aerodynamic duct the PEAS instrument was able to provide useful measurements as shown in Fig. 43 for measurements of potassium number density at differing seed loading during the LMF5-F test. The general trends agree with the planned facility seed loading changes.

Figure 40. Measurements of temperature and potassium atom number density in the diffuser for the CFFF LMF5-C test. The solid lines plot the average of approximately 50 samples while the dotted lines plot plus and minus one standard deviation away from the average.

Figure 41. Optics for spatially coincident, temporally separate emission absorption signals.

Figure 42. Measurements of temperature and potassium atom number density in the aerodynamic duct of the CFFF for the LMF5-C test.

Figure 43. Potassium atom number density measurements in the aerodynamic duct of the CFFF for the LMF5-F test.

At the aerodynamic duct the flow velocity is quite high (>1 km/s) and the high potassium density measurement standard deviation was believed to be due to the non-coincidence of the exposures for the two separate signals, i.e. flame-emission and lamp transmission. Therefore, for later experiments the single beam optics were replaced with a two-beam optical arrangement for

spatially separate, but temporally coincident signal collection as shown in Fig. 44. A single optical chopper with a 5° opening was used with the two fibers-- each signal is an 0.5 ms exposure corresponding to a view of 50 cm or more of flow at a velocity of greater than 1 km/s. Considerable reductions in the measurement uncertainties were found with this new signal collection scheme as seen in Fig. 45.

Figure 44. Optics for spatially separate, temporally coincident emission absorption signals.

The beam diameters at the crossing in the center of the flow are about 1 cm, so the beams are essentially overlapped while traveling inside the flow volume, especially considering that the signals average light from about 50 cm of flow during the 0.5 ms exposures. A major possible source of systematic error is the scattering by ash/slag particle of lamp light into the flame-only beam. At the elevated temperatures of the aerodynamic duct, the particle loading is expected to be low and scattering is not expected to be a problem. This is confirmed by the low frequency of Doppler bursts recorded by the LDV system at this location.

The two beam optical scheme provides a standard deviation for the potassium number density of about 20%, a considerable reduction from the 50 to 100% for the temporal separation scheme, approaching the limits for a stable benchtop flame. The excellent agreement in average measured potassium density for the two schemes on different tests but with the same nominal conditions indicates that the temporal separation scheme does provide valid measurements in spite of the noise.

Figure 45. Measurements of temperature and potassium atom number density in the aerodynamic duct of the CFFF for the LMF5-G test.

Figure 46. Measurements of electron number density and conductivity in the aerodynamic duct of the CFFF for the LMF5-G test.

Figure 46 shows that with the lower standard deviations for temperature and potassium density, reasonable results are found for calculating the electron density and electron conductivity.

conductivity. These results were found using an estimated pressure of 1.78 atm. The calculations of electron conductivity are especially sensitive to any errors in pressure, so without a pressure measurement concurrent with the emission absorption measurements, the conductivity calculation can only be considered a rough estimate.

For a confined turbulent flame, the physical dimension of local equilibrium is limited by (not necessarily equal to) the smallest confinement size. Suppose that the smallest confinement dimension is d and the speed of the flow is v , then the time for a section of local equilibrium to fly by is less than d/v . This time is the upper limit allowed for collection of the flame emission and transmitted lamp signals in order to ensure that a temporal separation optical scheme will be valid. At the CFFF diffuser, the flow diameter is 76 cm and LDV measurements at the exit of the diffuser of the CFFF show the flow speed to be less than 100 m/s.⁶¹ Thus the local equilibrium characteristic time is about 7.6 ms which is well outside the 1-m/s signal collection delay for the temporal separation scheme. The one millisecond delay between the flame emission signal and the lamp plus flame signal is clearly not a problem for this location.

In contrast, at the aerodynamic duct the flow diameter is 12 cm and the average flow speed is approximately 1000 m/s, thus the local equilibrium time is about 0.12 ms. Also the flame is expected to be more turbulent at the aerodynamic duct than at the diffuser and considerable fluctuations in the flow parameters could and would be expected to occur during a 1 ms signal collection delay at the aerodynamic duct.

The two beam, spatially separated optical scheme improved the measurements considerably but not without tradeoffs. This optical setup requires greater optical access and an additional optical fiber, is more difficult to align, and the alignment is more difficult to maintain on a large scale facility with significant vibrations because of the low f# of the collimating lenses. However, the results clearly indicate that the coincident, spatially separate signal collection scheme is the solution for measurement in high speed, turbulent flows.

Model Analysis of Noncoincident Sampling. Winkleman and Giel studied the noncoincident sampling error in modified line reversal measurements and concluded that the large rapid fluctuations in MHD flow conditions will introduce significant error into the measurements.⁶² Their calculations assumed sequential collection of the multiwavelength signals. In our application of line reversal to MHD flows, we utilize multiwavelength detection so that all of the emission or absorption spectral information is collected from the same short time interval. The analysis given here studies the effect of noncoincidence on the averages and uncertainty from a sample of individual measurements collected in such a fashion.

To examine the effect of noncoincident sampling, Eq. 9 is rewritten in terms of the mean flow parameters Φ and τ with deviations from the mean in these parameters between the lamp-on and lamp-off signals.

$$\frac{I_{L+F}}{I_L} = (\Phi + \delta\Phi_L)(1 - e^{-\tau - \delta\tau_L}) + e^{-\tau - \delta\tau_L} \quad (49a)$$

$$\frac{I_F}{I_L} = (\Phi + \delta\Phi_F)(1 - e^{-\tau - \delta\tau_F}) \quad (49b)$$

Here the total extinction-to-absorption ratio term, $(\alpha_\lambda + \kappa\eta)/(\alpha_\lambda + \eta E)$ is assumed to be one and the in-scatter term is neglected. Experimental measurements on MHD flows support these simplifying assumptions.³⁴

To study the effects of fluctuations in the MHD flow on the measurements, the gas temperature and optical depth are both modeled as Gaussian distributions about the mean value. For temperature fluctuations, a distribution in the Planck blackbody ratio is

$$\Gamma(\bar{\Phi}, \sigma(\Phi)) = \frac{1}{\sqrt{2\pi} \sigma(\Phi)} \exp \left[\frac{-(\Phi - \bar{\Phi})^2}{2 \sigma(\Phi)^2} \right]. \quad (50)$$

Using the Wien approximation, the temperature deviation is related to the deviation in the Planck blackbody ratio by a factor of 7.5 for temperatures near 2500 K and wavelengths near the potassium D₂ line:

$$\frac{\delta\Phi}{\Phi} = \frac{C_2}{\lambda T} \frac{\delta T}{T} \approx 7.5 \frac{\delta T}{T}. \quad (51)$$

The mean Planck blackbody ratio and standard deviation are revealed by integration as

$$\langle \Phi \rangle = \bar{\Phi} = \int \Phi \Gamma(\bar{\Phi}, \sigma(\Phi)) d\Phi, \quad (52)$$

$$\langle \Phi^2 \rangle = \int \Phi^2 \Gamma(\bar{\Phi}, \sigma(\Phi)) d\Phi, \quad (53)$$

and

$$\sigma(\Phi) = \sqrt{\langle \Phi^2 \rangle - \langle \Phi \rangle^2}. \quad (54)$$

Similar expressions would describe Gaussian fluctuations in the optical depth so that $\tau = \bar{\tau} \pm \sigma(\tau)$.

Consider first the effect of a change in the flame temperature giving a variation of $\delta\Phi$ from the true average value for each of the transmitted lamp and gas emission-only signals. The measurement of optical depth will be biased as

$$\tau^{meas} = \tau - \ln \left(1 + (\delta\Phi_F - \delta\Phi_L)(1 - e^{-\tau}) \right) \quad (55a)$$

for

$$\delta\Phi_F - \delta\Phi_L < \frac{e^{-\tau}}{1 - e^{-\tau}}. \quad (55b)$$

An increase in temperature while sampling the emission signal compared to the transmitted lamp signal will bias the measurement of optical depth high as shown in Fig. 47.

Figure 47. Contour plot of the error in optical depth for fluctuations in the flame-to-lamp blackbody ratio.

The bias increases with optical depth and measurement is not possible when the fluctuation is large enough to give the logarithm of a negative number in Eq. 55a, so data rejection naturally limits the bias at high optical depths. Data rejection is significant only at large optical depths and for the values plotted in Fig. 47 is not invoked.

Modeling the temperature fluctuations in the two signals as independent Gaussian distributions allows for the calculation of the average as

$$\langle \tau \rangle = \iint \tau^{meas} \Gamma(\bar{\Phi}, \sigma(\Phi))_L \Gamma(\bar{\Phi}, \sigma(\Phi))_F d\Phi_F d\Phi_L \quad (56)$$

Similar calculation reveals $\langle \tau^2 \rangle$ and therefore measurement uncertainty $\sigma(\tau)$ found as the root mean square deviation.

