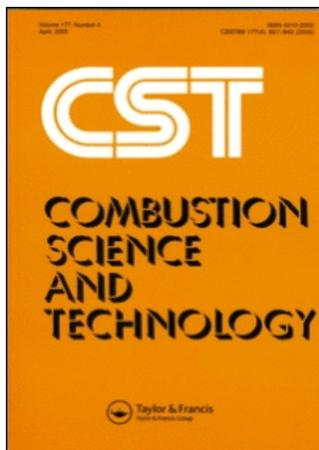


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INFLUENCE OF ABSORPTION BY ENVIRONMENTAL WATER VAPOR ON RADIATION TRANSFER IN WILDLAND FIRES

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The attenuation of radiation transfer from wildland flames to fuel by environmental water vapor is investigated. Emission is tracked from points on an idealized flame to locations along the fuel bed while accounting for absorption by environmental water vapor in the intervening medium. The Spectral Line Weighted-sum-of-gray-gases approach was employed for treating the spectral nature of the radiation. The flame and fuel bed for the simulations are modeled two-dimensionally with the flame being one-tenth as long as the fuel bed. Flame heights of 1 and 10 m were explored, and both vertical and angled flames were studied. Simulated flame temperatures of 1000 K and 1500 K were investigated. The study reveals that the effect of absorption of flame radiation by environmental water vapor is quite modest locally. For the worst-case scenario of 100% relative humidity, water vapor was found to reduce the incident radiant flux at the base of a vertically oriented flame at 1000 K flame by 9% for a 1 m flame and 16% for a 10 m flame. Radiation from the angled flame (30 deg from the vertical) experiences less attenuation from water vapor than the vertical flame. Further, local attenuation of the hotter flame (1500 K) from environmental water vapor is higher than for the 1000 K flame. The relative effect of the water vapor attenuation increases with distance from the flame base.

Keywords: Environmental water vapor; Radiation absorption; Wildland fires

INTRODUCTION AND REVIEW OF PRIOR WORK

Modeling of combustion and transport in wildland fires has evolved significantly in the past several decades, and a relatively recent review summarizes the progress (Albini, 1997). While early work was rather approximate (e.g., Fons, 1946; Emmons, 1964; Hottel et al., 1965; Rothermel, 1972; Sullivan et al., 2002, Cekirge, 1978), more recent studies have sought to develop physically-based modeling strategies (Albini, 1985; Grishin et al., 1986; Weber, 1989, 1991; Grishin, 1997; Baum and Mell, 1998; Porterie et al., 2000; Bellemare et al., 2001; Sullivan et al., 2002; Catchpole et al., 2002; Morvan and Dupuy, 2002; Porterie et al., 2003; Butler et al., 2004b; Linn and Cunningham, 2005). The importance of radiation transport

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as an important mechanism in the spread of wildland fires has been documented (Emmons, 1964; Hottel et al., 1965; Telitsin, 1974; Albini, 1986; De Mestre et al., 1989; Carrier et al., 1991; Call and Albini, 1997; Catchpole et al., 1998; Butler et al., 2004a,b). Radiation from products of combustion radiates to the unburned fuel ahead of advancing flames, which contributes to pre-heating, drying, and eventual ignition of the fuel. Environmental water vapor is a mechanism for attenuation of flame radiation from flame to fuel. The magnitude of this influence has been a question among wildland fire scientists for some time, but has not been heretofore explored. It is recognized that attenuation of radiation from flame to unburned fuel can also occur from smoke and combustion products entrained in the intervening air. This attenuation mechanism is a complex function of fuel, flame, wind, and other environmental conditions. While these effects are acknowledged as important, perhaps dominant in real wildland fires, the present study seeks only to settle the question of the magnitude of the attenuation of radiation from flame to fuel by environmental water vapor in the intervening medium. This investigation quantifies this mechanism by modeling the spectral radiation transfer from an idealized flame to a flat, horizontal fuel bed, accounting rigorously for the absorption by environmental water vapor. The assumptions invoked in the study provide a limiting case bounding the effect.

