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Potassium D-Line "Blue" Wing Absorption Coefficient Under Combustion-Fired Magnetohydrodynamic Conditions

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A model is proposed for the adsorption coefficient of the far "blue" wing of the potassium D-line under combustion-fired magnetohydrodynamic (MHD) conditions. Such a model is important because of the need to measure potassium seed-atom densities on large-scale MHD facilities. The model was developed using experimental emission profiles on a 20-cm diam oil-fired, simulated MHD flow. A two-parameter model, constructed of a sum of power laws matched to a Voigt profile in the near blue wing, fits the 730–760 nm region well with a power-law exponent of −1.07 matched to the Voigt at 764.6 nm. Using this model, emission absorption measurements on coal-fired MHD flows with diameters of 33 and 76 cm compared well to chemical equilibrium calculation predictions. The model should allow accurate measurements of seed-atom density irrespective of the flow dimensions and geometry using two-wavelength wing emission absorption measurements, a technique suitable for real-time monitoring. Such measurements should then provide a useful indirect measure of the electron density which is a critical parameter for analyzing MHD power generation.

Nomenclature

c = speed of light
e = electron charge
f_i = emission line strength of atomic line i
k = Boltzmann constant
L = optical path length
m_e = electron mass
m_f = foreign atom mass
m_K = potassium atom mass
n_K = potassium atom number density
n_s = number density at standard temperature and pressure
P = pressure
P_s = standard pressure
T_g = gas temperature
T_s = standard temperature
α_λ = atomic resonance line absorption coefficient
λ = wavelength or subscript denoting wavelength
σ_i^2 = collision cross section for line i
τ = optical depth

Introduction

RESEARCH into magnetohydrodynamic (MHD) electrical power generation in the United States is concentrated on high-temperature, potassium-seeded, coal-fired combustion product flows. Potassium, typically added at 1% by weight, serves as the seed atom for electrons (the primary source of conductivity). Diagnostic measurements of potassium seed-atom density are crucial for analysis of MHD channel performance and important for analysis of downstream component performance through chemical effects on seed regeneration and fouling and through heat transfer effects. The broad self-reversed D-line has been widely used for diagnostic measurements of gas temperature and potassium number density through emission absorption techniques. An accurate model for the atomic absorption is essential for such measurements. On small-scale facilities, measurements can be made near the line center where the absorption is well represented by a classical Voigt profile. However, the high-seed loadings, particle densities, and long path lengths of large-scale experimental MHD facilities render the potassium D-line opaque near line center 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.[1] Theoretical quasistatic models for far-wing broadening have typically been at low pressures for alkali-rare gas systems.[2,3] 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, therefore, such a model is best determined experimentally.

Vasileva et al.[4] studied potassium emission in a torch as well as in the 20-cm-diam U-02 MHD facility.[4] 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 of −1.3, and the red wing with an exponent of −1. Goodwin and Mitchner[5] 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. Im and Ahluwalia[6] also studied the potassium D-line absorption coefficient determined by Vasileva et al.[4] and proposed a model profile to use for calculating radiant heat transfer in MHD facilities.

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 response is 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[5] 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.[4]; 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

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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.

Absorption Coefficient Models

The classical model for an atomic line when both Doppler and collisional broadening are important is the Voigt profile which is a convolution of a Gaussian profile with a Lorentzian profile.[7] The wavelength-dependent Voigt absorption coefficient α_λ in the near wings is essentially Lorentzian and can be modeled as[8]

$$\alpha_{\lambda,V} = n_K a_2 a_\lambda / T g^{0.5} \tag{1}$$

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

$$a_2 = \frac{e^2}{2 m_e c^3}\left[\frac{8k}{\pi}\left(\frac{1}{m_K}+\frac{1}{m_f}\right)\right]^{0.5} n_s T_s \frac{P}{P_s} \tag{2}$$

$$a_\lambda = \sum_{i=1}^{2} f_i \sigma_i^2 \left(\frac{1}{\lambda}-\frac{1}{\lambda_i}\right)^{-2} \tag{3}$$

The potassium D-line oscillator strengths and collisional cross sections can be found in tabulations by Radzig and Smirnov[9] and Hofmann and Kohn,[10] respectively. Constants used in these calculations included: $\lambda_1 = 769.90$ nm, $\lambda_2 = 766.49$ nm, $f_1 = 0.35$, $f_2 = 0.70$, $\sigma_1^2 = 57.7 \times 10^{-16}$ cm^2, and $\sigma_2^2 = 60.4 \times 10^{-16}$ cm^2. Nitrogen was used for estimating the foreign atom mass for the collisional broadening.