The near symmetry for positive and negative temperature deviations leads to negligible biasing of the average values for a Gaussian temperature distribution of standard deviation of $\sigma(\Phi) = 0.05$ as shown in Fig. 48. The temperature fluctuations do however introduce a significant uncertainty into the measurement increasing with the optical depth. Typically the measured optical depths are between 0.5 and 1.5.

With multiwavelength detection all of the spectral information from the emission signal is from the same time exposure, similarly for the absorption signal. Therefore temperature fluctuations will bias the two measured optical depths in the same direction with a larger bias at the greater optical depth. Figure 49 illustrates the bias and measurement uncertainty arising in measuring an optical depth difference of 0.7.

Figure 48. Bias and uncertainty introduced into an average measurement of optical depth by temperature fluctuations of $\sigma(\Phi) = 0.05$.

Figure 49. Bias and uncertainty introduced into a measurement of an optical depth difference of 0.7 by temperature fluctuations given by a Gaussian distribution with a standard deviation of $\sigma(\Phi) = 0.05$.

The bias is slightly increased in the two-wavelength calculations compared to the one-wavelength calculation. The uncertainty in the two-wavelength measurement is about the average of the one-wavelength measurements at the same optical depths. The measurement of atomic density from the measured optical depth difference will not be significantly biased by noncoincident sampling and fluctuations in the flow temperature.

Fluctuations in temperature will bias the measure of blackbody ratio as

$$\Phi^{meas} = \frac{\Phi + \delta\Phi_F}{1 + \delta\Phi_F - \delta\Phi_L} \quad (57)$$

Here fluctuations in the emission-only signal have little effect on the measurement while fluctuations in the transmitted lamp signal dominate the measurement. Figure 50 shows a contour plot of the error introduced into the measurement of Φ by a temperature deviation from the mean value during the transmitted lamp signal.

Figure 50. Error in measured blackbody ratio for temperature deviations from the average in the transmitted lamp signal.

Figure 51 illustrates the bias and measurement standard deviation in the measured Planck blackbody ratio for fluctuations in temperature described as a Gaussian distribution with a standard deviation of $\sigma(\Phi) = 0.05$. Here the uncertainty curve is purely that of a measurement uncertainty of 17 K. At $\Phi=1$, the bias in the measured temperature is less than 2 K. Doubling the fluctuations to $\sigma(\Phi) = 0.10$ increases the bias to about 5 K.

Figure 51. Bias and uncertainty introduced into an average measurement of Planck blackbody ratio by temperature fluctuations of 17 K.

With purely temperature fluctuations a two-wavelength measurement yields the same average value and uncertainty as the one-wavelength measurement since the measured Φ is independent of the optical depth. So the measurement uncertainty will just be that due to the real temperature fluctuations.

Now to consider optical depth fluctuations, such fluctuations can be either broadband arising from changes in the particle loading or properties or wavelength dependent arising from changes in the atomic absorption coefficient. In general the error in measuring a single wavelength optical depth will be given by

$$\tau^{meas} = \tau - \ln\left((1-\Phi)e^{-\delta\tau_L} + \Phi e^{-\delta\tau_F}\right). \quad (58)$$

Figure 52 illustrates the error in the measured optical depth caused by a 15% deviation from the mean value during the emission-only signal collection.

Figure 52. Error in optical depth introduced by an increase in optical depth of 15% during the sampling of the emission signal.

For most line reversal applications, the lamp temperature is chosen to be approximately equal to the expected flame temperature so that $\Phi \approx 1$ and deviations from the mean during the transmitted lamp signal will not affect the measured optical depth. For this case, $\tau^{meas} = \tau + \delta\tau_G$ and measurement of optical depth will reveal the mean optical depth and true fluctuations. Bias and uncertainty for 15% fluctuations in optical depth are shown in Fig. 53 for $\Phi=1.2$ and $\Phi=0.8$.

If the fluctuations are broadband, such as from particle loading changes, the introduced error will be independent of wavelength and a two-wavelength measurement of optical depth difference will cancel out the error revealing the mean optical depth difference and a measurement uncertainty which is just the level of fluctuations in the atomic absorption coefficient. Optical depth fluctuations due to particle loading will not bias two-wavelength number density measurements.

Figure 53. Bias and uncertainty introduced into a measurement of optical depth by optical depth fluctuations described by a Gaussian distribution with a standard deviation 15% of the mean.

Fluctuations in the atomic density will cause proportional fluctuations in the atomic absorption coefficient as $\delta\alpha_{\lambda_1}/\alpha_{\lambda_1} = \delta\alpha_{\lambda_2}/\alpha_{\lambda_2}$. At the reversal point, i.e., $\Phi \approx 1$, the measured optical depth difference will be

$$\tau_{\lambda_2}^{meas} - \tau_{\lambda_1}^{meas} = (\alpha_{\lambda_2} - \alpha_{\lambda_1})L \left(1 + \frac{\delta\alpha_{\lambda_1}}{\alpha_{\lambda_1}} \right) \quad (60)$$

so that the measured atomic density will reflect the true mean value and standard deviation. The results are only little changed for conditions away from the reversal point.

Figure 54 shows the bias introduced into an average measurement of optical depth difference 0.7 by 15% fluctuations in atomic absorption coefficient. The measurement standard deviation is for the same range of variable approximately 15%, i.e., $0.7 \times 0.15 = 0.1$.

Figure 54. Contour plot of the bias in the average measurement of an optical depth difference of 0.7 by fluctuations in the atomic absorption coefficient of 15%.

Optical depth fluctuations will also affect the measured Planck blackbody ratio as

$$\Phi^{meas} = \frac{\Phi(1 - e^{-\tau - \delta\tau_F})}{(1 - \Phi)(1 - e^{-\tau - \delta\tau_L}) + \Phi(1 - e^{-\tau - \delta\tau_F})}. \quad (61)$$

Close to the reversal point only the deviations from the mean in the emission-only signal will introduce error into the measurement of temperature. Figure 55 shows the fractional error in a measured $\Phi=1.2$ for an array of deviations. The plot would be similar for $\Phi=.8$ with just a change of sign for the errors.

Figure 55. Contour plot of the fractional error in a measured Planck blackbody ratio of 1.2 for optical depth deviations. Calculations was performed at $\tau=1$.

Figure 56 illustrates the negligible bias introduced in the measured Φ by a fluctuations in the optical depth described with a Gaussian distribution of standard deviation of 15%. The introduced measurement standard deviation is small, to a good approximation about 10 times the bias shown in Fig. 56.

With both changes in temperature and optical depth the measured optical depth can be written as

$$\tau^{meas} = \tau - \ln \left[(\delta\Phi_L - \delta\Phi_F)e^\tau + (1 - \Phi - \delta\Phi_L)e^{-\delta\tau_L} + (\Phi + \delta\Phi_F)e^{-\delta\tau_F} \right]. \quad (62)$$

Again, if fluctuations cause the emission-only signal to be greater than the transmitted lamp signal then the data set would be rejected. Fig. 57 shows that small deviations can lead to large errors in the measured optical depth.

The measured Planck ratio is given by

$$\Phi^{meas} = \frac{(\Phi + \delta\Phi_F)(1 - e^{-\tau - \delta\tau_F})}{(1 - \Phi - \delta\Phi_L)(1 - e^{-\tau - \delta\tau_L}) + (\Phi + \delta\Phi_F)(1 - e^{-\tau - \delta\tau_F})}. \quad (63)$$

Figure 56. Error introduced into the measured average blackbody ratio by optical depth fluctuations given by a Gaussian distribution with a standard deviation 15% of the mean.

Figure 57. Contour plot of the error introduced into a measurement of an optical depth of 1.0 by deviations from the mean in the Planck blackbody ratio and the optical depth during the emission-only signal.

Here deviations from the mean optical depth during the emission-only signal and from the mean temperature during the transmitted lamp signal will give the greatest error in the measured temperature. Figure 58 illustrates the error introduced by $\delta\Phi_L$ and $\delta\tau_F$ for $\Phi=1.2$ and $\tau=1.0$. The errors in measuring Φ are smaller than for those for τ for the same deviations.

Although these formulas are simple to write, the analysis of the fluctuations effect upon measurement is complicated because the temperature and optical depth fluctuations are most likely coupled and not independent. Deviations to higher temperature will likely increase the atomic potassium loading and hence optical depth as the potassium chemical equilibrium is

strongly a function of temperature. On the other hand deviations to higher temperatures is likely to decrease the particle loading since at higher temperatures more of the species will be in the gaseous state rather than liquid or solid.

Figure 58. Contour plot of the error introduced into a measurement of a Planck ratio of unity by deviations from the mean in the Planck blackbody ratio and the optical depth.

Looking at the errors shown in Figs. 57 and 58, it is clear that for independent or coupled deviations the near symmetry of the error will leave the average measurement near the true mean value of the flow. If the fluctuations are coupled then the measurement uncertainties could range from small to large depending upon the form of the coupling.

The most important result of the preceding analysis of noncoincident sampling is that the average two-wavelength measurements of temperature and optical depth are not significantly biased from the mean values of the flow. This is true even for large fluctuations in flow parameters between collection of the emission and transmitted lamp signals. This agrees with the experimental results showing a good match between the average atomic density results for noncoincident and coincident sampling. The slight bias between the average temperatures measured by the different methods may be due to test-to-test variations.