Model

Consider a planar flame of height H and characterized by uniform temperature T_f advancing along a horizontal fuel bed, as shown in Figure 1a. The length of the fuel bed L is specified arbitrarily in this study to be 10 times the flame height, $L/H = 10$. (Incident flame radiation beyond this point is negligibly small.) The angle between flame and the vertical is specified to be ϕ . Environmental water vapor with specified relative humidity is present in the air separating the flame from the fuel bed.

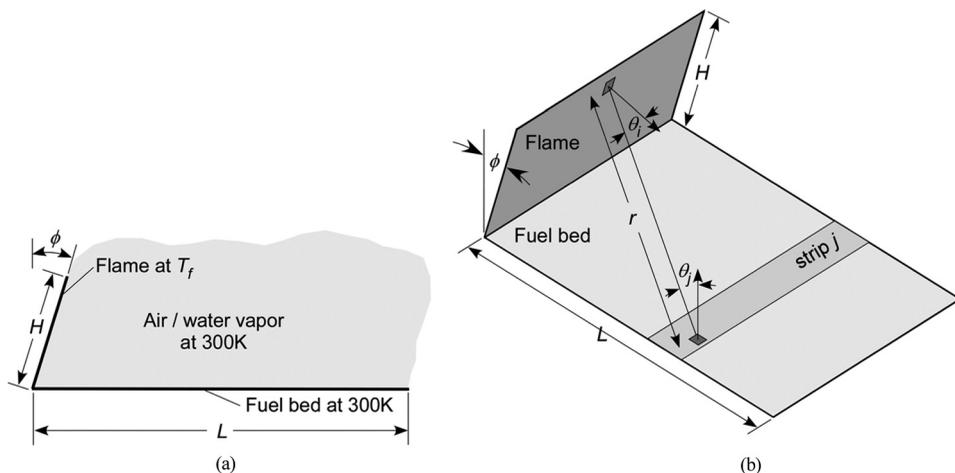


Figure 1 (a) Schematic illustration of configuration investigated, and (b) nomenclature for numerical integration of spectral volumetric exchange factor and local incident flux.

It is assumed that the intervening medium (air/H₂O vapor) and the fuel bed are at a uniform temperature of 300 K. As this study seeks only to identify the effect of environmental water vapor, attenuation of radiation by entrained combustion products (ash, H₂O, CO₂, soot, etc.) is not considered here.

The challenges associated with rigorously modeling mathematically the attenuation of flame radiation by water vapor are significant. The spectral emission characteristics of the flame are a strong function of fuel type, humidity, water content, wind conditions, etc. Further, absorption of flame radiation by the environmental water vapor occurs by its interaction with hundreds of thousands of extremely narrow spectral lines within the primary infrared vibration-rotation bands of water vapor. In this study, the flame is idealized as a planar, isothermal surface whose spectral emission of radiation can be taken to be that of a blackbody at the flame temperature T_f . While real wildland fires exhibit non-isothermal flame conditions, invoking an isothermal flame assumption explores the maximum effect by environmental water vapor.

The total radiative flux emitted by black surface i , which is incident on surface j may be expressed generally as (Hottel and Sarofim, 1967)

$$q_{i \rightarrow j} = \int_0^\infty \int_{A_i} \int_{A_j} e^{-\kappa_\eta r} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} dA_i dA_j E_{bi,\eta} d\eta \quad (1)$$

Here, $E_{bi,\eta}$ is the spectral blackbody emission from surface i , described by the Planck blackbody radiation spectral distribution at the temperature of surface i . The exponential term $e^{-\kappa_\eta r}$ in Eq. (1) accounts for absorption of radiation by the intervening medium of spectral absorption coefficient κ_η . Integrating over the spectrum as in the development of the classical weighted-sum-of-gray-gases model (Modest, 2003), it can be shown that the total (spectrally integrated) radiative flux emitted by surface i which is incident on surface j is

$$q_{i \rightarrow j} = \int_0^\infty (\overline{s_i s_j})_\eta E_{bi,\eta} d\eta \quad (2)$$

where $(\overline{s_i s_j})_\eta$ is termed the spectral volumetric exchange factor, defined as

$$(\overline{s_i s_j})_\eta = \int_{A_i} \int_{A_j} e^{-\kappa_\eta s} \frac{\cos \theta_i \cos \theta_j}{\pi r^2} dA_i dA_j \quad (3)$$

The dependence of both the volumetric exchange factor defined in Eq. (3), and the total radiant flux, Eq. (2), on wavenumber is evident. Because of the complex spectral variation in the absorption coefficient of water vapor, the Spectral Line Weighted-sum-of-gray-gases (SLW) model (Denison and Webb, 1993a, 1993b) was used to account for its spectral absorption characteristics. The SLW model has been shown to yield accuracy approaching that of computationally intensive line-by-line integrations for a small fraction of the computational cost.