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

$$\alpha_{\lambda,P} = n_K b \sum_{i=1}^{2} f_i \left(\frac{1}{\lambda}-\frac{1}{\lambda_i}\right)^{m} \tag{4}$$

where b is

$$b = \frac{a_2 a_\lambda / T g^{0.5}}{\sum_{i=1}^{2} f_i \left(\frac{1}{\lambda_m}-\frac{1}{\lambda_i}\right)^{m}} \tag{5}$$

Here m is the power law exponent and λ_m is the wavelength at which the Voigt and power-law profiles match. 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 a MHD channel or diffuser (2300–2800 K), this corresponds to a nearly constant behavior with temperature.

Figure 1 shows how various power-law exponents affect the model shape of the potassium blue wing absorption coefficient.

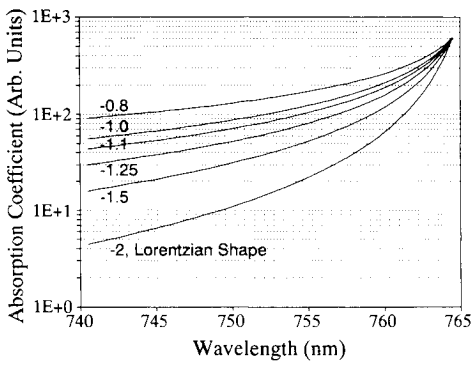

Fig. 1 Illustration of the potassium D-line absorption coefficient for various power-law exponents.

Far-Wing Experiments and Results

Figure 2 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.[11,12] The flow diameter was 20 cm and the pressure was about 1.1 atm. This combination of size and loading fortuitously provided D-line profiles that were strong enough to study in 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, which is adequate for this study.

The profiles generally resemble those observed by Vasileva et al.[4] and the observations of Goodwin and Mitchner[5] resemble those in the red wing. Later experiments at higher temperatures, using a different combustor to provide oxygen enrichment, yielded more exaggerated wings. A reanalysis indicates that all the experimental line shapes can be fit reasonably with a single profile, adding a background luminosity for the later anomalous experiments. A spectral scan of the flame without seed loading at the start of the two experiments shown in Fig. 2 shows no significant background.

Figure 3 illustrates the model profile for the 1% seed-loading case as shown in Fig. 2. First this model was found by least-squares fitting the central line region (765–767 nm) to a Voigt profile integrated over a model boundary-layer flow.[13] Such a method has been suggested by Hommert and Viskanta[14,15] 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 Onda[8] to provide an average gas temperature for an accurate Voigt profile for the near wings. For the 6 lb/h 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.

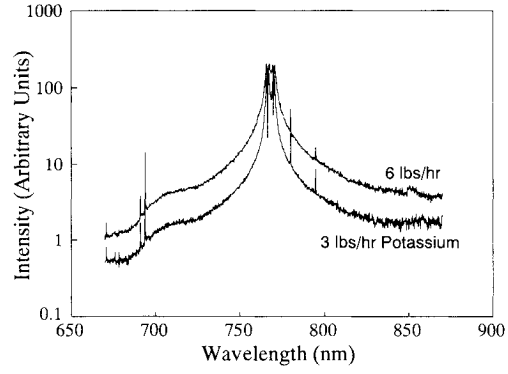

Fig. 2 Atomic potassium emission profiles from seeded oil-fired combustion products. The flow diameter was 20 cm and the seed loadings correspond to 0.5 and 1% potassium by weight.