The analysis also indicates that purely temperature fluctuations will not introduce additional measurement uncertainty into the two-wavelength measurement of temperature. Since both the atomic density and temperature measurement uncertainties decreased substantially with coincident sampling this suggests that rapid fluctuations in optical depth must be important.

Broadband fluctuations in optical depth from rapid changes in the particle cloud properties will not introduce uncertainty in the measurement of optical depth so these fluctuations must arise from fluctuations in the atomic absorption coefficient. Fluctuations in only the atomic absorption coefficient will not introduce additional uncertainty into the two-wavelength measurement of atomic density. This suggests that temperature fluctuations are important in explaining the large atomic density uncertainties.

So fluctuations in both the temperature and the atomic absorption coefficient must have contributed to the increased measurement uncertainty during the LMF5-C test with noncoincident sampling. A more complete analysis of coupled fluctuations including data rejection would be necessary to determine whether the temperature bias between the two tests is explained by noncoincident sampling.

In conclusion, this preliminary analysis suggest that the large measurement uncertainties in the LMF5-C test may be explained by rapid fluctuations in flow parameters and noncoincident sampling. The time-resolved, spatially separated measurements clearly give better results and should be used for any further experiments in the upstream of an MHD flow. However, if optical access is not sufficient to allow for separate optical paths then these results demonstrate that temporal separation of the emission and absorption signals still provides valid average measurements.

Lineshape Fitting for Boundary Layer Information

Vitally important for accurate heat transfer and conductivity models of magnetohydrodynamic (MHD) flows is knowledge of the profiles of temperature and seed atom density in the thermal boundary layers of the flow. In the upstream combustor/channel components the fluctuations from typical flow conditions may also be significant. Such information can be provided by lineshape fitting multiwavelength potassium emission absorption spectra. The following is an excerpt from a previously published paper demonstrating the utility of such calculations.⁶³

Lineshape fitting is a standard tool for simultaneous measurement of temperature and specie number density, usually with the assumption of a homogeneous gas. Early work by Hommert and Viskanta demonstrated theoretically and experimentally the ability to determine temperature profiles to within 3% in hot ovens by inverting CO₂ emission spectra, concluding that such spectral remote sensing would be a useful and easily implemented high temperature gas diagnostic.⁵² Recent work by Vasileva et al. applied such a technique to the potassium emission from the natural gas fired U25BM MHD facility, comparing model calculations of temperature profiles to an inverse solution for potassium D-line emission.⁶⁴

A preliminary model and least squares fitting algorithm was reported previously showing example fits of potassium D-line emission absorption spectra from lower temperature MHD diffuser test sections.⁶⁵ Emission absorption at an atomic resonance line is the more general category for line reversal, a technique that has long been a simple, robust and nonintrusive diagnostic for MHD temperature measurements. The preliminary results indicated that fitting of emission only spectra could not unambiguously determine a temperature profile; however, with the addition of absorption spectra it is possible to recover a temperature profile and the bulk atomic density. Fitting absorption data as well as emission is necessary to account for the broadband particle effects. For a *clean* flow, i.e., one in which the optical depth is due entirely to the atomic absorption, fitting only the emission may be possible. With promising preliminary results and an excellent data set of time resolved emission absorption spectra from a simulated MHD channel, the fitting routine was automated and lineshapes from 10 hours of testing were fit and the results are reported here.

Potassium D-line spectra recorded on coal-fired MHD facilities are deeply self-reversed due to relatively cooler boundary layers surrounding the hot core flow. The actual shape of the line is a complicated path integral of the temperature and potassium number density with influences due to the pressure and composition of the flow in collisional broadening of the line and the broadband effects of particle scattering and emission/absorption. Solving the inverse problem of recovering the boundary layer profile by fitting the recorded spectral lineshapes to a model requires an accurate model of the potassium absorption coefficient and computation of the radiative transfer integral.

The D-line emission absorption spectra are modeled at each wavelength by an optical path integral across the flow as

$$I_{\lambda_1}(L) = e^{-\tau_L} \int_0^L (\alpha_{\lambda_1} + z\eta) B_{\lambda_1}(T_x) e^{\tau_x} dx + I_{\lambda_1}(0) e^{-\tau_L}, \quad (64)$$

where the optical depth is

$$\tau_x = \int_0^x (\alpha_{\lambda_1} + \eta E) dx'. \quad (65)$$

Here $I(0)$ is the incident lamp signal and $I(L)$ is the outgoing light from the flow at a path length of L . In scattering by particles is not included in the model. The emission only intensity is found by setting $I(0)$ to zero. The atomic absorption coefficient, α_{λ} , is a function of the path position x through its dependence upon temperature and density.

Broadband particle effects are included as ηE and $z\eta$, where η is the particle absorption coefficient, E is the particle extinction-to-absorption ratio, and z is the ratio of Planck blackbody functions at the particle temperature to the gas temperature at x as $z = B_{\lambda}(T_p)/B_{\lambda}(T_x)$. Scattering in by the particles is ignored. The particle cloud albedo is related to the E parameter as

$$\Omega_p = (E-1)/E.$$

The thermal boundary layer model chosen is that typical for turbulent flow and is given by

$$T = \begin{cases} T_w + (T_c - T_w) \left(\frac{x}{\delta} \right)^{1/N} & 0 \leq x \leq \delta \\ T_c & \delta < x < L - \delta \\ T_w + (T_c - T_w) \left(\frac{L-x}{\delta} \right)^{1/N} & L - \delta \leq x \leq L \end{cases} \quad (66)$$

where T_x is the gas temperature at position x , T_c is the core temperature, T_w is the wall temperature, δ is the boundary layer width, N is the boundary layer shape exponent, and L is the optical path length across the flow. For turbulent boundary layers N will typically be in the range of 7 to 10. The flow was assumed to be symmetric. The line-of-sight emission absorption spectra are not sensitive to the far boundary layer, so asymmetry in the flow cannot be studied with this technique. Figure 59 illustrates the thermal profile for a symmetric boundary layer flow.

Figure 59. Illustration of a temperature profile across a boundary layer flow.

A single parameter model for the potassium atom profile as a function of temperature was developed from chemical equilibrium predictions for conditions representative of the CFFF diffuser. In this model the number density is related to the density at the core temperature through an exponential function as

$$n_K(T_x) = n_K(T_c) \exp \left[- \left(1 - \frac{bT_c}{T_x^2} \right) \left(1 - \frac{T_x}{T_c} \right) \right] \quad (67)$$

For b equal to zero this model resembles an ideal gas law relationship, while much larger values model equilibrium chemistry, with a smooth transition between these two cases. Figure 60 illustrates this model for chemical equilibrium calculations for nominal conditions in the diffuser of the Coal-Fired Flow Facility: $b=12,200$ referenced to $T_c=2500$ K. The chemistry is only weakly a function of pressure and so this one parameter model should be valid for the aerodynamic duct as well.

Figure 60. Model curves of potassium density versus temperature compared to chemical equilibrium calculations.

Given the potassium mole fraction, the density is found from the flow pressure and the temperature at each position, and the potassium absorption coefficient is then calculated for each position across the flow. This coefficient is wavelength dependent and the model used for the absorption coefficient of the individual atomic lines of the doublet is that of power law profiles in the *red* and *blue* wings matched to a Voigt profile near line center.⁴⁴ The classical Voigt model combines Doppler and Lorentzian broadening as given by 18 on page 10. In the near wings the Voigt profile is essentially Lorentzian and can be approximated with Eq. 20 on page 11. The potassium D-line oscillator strengths and collisional cross sections can be found in tabulations by Radzig and Smirnov¹¹ and Hofmann and Kohn,¹² respectively.

The potassium line wings have been observed to deviate considerably from a Voigt profile and can be well fit with power law profiles.^{48,35} The far wings were modeled by a power law matched to a Voigt profile in the near wing as given by Eq. 46 on page 48. In the *blue* wings the match was made 2.3 nm from line center, i.e., $\lambda_i - \lambda_m = 2.3$ nm, with a power law exponent of $m = -1.07$, while in the *red* these values were 1.5 nm and -1.25. This model predicts that the temperature dependence of the absorption coefficient per atom at a particular wavelength will vary as one over the square root of temperature. For temperatures of interest in an MHD channel or diffuser, 2300 to 2800 K, this corresponds to a nearly constant behavior with temperature.

The lineshape fitting algorithm and preliminary results were reported previously. The fitting was accomplished using a Marquardt method nonlinear least-squares algorithm⁶⁶ on the following eight parameters: T_c ; T_w ; δ ; N ; the mole fraction of potassium atoms at the core temperature, $[K]$; b ; $z\eta$; and ηE . The initial values for T_c , $[K]$, $z\eta$, and ηE were found from a two-wavelength emission absorption calculation. The intensity factor was determined from the reference lamp signal at the D_2 line center wavelength (766.5 nm); the core temperature is correlated with the intensity multiplicative factor and cannot be determined from fitting unless this factor is fixed. The core temperature is typically adjusted only slightly during the fitting. The initial value for T_w was found by comparing the recorded D_2 line center emission intensity to that for a blackbody emitter. Initial guesses for δ , N and b were fixed at 2 cm, 7 and $12E+3$, respectively. The following parameter bounds were used in the calculation. These bounds were only rarely invoked and then almost always for T_w and N , lower and upper limits, respectively. The upper bound was occasional invoked on δ and for subsequent cycles δ was fixed as $L/2$.

Table 6. Parameter bounds used in lineshape fitting.

Parameter	Bounds
T_c	2000 to 3000 K
T_w	500 K to T_c
δ	0 to $L/2$
N	0 to 13
$[K]$	0 to 1
b	-1×10^4 to 1×10^6
$z\eta$	0 to 1
ηE	0 to 1

The potassium emission and absorption lineshapes were calculated numerically, using a trapezoidal integration of the optical depth and a Simpson's rule integration of the intensities. The Voigt function was approximated using the method of Humlicek.⁹ Assuming flow symmetry and integrating across only one boundary layer reduced computation time by half. Contributions from the exact solution for the core of the flow were added, then the lines were convoluted with a triangular function to approximate the detector bleed between channels that degrades the instrument resolution.

At each cycle a Jacobian matrix was calculated to provide the gradient to determine the step for the next iteration. The Jacobian was determined by numerical calculation of the derivatives using forward differences rather than central differences in order to save computational time. Also included in the fitting was minute adjustment of the wavelength scale by shifts and scale expansion. This was necessary because the fitting is sensitive to wavelength errors near line center and experimentally the scale could only be determined to within one channel, i.e., generally 0.06 nm. Fitting continued until the sum of the least squares changed by less than 0.1%, usually six cycles, or the number of cycles reached 12. Final values of the average deviation were typically two times the noise in the data.

At the aerodynamic duct the flow velocity is quite high (>1 km/s) and previous PEAS measurement showed considerable measurement standard deviation that was believed due to the non-coincidence of the exposures for the two separate signals, i.e., flame-emission and lamp transmission. Therefore, for this experiment the typical optics were replaced with a two-beam scheme for spatially separate, but temporally coincident signal collection as shown in Fig. 44. A single optical chopper with a 5° opening was used with the two fibers-- each signal is an 0.5 ms exposure corresponding to a view of 50 cm of flow at a velocity of 1 km/s. Considerable reductions in the measurement uncertainties were found with this new signal collection scheme.⁶⁰

Potassium emission absorption spectra were recorded over a period of about 10 hours in the aerodynamic duct of the U. S. Department of Energy Coal-Fired Flow Facility at the University of Tennessee Space Institute during the LMF5-G test on Sept. 29, 1992. The test conditions were nominally western coal with 1% potassium seed added as a 47% solution of potassium carbonate, 0.85 primary stoichiometry and 1.10 secondary stoichiometry.⁶⁷ The location of the optical ports⁵⁷ is approximately three diameters downstream from the combustor. At the location the flow diameter is 12 cm and the pressure is estimated as 1.78 atm. The results of the two-wavelength measurements are shown in Fig. 45 on page 59. The optical ports were closed during a period for adjustment of secondary combustion early in the test and the dip in temperature and number density between 12:23 and 12:30 corresponds to an interruption in the coal flow because of a plugged coal line. The results show an average gas temperature of just above 2500 K and a density of around $5 \times 10^{22} \text{ m}^{-3}$.

The recorded lineshapes show considerable variation as is shown in Fig. 61 for ten consecutive lineshapes recorded at 2 second intervals early in the test. The shape features can be clearly correlated with the temperature profile across the flow, e.g., center dip value with the wall temperature, shoulder shape with boundary layer width, etc. The extreme variation in lineshape illustrates the need for a time-resolved instrument and why it is appropriate to present results in the form of probability distributions as is done here rather than simple averages.

Figure 61. Example potassium lineshapes from the CDIF aerodynamic duct during the LMF5-G test.

The model and least square algorithm were able to fit virtually all of the recorded 6006 lineshapes. Two example fits are shown in Fig. 62 and 63. The first, (File 90, scan 15) shows sharp shoulders and steep center dips that fit to a narrow boundary layer while the second (File 90, scan 18) shows broad shoulders and is fit to nearly merged boundary layers. The final fit parameters are given for both in Table 7.

Table 7. Fit parameters and estimated uncertainty limits for example lineshapes.

Parameter	File 90/15	File 90/18
T_c (K)	2540 ± 1	2648 ± 16
T_w (K)	1604 ± 213	902 ± 223
δ (cm)	0.31 ± 0.07	5.0 ± 1.1
N	3.1 ± 1.6	9.7 ± 1.1
$[K]$	0.0094 ± 0.0005	0.0099 ± 0.0012
b	20300 ± 5500	3281 ± 1827
$z\eta$	0.013 ± 0.006	0.012 ± 0.004
η E (/cm)	0.028 ± 0.006	0.023 ± 0.004

Estimates of the parameter uncertainties were found from the parameter space curvature matrix. Estimating the uncertainties by searching for a doubling in the sum of the square deviations gives roughly similar uncertainties and was only performed for only a few spectra because of the excessive time required. Table 8 gives the correlation matrices for these two example fits.

Figure 62. Example lineshape fit for a narrow boundary layer: file 90, scan 15.

Figure 63. Example lineshape fit for a wide boundary layer: file 90, scan 18.

Table 8. Parameter correlation matrices for example lineshape fits.

90/15	T_c	T_w	δ	N	n_K	b	$z\eta$	ηE
T_c	1							
T_w	-.32	1						
δ	.09	.39	1					
N	.26	-.86	-.79	1				
n_K	-.52	.36	.53	-.61	1			
n_K	-.10	.51	.97	-.88	.69	1		
$z\eta$	.65	-.13	.04	.17	-.80	-.15	1	
ηE	.72	-.15	.05	.17	-.79	-.14	.99	1

90/18	T_c	T_w	δ	N	n_K	b	$z\eta$	ηE
T_c	1							
T_w	-.20	1						
δ	.98	.32	1					
N	.19	-.94	.34	1				
n_K	-.83	-.15	-.84	-.01	1			
n_K	.14	-.81	.18	.56	.38	1		
$z\eta$	-.30	.74	-.31	.47	-.25	-.98	1	
ηE	-.38	.81	-.45	-.60	.09	.94	.94	1

Results for the core temperature are shown in Fig. 64 as a sample population distribution for the total of 6006 fitted lineshapes. The values are sharply peaked about 2550 to 2575K with an average value of $2527 \pm 77K$. Some of the lower temperature values correspond to a momentary interruption of the flow and to periods of instability thus biasing the average temperature slightly low. The peak values are well fit with a Gaussian distribution centered at 2563K with a standard deviation of 20K.

Figure 64. Sample distribution for the core temperature in the aerodynamic duct.

The wall temperatures showed wide fluctuations that are most likely not meaningful because of the steep slope of temperature versus position curve near the wall ($x=0$) for large values of N . Integrating the temperature profile for x from 0 to 0.5 mm with a Planck blackbody averaging provides a physically reasonable result for the temperature near the walls as shown in Fig. 65. The distribution is broadly peaked about values between 1975 and 2000K. A Gaussian fit to the peak values gives 1995 ± 135 K.

Figure 65. Sample distribution for the near wall temperature found as an average over 0.5 mm.

The sample distributions for the boundary layer width and shape are shown in Figs. 66 and 67. The boundary layer width shows a most probable value between 0.25 and 0.50 cm. Occasionally larger values are also seen, approaching half the width of the flow, indicating conditions of merged boundary layers. An average of all of the values gives a width of 1.2 ± 1.2 cm. Although the thermal profile shape exponent is only loosely determined, the average value of 6 ± 3 is close to the expected values of between 7 and 10 for a turbulent flow. The most probable values are around 7.

Figure 68 illustrates the average spatial distribution of temperature found by averaging the individual temperature profiles. This average is equivalent to a temporal average as would be found by a spatially resolved diagnostic and shows that with the large fluctuations in the flow parameters the average boundary layer width is about 2 cm. At this same location and under similar conditions, the velocity profile measured by laser velocimetry with a spatial precision of 0.5" indicates a velocity boundary layer width of about 1".⁶⁸ Attempts using a coherent anti-Stokes Raman spectroscopy system to determine the boundary layer temperature profile were unsuccessful because of a large interaction volume.⁶⁹ Although the most probable results indicate that the thermal boundary layer width is quite thin, in agreement with the model calculations, there are enough fluctuations to wide boundary layers that only a time resolved technique will accurately reveal the thin boundary layer width.

Figure 66. Sample distribution for the thermal boundary layer width.

Figure 67. Sample distribution for the thermal boundary layer shape.