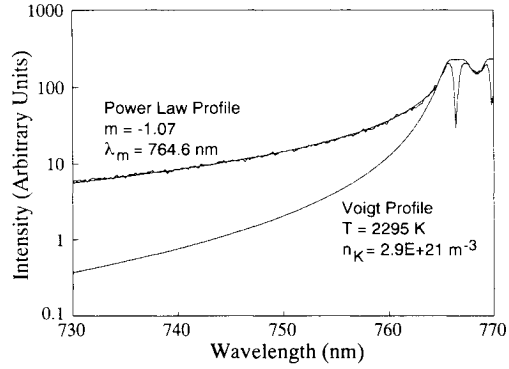

Fig. 3 Blue wing potassium D-line emission from the MSU test facility (6 lb/h case) and model profiles: a Voigt profile (lower line) and a power-law profile of exponent −1.07 matched to the Voigt profile at 764.6 nm (smooth line through the experimental data).

Table 1 Line shape fitting results compared to chemical equilibrium calculation predictions

	Test seed 1A	Test seed 1B
Test condition		
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	0.009
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 ± 0.055

Table 1 gives the results for the two cases shown in Fig. 2 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 et al.[4] who studied the profiles over three orders of magnitude.[16]

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, 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.[4]

Number Density Measurements

To validate the absorption coefficient model, emission measurements of temperature and atomic number density were made on larger scale flows and the results were 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,[17] width of the self-reversed line center dip,[18] single wavelength, wing emission absorption,[8] and two wavelength—wing emission absorption.[19] 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. 2. 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 measurements are necessary to account for broadband absorption of the particles.[19]

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

$$n_K = \tau_\lambda T g^{0.5}/a_2 a_\lambda L \tag{6}$$

On coal-fired combustion flows considerable error is introduced into such a single wavelength measurement by the particles in the flow. Spectrally resolved two-wavelength measurements can eliminate the broadband absorption and the out-scattering and considerably cancel the in-scatter error.[20] The equation then involves differences in both measured optical depth and the absorption coefficient

$$n_K = \frac{\tau_{\lambda 1} - \tau_{\lambda 2}}{(\alpha_{\lambda 1}/n_K - \alpha_{\lambda 2}/n_K)L} \tag{7}$$

This is a measurement technique which has been used successfully at smaller scale MHD test facilities.[19] The error introduced into an absorption measurement of emitter density by a Voigt analysis is illustrated in Fig. 4 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 that a Voigt analysis on a nonVoigt shape will measure high by a factor of at least 2 and possibly more.

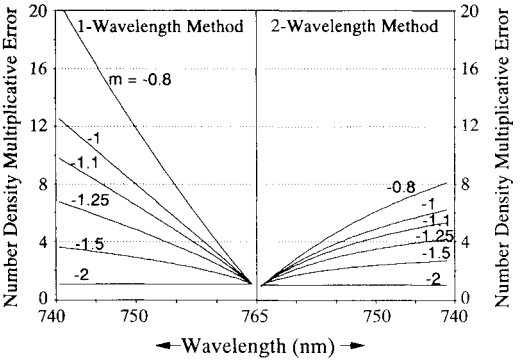

Fig. 4 Multiplicative error introduced into the determination of potassium number density by applying a Voigt analysis to a nonVoigt line shape.

Large-Scale Facility Experiments and Results

Figure 5 illustrates the potassium D-line emission absorption profiles recorded at the Department of Energy Component Development and Integration Facility (CDIF) in Butte, Montana at the middle optical port of the subsonic diffuser test section. The optical path length at this position was Rosebud coal with nominally 1.59% by weight potassium as a seed during the time in which this data was taken.

Figure 6 shows the calculation of the potassium number density from the data presented in Fig. 5 for two different methods: 1) a two-wavelength analysis using a Voigt profile; 2) 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.