Rather than the core flow temperature, an average temperature may provide the best comparison of these fitting results to one-dimensional model calculations of an MHD flow temperature. The line-of-sight average temperature should read slightly low due to the cooler boundary layers surrounding the flow.^{10,29} Averaging the thermal profiles as

$$e^{-C_2/\lambda\bar{T}} = \left(1 - \frac{2\delta}{L}\right)e^{-C_2/\lambda T_c} + \frac{2}{L} \int_0^\delta e^{-C_2/\lambda T_x} dx \quad (68)$$

gives an average flow temperature, $\bar{T}$, which should compare well with the two-wavelength measurements. The sample population distribution for such an average is shown in Fig. 69. Overall the average temperature is 25K lower than the core temperature because of the cooler boundary layers.

Figure 68. Average temperatures and standard deviations versus spatial position.

Figure 69. Sample distribution for the average temperature of the flow.

The results for the potassium number density at the core temperature are shown in Fig. 70. The neutral potassium atom density is predicted to be on the order of $5 \times 10^{22} / \text{m}^3$ in the core flow, in excellent agreement with the PEAS instrument two-wavelength measurements. The few samples of much lower value correspond to the portion of the test with an interruption of the coal flow.

Figure 70. Sample distribution for the bulk potassium atom density.

Shown in Fig. 71 are the fitting results for the atomic density profile constant, b . The profile constant is only weakly fit and the results may not be meaningful; the few preliminary fits on diffuser data indicated that only the bulk potassium density could be determined with any certainty. The most probable value for b is between 15,000 and 17,500 while the average value is $17,900 \pm 12,500$. This is a weak indication of a density distribution in the boundary layer that follows chemical equilibrium predictions. Many spectra fit to near zero or negative b with small uncertainty, which would indicate a greater number density near the walls than in core flow. These results may not be unreasonable in that these lower values are loosely correlated with lower values of the potassium density in the core and so may represent instances of time where potassium seed flow is reduced and the source of potassium is leaching from the walls.⁷⁰

Figure 71. Sample distribution for the potassium density profile constant b .

The particle parameters, $z\eta$ and ηE were quite variable due to large fluctuations in the particle loading. Figure 72 shows the distribution for ηE . The average of all the samples gives 0.04 ± 0.03 /cm. With a path length of 12 cm and a most probable value of 0.05, the average particle contribution to the optical depth, ηEL , was about 0.6, a value that reduces the transmitted lamp by half across the entire optical path length of the flow. Though the particle extinction showed a wide fluctuation, the particle E/z ratio clearly showed a most probable value between 1.25 and 1.50 as shown in Fig. 73. The overall average was 1.5 ± 0.5 . The sharply peaked distribution for E/z and correlation between E/z and $z\eta$, suggests that fitting E/z would be a better choice than $z\eta$.

Figure 72. Sample distribution for the particle cloud contribution to the optical depth.

Figure 73. Sample distribution for the particle extinction-to-absorption ratio, E/z .

Model calculations predict very little particle scattering at these temperatures and this is supported by the low frequency of signal bursts recorded by the forward scatter laser velocimeter system at this location in the aerodynamic duct. If the scattering is small, then E would be expected to be close to 1. If this is true then the slightly higher value of E/z arises from a particle temperature lower than the gas temperature. For values of z of 1/1.25 and 1/1.5, this would correspond to particles that are lower than the gas temperature by about 70K and 130K, respectively.

The previous figures show results for the entire 10 hours of data collection. If instead averages and standard deviations are computed for subsets of lineshapes over time intervals of a few minutes, then the results follow the PEAS results (Fig. 60), as would be expected. For example, Fig. 74 shows the core temperature probability distribution for a portion of the test that appears to be very stable according to the PEAS results while Fig. 75 shows similar results for a portion where the PEAS system indicates a drop in average temperature with an increase in standard deviation. The median core temperature is clearly unchanged for these two subsets, the difference is the presence of spectra with much lower core temperatures. Occasional spectra with much lower core temperatures are present throughout the test but occur more often for the portions of the test that appear as temperature drops in the PEAS results.

Figure 74. Sample distribution for the core temperature during a particularly stable portion of the test.

During the unstable portions of the test there is a clear correlation between the core gas temperature and the particle parameter E/z as shown in Fig. 76 for the early portion of the test data. Values with high values of E/z would seem to be associated with much lower particle temperatures. These lower temperatures may be associated with the *rumble* reported by Winkleman and Lineberry and believed to be due to periodic entrainment of slag into the flow from the CFFF 100% carry over combustor.⁷¹ A much higher particle loading with lower particle temperatures would bias a line reversal reading to a lower temperature.

Figure 75. Sample distribution for the core temperature during an unstable portion of the test around 13:45 as evidenced by the PEAS measurement indicating a drop in temperature and an increase in the temperature uncertainty.

Figure 76. Particle extinction-to-absorption ratio versus the average gas temperature for the early portion of the test data prior to adjustment of secondary combustion.

At the other end of the curve, low values of core temperature are correlated with low values of E/z . As E cannot be less than one, these low values must be associated with large values of z which implies high particle temperatures. This is not an unreasonable result, as it could be explained by a flame-out condition in the combustor with hot, burning particles present in the optical path across the aerodynamic duct. Combustion models do predict that particle temperatures may exceed gas temperatures. A model study of the effect of nonequilibrium particle temperatures predicts only moderate impact on channel performance.⁷²

The results presented here demonstrate the viability of lineshape fitting emission absorption spectra to provide valuable information about the thermal profiles in turbulent, high temperature boundary layer flows. The technique is robust and requires only limited optical access compared to spatially resolved optical techniques. The fitting results for core temperature and bulk potassium density are in good agreement with model predictions and the two-wavelength calculations: 2563 ± 20 K and $(5.1 \pm 0.8) \times 10^{22} / \text{m}^3$, respectively. The near wall temperature showed slightly greater fluctuations, 1995 ± 135 K. The large fluctuations in lineshapes due primarily to fluctuations in the boundary layer width and shape. Although the most probable boundary layer width was found to be very thin, 0.25 to 0.5 cm, there are excursions to wider boundary layers with even occasional predictions of what would be fully merged boundary layers for a symmetric flow.

Of interest for accurate radiative heat transfer models in the channel may be the in-situ measurements of the particle cloud extinction-to-absorption ratio. Work by Mengüç and Viskanta predicts that scattering of a fly-ash cloud impedes radiant heat transfer from the core flow to the walls and is strongly a function of temperature. The potassium radiation contributes strongly to the radiant heat transfer³⁵ and these results should be of interest to modelers.

PERFORMANCE EVALUATION

The Potassium Emission Absorption System has been well utilized for field test measurements at the CDIF and CFFF MHD facilities from 1986 to 1993. Table 9 on the following page lists the field tests for which PEAS measurements were made. The development of the system was on-going throughout this period with the experiences gained in application of PEAS to these prototype scale MHD flows. No attempt has been made to include all of the test results in this report; however, scattered throughout the report and in the section *Additional Examples of PEAS Measurements* on page 93 enough test results have been included to indicate the worthy performance of the instrument and its usefulness in supplying data to support the development of MHD power systems. The instrument certainly met design requirements of measuring temperature and potassium density. With the final tests at CFFF in the aerodynamic duct, measurements of electron density and conductivity were also demonstrated. The conductivity measurement depends upon the flow pressure which was not available at that time, so the conductivity measurements cannot be viewed as absolute measures but as good relative measures of variation of the MHD fluid conductivity during the tests. Please refer to Fig. 46 for a plot of the LMF5-G conductivity measurements.

Temperature Measurement Accuracy and Uncertainty

The accuracy of the line reversal temperature measurement is fundamentally that of the accuracy of the measured effective lamp temperature. Please refer to Appendix 2 for the method by which the lamp temperature is determined by pyrometer measurements. The uncertainty in the effective lamp temperature will be to a good approximation twice the uncertainty in each individual pyrometer measurement. The uncertainty in the filament temperature depends upon the uncertainties in the temperature measurement, δT_{red} , the red filter wavelength, $\delta \lambda_{red}$, the optical transmission coefficient, δt_{optics} , and the tungsten emissivity, $\delta \epsilon$. Treating these as independent errors the uncertainty in the filament temperature is

$$\frac{\delta T_{fil}}{T_{fil}} = \left[\left(\frac{\delta T_{red}}{T_{red}} \right)^2 + \left(\frac{\delta \lambda_{red}}{\lambda_{red}} \left(\frac{1}{T_{fil}} - \frac{1}{T_{red}} \right) \right)^2 + \left(\frac{\lambda_{red}}{C_2} \right)^2 \left(\left(\frac{\delta t_{optics}}{\epsilon(\lambda_{red}, T_{fil})} \right)^2 + \left(\frac{\delta \epsilon(\lambda_{red}, T_{fil})}{t_{optics}} \right)^2 \right) \right]^{\frac{1}{2}}. \quad (69)$$

Typical operation of the lamp for high temperature flows is between 18 to 21 A, giving measured *red* temperatures in the 2400 to 2600 K range. The pyrometer measurements are accurate to ± 10 K in this range. This leads to an uncertainty in the finding the filament temperature of about 1%, i.e., $T_{fil} \approx 3200 \pm 32$ K. With only one intervening optical element, the uncertainty in $T_{red,c}$ is very nearly just the uncertainty in the pyrometer measurement of 10 K. Putting it all together, the uncertainty in T_{eff} is

$$\frac{\delta T_{eff}}{T_{eff}^2} = \left[\left(\left(1 - \frac{\lambda}{\lambda_{red}} \right) \frac{\delta T_{fil}}{T_{fil}^2} \right)^2 + \left(\frac{\lambda}{\lambda_{red}} \frac{\delta T_{red,c}}{T_{red,c}^2} \right)^2 + \left(\frac{\lambda}{C_2} \right)^2 \left(\left(\epsilon(\lambda_{red}) \frac{\delta \epsilon(\lambda)}{\epsilon(\lambda)} \right)^2 + \left(\frac{\delta \epsilon(\lambda_{red})}{\epsilon(\lambda) \epsilon(\lambda_{red})} \right)^2 \right) \right]^{\frac{1}{2}} \quad (70)$$

This expression assumes that a fiber is not used on the lamp-side optics, i.e., $t_{fiber} = 1$. Assuming emissivities of about 0.4 with an uncertainty of 2%, this leads to an uncertainty in the effective lamp temperature of about 20 K for typical measurements at the potassium D-line wavelengths.

Table 9. List of DOE MHD tests supported by the PEAS instrument.

Test Run Name	Date	Facility	Location
LMF4-H	August 18-21, 1986	CFFF	Diffuser
LMF4-K	August 24-26, 1987	CFFF	Diffuser
88-SLAG-5	September 27, 1988	CDIF	Diffuser
89-CFC-2	March 28, 1989	CDIF	Post-Nozzle
89-CFC-3	March 31, 1989	CDIF	Post-Nozzle
89-CFC-4	April 5, 1989	CDIF	Post-Nozzle
89-CFC-8	May 19, 1989	CDIF	Diffuser
LMF4-Q	May 31, 1989	CFFF	Diffuser
89-CFC-15	August 10, 1989	CDIF	Diffuser
89-DIAG-4	August 16, 1989	CDIF	Diffuser
89-DIAG-5	August 22, 1989	CDIF	Diffuser
90-MATL-5	August 14, 1990	CDIF	Diffuser
90-MATL-6	September 20, 1990	CDIF	Diffuser
91-SEED-2	May 7, 1991	CDIF	Diffuser
91-SEED-3	May 9, 1991	CDIF	Diffuser
91-SREJ-4	May 16, 1991	CDIF	Diffuser
91-COAL-1	May 17, 1991	CDIF	Diffuser
LMF5-B	August 27-29, 1991	CFFF	Diffuser
LMF5-C	September 23, 1991	CFFF	Diffuser
LMF5-D	November 18, 1991	CFFF	Aerodynamic Duct
92-RJRM-3	February 5, 1992	CDIF	Diffuser
92-RJRM-4	February 7, 1992	CDIF	Diffuser
92-RJRM-5	February 11, 1992	CDIF	Diffuser
LMF5-E	April 15, 1992	CFFF	Aerodynamic Duct
92-COMB-3	June 10, 1992	CDIF	Diffuser
92-COMB-4	June 11, 1992	CDIF	Diffuser
92-COMB-5	June 15, 1992	CDIF	Diffuser
92-COMB-6	June 16, 1992	CDIF	Diffuser
92-COMB-7	June 17, 1992	CDIF	Diffuser
LMF5-F	August 17, 1992	CFFF	Aerodynamic Duct
LMF5-G	September 29, 1992	CFFF	Aerodynamic Duct
LMF5-H	April 20, 1993	CFFF	Aerodynamic Duct

The system was developed on stable benchtop flames: a Perkin-Elmer burner with aqueous salt solution injection for a clean flame and a knife-edge burner with a fluidized bed for ash and salt injection. The standard deviation for a set of 100 time-resolved temperature measurement is around 20 K for these flames.

The long-term stability of the vidicon detector was studied over a 24 hour period using a blackbody source and was found to be stable within 1%, better than the quoted stability of the source. The regulated lamp power supply is exceedingly stable over both short and long time periods of time providing a stable reference lamp signal. The PEAS instrument is capable of accurate measurements over extended periods approaching the lifetime of the tungsten bulbs.

A demonstration of the accuracy of the method for determining the effective lamp temperature was made during the 89-CFC-3 test at the CDIF on March 31, 1989. This test was designed for CFPC checkout and no potassium was injected into the flow. The measurements were made through 1" diameter optical windows tapering to 0.5" openings across a 3.5" width of gas flow. The ports were located in a specially inserted section between the nozzle and the MHD channel. Without potassium injection, it was uncertain as to whether there would be enough potassium for a measurement but certainly there would be sufficient sodium since it is present in coal. So in order to assure a line reversal measurement, two PEAS instruments were used. Only one lamp was used but two pickup fibers were placed at the lamp image on the other side of the flow. One fiber was interfaced to the field PEAS instrument and the other to the laboratory development system set up for operation on the sodium D-lines. Figure 77 shows an emission scan recorded with the PEAS instrument during the test showing the narrow atomic lines.

Figure 77. Emission spectrum from the CDIF post-nozzle test section during the 89-CFC-3 test with no seed injection.

The average measurements recorded for the 89-CFC-3 test are shown in Fig. 78. Here the excellent agreement between the two measurement attests to the accuracy of the lamp calibration since both instruments were operated using essentially the same light signals.

Figure 78. Line reversal measurement recorded during the FCC-3 test on March 31, 1989. The measurement standard deviations were approximately 50 for sodium line reversal and 70 K for potassium line reversal.

This post-nozzle location represents the highest temperature regime studied with the PEAS instrument. Measurement up to about 3000 K are possible using a tungsten strip lamp. At the very highest temperatures for the tungsten bulb the lifetime is on the order of tens of hours rather than hundreds of hours at lower temperatures.

Potassium Atomic Density Measurement Accuracy and Uncertainty

The accuracy with which the system can measure potassium density depends fundamentally upon the knowledge of the atomic absorption coefficient and its spectral dependence. The primary potassium D-line strengths are only known to within $\pm 10\%$ so this is a fundamental limit upon the accuracy of the system. In addition, the broadening model in the line wings adds additional uncertainty to the measurement accuracy. Although, the density determination is not as accurate as the temperature determination, the method still provides a good relative measure for diagnosing MHD flows.

The measurement uncertainty depends upon two measures of optical depth. To estimate the instrument uncertainty was estimated by measurement of the optical depth of neutral density filters. The uncertainties found were ± 0.008 for an 0.1 optical density filter, ± 0.009 for an 0.3 optical density filter, and ± 0.012 for an 1.0 optical density filter. This implies an instrument uncertainty of about 10%. Measurements of potassium density on stable flames give measurement standard deviation of about 15% using a two-wavelength calculation.

The multiwavelength nature of the PEAS instrument allows for measurements over orders of several magnitude of potassium density. Figure 79 illustrates such measurement made during the CDIF 91-SREJ-3 test in which the seed flow was interrupted periodically. At the lowest potassium density an integrated line analysis was employed rather than a two-wavelength analysis since the line width was approaching the resolution of the detector system. The figure compares the facility recorded potassium seeding with the PEAS measurements and it is clear that the system provides an excellent monitor of the potassium loading.

Figure 79. Comparison of PEAS measurement of potassium density with facility seed loading for the CDIF 91-SREJ-3 test.

Electron Density Measurement versus Faraday Rotation Measurement.

The PEAS instrument was used to provide an independent measure of electron density during the demonstration of far infrared Faraday rotation as a nonintrusive diagnostic for pulsed MHD sources.¹³ Fig. 80 illustrates the comparison between electron densities measured with Faraday rotation and with a Saha calculation using the emission absorption measurements of temperature and neutral atom density. These measurements were made on a cesium-seeded nitrous oxide/acetylene burner. The comparison shows no obvious bias between the direct measurements of electron density with the Faraday rotation system and the indirect emission absorption measurement.

The uncertainty in the Faraday rotation measurements are shown as horizontal bars, while the uncertainty in the emission absorption/Saha measurements are shown as vertical bars. The emission absorption uncertainty is slightly underestimated since the instrument uses a data rejection scheme for points two standard deviations away from the average; typically only 38 data points were kept out of 40 measurements.

Fig. 80. Comparison of electron number density measured by Faraday rotation and emission absorption/Saha calculation.

Fig. 81 shows a similar comparison for electron conductivity. Again the error limits are shown as horizontal and vertical bars. The emission absorption measured temperature was used along with a collision frequency model to estimate the electron mobility, which with the electron number density gives conductivity. The uncertainty in the emission absorption/Saha/modeling calculation was found as the square root of the sum of the squares for the calculated electron density and a 20% error limit for the collision frequency model.

The measurements of electron number density and electron conductivity agree for most of the points within error limits with the independent measurements. Some of the differences could be due to a lack of coincidence between the two measurements, although Faraday rotation data points where the flame did not appear to be stable were not included in the comparison.

Fig. 81. Comparison between electron conductivity measured by Faraday rotation and emission absorption/Saha/collision frequency modeling.