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 coal-fired flow facility (CFFF) as shown in Figs. 7 and 8. The optical path length in the

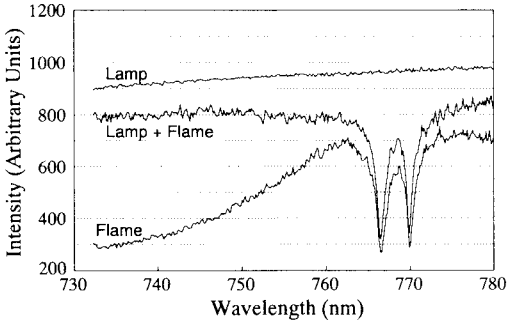

Fig. 5 Potassium D-line emission absorption profiles from the diffuser test section of the U.S. Department of Energy CDIF in Butte, Montana.

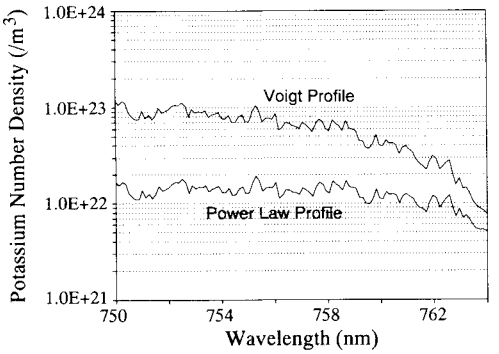

Fig. 6 Comparison of methods for calculating seed-atom number density from the emission absorption profiles shown in Fig. 5.

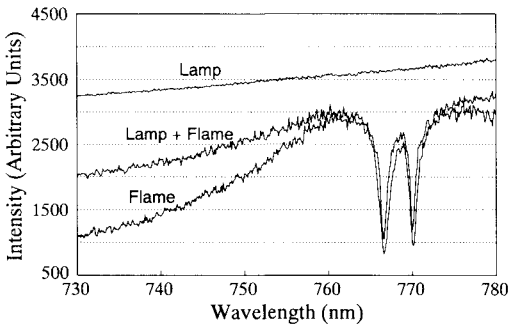

Fig. 7 Potassium D-line emission absorption profiles from the diffuser test section of the U.S. Department of Energy CFFF at the University of Tennessee Space Institute.

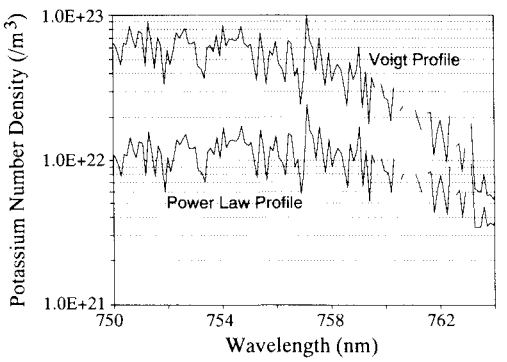

Fig. 8 Comparison of methods for calculating seed-atom number density from the emission absorption profiles shown in Fig. 7.

diffuser where the measurements were made as 76 cm (double that of the CDIF) and the facility was burning Illinois #6 coal with potassium 0.83% by weight.

Table 2 shows that for these two measurements, the agreement between the power-law model results and chemical equilibrium calculations is very reasonable, within the ±10–20% for such calculations. The pressures were taken from the facility reports and the temperatures were found with the potassium emission absorption system.[21] The listed densities are the average and standard deviation of the results shown in Figs. 6 and 8 over the wavelength region of 750–760 nm.

Table 2 Comparison between measured neutral potassium atom number density using a power-law profile for the far wing and chemical equilibrium calculations

	CDIF	CFFF
Test conditions		
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

Conclusions

In summary, the proposed model seems to fit the observed spectra quite well and should provide the basis for an accurate monitor of the seed-atom loading in these large-scale experimental MHD facilities with combustion product flows. Combined with the previous demonstration of the utility of a two-wavelength emission absorption technique for accurate measurements of coal-fired MHD gas temperatures, the technique should additionally provide (through a Saha calculation) an indirect measure of the electron density. The most critical parameter for MHD power generation is the electron density, so consequently this model profile should provide the basis for an accurate and convenient monitor to aid analysis of MHD channel performance on large-scale facilities. Although, further study of the model at higher temperatures is necessary before application in MHD channel flows.

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