Additional Examples of PEAS Measurements

To illustrate the instrument performance on other than a prototypical MHD flow, Figures 82 through 84 show PEAS measurements on an oil-fired flow in the aerodynamic duct at the CFFF. The lowest PEAS measurements of potassium density were recorded for this test.

Figure 82. Temperature measurement during the LMF5-E test on April 23, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figure 83. Potassium density measurement for the LMF5-E test on April 23, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figure 84. Electron density measurement for the LMF5-E test on April 23, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figures 85 through 88 show the last measurements made at the CDIF before optical access to the diffuser was no longer available. The missing data between about 18:00 and 18:30 corresponds to a period when slag blocked the optical ports. The measurements of conductivity can only be considered a relative measure as the calculation is based upon an estimate of the flow pressure.

Figure 85. Temperature measurement for the 92-COMB-7 test on June 17, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figure 86. Potassium density measurement for the 92-COMB-7 test on June 17, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figure 87. Electron density calculation for the CDIF 92-COMB-7 test on June 17, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

Figure 88. Conductivity calculation from the CDIF 92-COMB-7 test on June 17, 1992. The heavy line plots the average of approximately 50 samples while the lighter lines plot plus and minus one standard deviation away from the average.

CURRENT STATUS

Instrument Capabilities.

The PEAS instrument has proven itself as a valuable nonintrusive diagnostic for high temperature systems. It is capable of measuring temperatures over the range from 1600 to 3000 K and of measuring atomic densities over any range that gives a measurable absorption. For seeded flows, the instrument can also provide indirect measures of the electron density and conductivity. The measurements are made from $\frac{1}{2}$ ms time-resolved exposures with a repetition frequency up to 25 Hz. The typical operation of the instrument is for collection of complete spectral information and this is done at a maximum repetition rate of 2 Hz. The instrument has been packaged for operation in harsh environments and is robust and capable of measurements over several days.

Instrument Availability.

The instrument is available upon request if travel and salary funds are provided for instrument operation and data analysis. One version of the instrument is packaged for easy transport and the individual components can be air shipped. The original system used for laboratory development of the system is also available for testing but is not packaged for easy shipment.

Different monochromator gratings are available for optimizing the resolution versus wavelength range trade-off for a particular facility and expected operating conditions. It is helpful prior to a test to estimate the potassium D-line widths in order to choose the grating. The necessary information for this is the path length across the flow, the anticipated seed loadings, flow pressure and approximate temperature, and fuel/oxidizer chemistry and stoichiometry.

Future Development.

The hardware of the system as configured in the early 1980s was indeed state of the art but that is no longer the case. Converting the system to a faster array detector and computer system could easily provide an order of magnitude improvement in the data collection frequency. As an interim measure before replacing the computer, the aging computer monitors have been replaced with a terminal emulator running on a PC with a VGA screen display. With the use of a miniature tungsten halogen bulb rather than the strip lamp, the lifetime of the bulb would extend into the hundreds to thousands of hours and facilitating the use of the instrument for long term monitoring of high temperature systems.

SUMMARY

The Potassium Emission Absorption System provided useful measurements of temperature and seed atom density as designed for MHD channel and diffuser test sections. Originally developed in the early 1980s, the instrument provided field test measurements in support of the development of prototype MHD facilities from 1986 to 1993.

Utilizing a multiwavelength detector, the instrument is capable of measurements over wide ranging conditions without instrument modification or operator intervention. Measurement are based upon a two wavelength spectroscopic method which eliminates broadband particle effects allowing accurate measurements on coal-fired flows. The spectral measurements are made on the wings of the atomic resonance line so that the results yield values that approximate the hot core region of the flow, reasonably unaffected by any thermal boundary layers. An experimental determination of the potassium far wing absorption coefficient allowed measurements of potassium density in the diffuser test sections. A notable advancement in the state of the art in emission absorption spectroscopy was the demonstration of extraction of boundary layer flow information from the potassium lineshapes.

As MHD flows have inherently large flow fluctuations, the instrument was designed to provide time resolved measurements of temperature and seed atom density. The instrument measures millisecond time-resolved intensities, the data collection is typically at the rate of one frame per second and results are reported as averages and standard deviations, i.e. as a probability distribution function, for a set of 50 frames covering about one minute. Although the instrument does not follow the flow properties in real-time, the probability distribution functions provide an indication of the fluctuation in the flow properties. As reported the system was reconfigured successfully with spatial separation of signals for measurements on the high speed aerodynamic duct. In this configuration, the instrument was able to provide relative measures of conductivity at a location approximating the conditions of an MHD channel.

With a lower temperature limit of about 1600K, the system can be used on any flow that provides a measurable atomic absorption. The high temperature limit is determined by the maximum effective lamp temperature and is estimated to be about 3000 K. The accuracy of the temperature measurement is determined by the accuracy in determining the reference lamp temperature and is approximately 20 K. On a stable benchtop flame, the instrument has a precision of better than 10 K. The accuracy of the seed atom number density determination is limited by the knowledge of the atomic absorption strength ($\pm 10\%$) and the lineshape model. The instrument precision for atomic density measurements on a benchtop flame is about 10%. Complications from particle effects, boundary layer profiles and inherent flow fluctuations will increase the uncertainties and reduce the precision. On typical MHD flows, the measurement standard deviations are typically ± 20 K and $\pm 25\%$ for the temperature and atomic density, respectively.

APPENDIX 1. ATOMIC AND SPECTROSCOPIC CONSTANTS

The primary alkali doublets arise from transitions of the single outer s electron: the D_1 (I) from $ns^2S_{1/2} - ns^2P_{1/2}$ and the D_2 (I) from $ns^2S_{1/2} - ns^2P_{3/2}$, where n varies from 2 for lithium to 6 for cesium. The secondary doublets (II) arise from $ns^2S_{1/2} - (n+1)s^2P_{3/2,1/2}$. The statistical weight g_J is 2 for each of the alkali $J=1/2$ states and 4 for the $J=3/2$ states. Therefore, the D_2 lines are approximately twice as strong as their respective D_1 lines. The uncertainty in the listed line strengths are quoted as $\pm 10\%$ for the lithium, potassium and rubidium primary D-lines, $\pm 3\%$ for the sodium D-line and $\pm 25\%$ for the secondary D-lines of potassium and cesium. The collision cross sections used in calculating the line broadening are those found for broadening by nitrogen.

Table 10. Alkali atom constants.

Line	Wavelength λ (nm)	Line Strength f (dimensionless)	Collision Cross Section, σ^2 (10^{-16} cm^2)	Ionization Energy E_i (eV)	Atomic Mass m (amu)
Lithium (Li)					
D_1	670.79	0.25	46.5	5.39176	6.941
D_2	670.78	0.50			
Sodium (Na)					
D_1	589.592	0.33	59.7	5.13912	22.98977
D_2	588.995	0.66	58.9		
Potassium (K)					
D_1 (I)	769.90	0.36	57.7	4.34070	39.0983
D_2 (I)	764.49	0.73	60.4		
D_1 (II)	404.721	0.00608			
D_2 (II)	404.414	0.00304			
Rubidium (Rb)					
D_1	780.03	0.689	79.3	4.17717	85.467
D_2	794.76	0.344	73.3		
Cesium (Cs)					
D_1 (I)	852.1	0.711	91.2	3.89394	132.9054
D_2 (I)	894.4	0.355	86.9		
D_1 (II)	455.54	0.01170	12		
D_2 (II)	459.32	0.00253	15		

APPENDIX 2. EFFECTIVE LAMP TEMPERATURE

Rather than use a large, unwieldy and very costly radiance source calibrated by a standards laboratory as the reference lamp for the line reversal measurements, a decision was made to use an uncalibrated tungsten strip lamp and to calibrate the lamp using pyrometer measurements.⁷³ The white light source used as the reference lamp is a ribbon filament tungsten bulb, General Electric model 18A/T10/1P⁷⁴ powered by a regulated DC power supply, Hewlett Packard model 6261B. The color temperature of the tungsten filament is measured with an optical pyrometer, Pyro Micro-Optical Pyrometer⁷⁵ and then corrected as described below for the effective blackbody temperature at the measurement wavelength. The pyrometer was purchased calibrated against standards traceable to the National Institute of Standards and Technology and is certified with a maximum uncertainty of $\pm 6^\circ$ at 1800°C , $\pm 10^\circ$ at 2500°C , and $\pm 12^\circ$ at 3200°C .

All of the equations given below are based upon the Planck blackbody law which states that an ideal emitter at a temperature T will emit radiation according to

$$B(\lambda, T) = \frac{C_1 \lambda^{-5}}{\exp(C_2 / \lambda T) - 1} \approx C_1 \lambda^{-5} \exp(-C_2 / \lambda T), \quad (71)$$

where the approximate expression is known as the Wien Law. An object will emit less than this blackbody radiation depending upon the object's emissivity, ϵ , as $I(\lambda, T) = \epsilon(\lambda, T)B(\lambda, T)$.

Figure 89. Illustration of the measurement of the effective lamp temperature.

Figure 89 illustrates a typical configuration for the two pyrometer measurements necessary for calculating the lamp effective temperature: the lamp filament temperature and the temperature of the lamp filament image at the flame position. First, a pyrometer measurement is made of the lamp filament with as few intervening optics as possible. The optical pyrometer uses a red filter at about $\lambda_{red} = 655 \text{ nm}$ for viewing the internal calibrated filament against the bulb

filament with a scale reading in °C which is converted to K for the so-called *red* temperature, T_{red} . The relationship between the measured temperature and the actual temperature of the tungsten filament, T_{fil} , is

$$B(\lambda_{red}, T_{red}) = t_{optics} \varepsilon(\lambda_{red}, T) B(\lambda_{red}, T_{fil}), \quad (72)$$

where t_{optics} is the transmission factor for the light from the filament to the optical pyrometer. Estimating the losses at each optical element, bulb envelope, lens, window, or prism, as 8%, the filament temperature is found from the measured *red* temperature, T_{red} as

$$\frac{1}{T_{fil}} = \frac{1}{T_{red}} + \frac{\lambda_{red}}{C_2} \ln \left[0.92^{n+1} \varepsilon(\lambda_{red}, T_{fil}) \right]. \quad (73)$$

For the illustration in Fig. 89, n would be zero, as there are no intervening optical elements between the pyrometer and the filament except the bulb envelope.

The method used for calculating the tungsten emissivity is that given by Pon and Hessler⁷⁶ using a polynomial approximation as

$$\begin{aligned} \varepsilon(\lambda, T) = & a_0 + a_1(T - T_0) + (b_0 + b_1(T - T_0) + b_2(T - T_0)^2)(\lambda - \lambda_0) \\ & + (c_0 + c_1(T - T_0))(\lambda - \lambda_0)^2 \end{aligned} \quad (74)$$

where the values for the polynomial constants are given in Table 11. Note the temperature is referenced to $T_0 = 2200$ K and is entered as degrees Kelvin divided by 1000 and the wavelengths are entered as μm , i.e., nm divided by 1000.

Table 11. Polynomial constants for calculating the emissivity of tungsten as a function of wavelength and temperature according to Eq. 74.

Spectral Range (nm)	λ_0 (nm)	a_0	a_1 (kK ⁻¹)	b_0 (μm^{-1})	b_1 ($\mu\text{m}^{-1} \cdot \text{kK}^{-1}$)	b_2 ($\mu\text{m}^{-1} \cdot \text{kK}^{-2}$)	c_0 (μm^{-2})	c_1 ($\mu\text{m}^{-2} \cdot \text{kK}^{-1}$)
340 - 420	380	0.47245	-0.0155	-0.0086	-0.0229	0.0	-2.860	0.0
420 - 480	450	0.46361	-0.0172	-0.1304	0.0	0.0	0.520	0.0
480 - 580	530	0.45549	-0.0173	-0.1150	0.0	0.0	-0.500	0.0
580 - 640	610	0.44297	-0.0177	-0.1482	0.0	0.0	0.723	0.0
640 - 760	700	0.43151	-0.0207	-0.1441	-0.0551	0.0	-0.278	-0.190
760 - 940	850	0.40610	-0.0259	-0.1889	0.0087	0.0290	-0.126	0.246
940 - 1600	1270	0.32835	0.0	-0.1686	0.0737	0.0	0.046	0.016
1600 - 2600	2100	0.22631	0.0431	-0.0829	0.0241	0.0	0.040	-0.026

Next the lamp temperature is measured at the flame position and is corrected for any intervening optical elements to give the corrected red temperature, $T_{red,c}$

$$\frac{1}{T_{red,c}} = \frac{1}{T_{red}} + \frac{\lambda_{red}}{C_2} \ln(0.92^n). \quad (75)$$

For the illustration in Fig. 89, n would be 1 because of the use of a prism for convenient viewing the filament image at the flame position. Finally the effective lamp temperature at a particular wavelength is

$$\frac{1}{T_{eff}} = \frac{\lambda_{red} - \lambda}{\lambda_{red} T_{fil}} + \frac{\lambda}{\lambda_{red} T_{red,c}} - \frac{\lambda}{C_2} \ln \left(t_{fiber} \frac{\epsilon(\lambda, T_{fil})}{\epsilon(\lambda_{red}, T_{fil})} \right), \quad (76)$$

where t_{fiber} is the relative fiber transmission factor as given in Table 12. Other optical components are assumed to have a transmission that does not change significantly with wavelength. For most applications of the PEAS instrument a fiber is not used on the lamp side and the fiber factor would be left as one. This effective lamp temperature is that used in the modified line reversal calculations.

Table 12. Relative transmission factors for QSF-1000 optical fibers. These values were determined experimentally with spectral scans of a blackbody source as well as a tungsten lamp and match well the curve of attenuation versus wavelength published by the supplier.⁷⁷

Spectral Range (nm)	Relative Transmission
585 - 590	1.0875
655	1.00
747.5 - 752.5	0.8637
752.5 - 757.5	0.8595
757.5 - 762.5	0.8561
762.5 - 767.5	0.8480
767.5 - 772.5	0.8459

APPENDIX 3. PEAS PACKING LIST

#	Equipment	Essential	As Needed	Recommended	Optional
1.	Breadboard w/Optical Rails Breadboard Optics: 40 mm f.l. cylindrical lens 40 mm f.l. achromat lens Fiber Mount Rail Optics: Tungsten Bulb in Socket Optical Chopper w/Modified head Lenses as required from below	X			
2.	Electronics Cabinet Cables stored inside: Power Cable, OMA↔Vidicon Cables (2). OMA↔LSI Cables (2), Digital Control Cable, Chopper Head Cable, Chopper→OMA Cable, Shutter Head Cable	X			
3.	LSI Computer	X			
4.	Monitor w/Keyboard	X			
5.	Optical Pyrometer w/ Tripod w/Prism w/Spare Battery	X			
6.	Lamp Power Supply w/Optional Cover	X			
7.	HeNe Laser	X			
8.	Optical Fiber and Spare	X		X	
9.	Electronics & Cables: Source Comp Coaxial Cable, 100'; Chopper Sync. Cable, 70'; 1/73 to Terminal Cable; Terminal Power Cable; 11/73 Power Cable	X			
10.	Miscellaneous Necessary Items: Black Felt for Light Blockage, Optics Cleaner w/Wipes, Optics Duster, Flashlight	X			
11.	Line Isolator			X	
12.	Line Conditioner			X	
13.	Hg(A) Spectral Pen Light				X
14.	K-lamp w/Spare Bulb			X	
15.	Fiberlite			X	
16.	Chopper w/Blades			X	
17.	Spare Computer Boards a. 16-bit Parallel modified for OMA Control b. 16-bit Parallel for Digital Control c. Real-Time Clock Board c. Dual Extender Board for troubleshooting d. Quad Extender Board for troubleshooting			X	
18.	Output Mirror for HR-320 Monochromator				X

19.	Lenses:	X	
	Cylindricals: 40 mm, 100 mm, and 150 mm f.l.		
	Achromats: f.l. ϕ #		
	200 mm 40 2		
	300 mm 82 2		
	400 mm 72 4		
	600 mm 63 4		
	800 mm 63 4		
	1000 mm 80 3		
	1185 mm 80 2		
20.	Tungsten Strip Lamp w/Socket		X
21.	HR-320 Gratings: 600 lines/mm, 1200 lines/mm, 1800 lines/mm, or 2400 lines/mm	X	
22.	Miscellaneous Electrical Connectors: BNC T's, 25-Pin Pass through Connector		X
23.	Optical Mounting Components:	X	
	Spare 18" Rail, Lab Jacks (small & large), Lens Mounts (small & large), Adjustable Bases, Post Holders, Posts, Post Couplers, Finger Screws, Fiber Strain Release, 1/4" Allen Head Screws (1 1/2", 1", 1/2"), 1/4"-20 set screws w/Nylon tips, 1/8"-32 set screws w/Nylon tips, Washers (metal & Nylon), Cap head 1/4"-20 bolts, Collars, Clamps, Double-sided Foam Tape		
24.	Miscellaneous Electronics & Cables:		X
	Digital Voltmeter w/fiber detector, Oscilloscope, Strip Outlets (3), Extension Cords		
26.	Tools (Tool Box and Leather Pack)		X
	1/4"-20 Ball Drivers (2), Soldering Iron, Needle Nose Pliers, Scissors, Flat Screwdrivers (2 small, medium, large), Phillips-head Screwdrivers (small, medium), Allen Sets (metric & English), Level with Measure, 8" Level, Ball Driver Set, Nut Driver Set, Cable Ties, Wrenches, RTV Sealant, 5-minute Epoxy, Instant Glue, Tape Measures (10', 25'), Tape (Black Electrical, Aluminum Backed Tape, Yellow & Teflon)		
27.	Documentation		X
	RT-11 Manuals w/Mini Reference, LSI-11/73 Manuals, 480-XL Monitor Manual, Minicomputer Interfaces & Memories Books. Interface Boards Manuals, Instrument Manuals (Black Binder), Software Listings		

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