Rather than calculate the absorption of flame radiation by integrating on a line-by-line basis over the hundreds of thousands of lines, the SLW model specifies

several discrete values of the absorption coefficient κ_k (called gray gas absorption coefficients), determines the total radiation source spectral content corresponding to each discrete value of κ_k (characterized by gray gas weights w_k), and sums (or integrates) the total radiation from a blackbody source over the total number K of discrete gray gas absorption coefficients specified. The integration over a few carefully chosen values of the gray gas absorption coefficient thus takes the place of spectral integration over wavelength in the traditional line-by-line method.

The integration of Eq. (3) is used to evaluate the radiant flux from one finite area A_i to another A_j . As shown in Figure 1b, θ_i and θ_j are the angles between the normal vector to each surface and the line joining corresponding differential elements on surfaces i and j , respectively, and r is the distance between the two endpoints of the joining line. In order to determine the variation of local incident flux along the fuel bed, the fuel was divided into small but finite spatial strips running parallel to the shared flame/fuel edge, as shown by strip j in Figure 1b. The incident flux on the fuel was then calculated using Eq. (2) for each strip. Invoking the SLW model, the total radiative flux leaving the planar flame surface and arriving at finite spatial strip j along the fuel bed may be shown to be the sum of radiative contributions from all gray gases:

$$q_{flame \rightarrow fuel, j} = E_{b, flame} \sum_k^K (\overline{s_{flame s_{fuel, j}}})_k w_k \quad (4)$$

where $q_{flame \rightarrow fuel, j}$ is the spectrally integrated radiation flux emitted by the flame which is incident on strip j along the fuel bed, $E_{b, flame}$ is the total blackbody radiation flux emitted by the flame at temperature T_f , and $(\overline{s_{flame s_{fuel, j}}})_k$ and w_k are the volumetric exchange factor and gray gas weight, respectively, corresponding to gray gas absorption coefficient κ_k . The gray gas weights w_k are determined by evaluating the area under the Planck spectral blackbody radiation distribution $E_{b, flame, \eta}$ where the corresponding gray gas absorption coefficient κ_k prevails for the gas specie in question (Denison and Webb, 1993a). The gray gas weights sum to unity, $\sum_k^K w_k = 1$. Increasing the number of gray gases employed improves the accuracy of the predictions. In this study, $K = 20$ gray gases were used in Eq. (4). Further increases in the number of gray gases yielded no appreciable change in the solution.

Because the closed-form integration of Eq. (3) evaluating the volumetric exchange factor for each gray gas is generally not possible for arbitrary κ_k , the expression was evaluated using numerical integration. The approach followed here tracks radiation emitted from specified locations along the planar flame shown in Figure 1b to destination strip j along the fuel bed. Two-dimensional flame and fuel bed surfaces were used in the numerical integration as shown in Figure 1b, and the lateral extent of the flame and fuel surfaces was systematically increased to determine the size large enough to yield the one-dimensional variation in radiative flux along the fuel bed illustrated in Figure 1a. The lateral dimension required to achieve predictions independent of end effects was 20 times the flame height for all configurations. The surfaces of both flame and fuel were discretized in both spatial directions for numerical evaluation of the integrals in Eq. (3).

The multiple spatial strips along the fuel bed were clustered near the base of the flame in order to accurately resolve the steep gradient of incident radiant flux with position along the fuel. Each strip j was subsequently discretized into smaller differential elements used to integrate Eq. (3). The numerical integration procedure sweeps through differential area elements on each strip of the fuel bed and on the entire flame surface, evaluating the local angles θ_i and θ_j for each of the elements and the corresponding distance r separating the two differential elements. The solution thus determines the radiative transport arriving at strip j from the entire flame surface after being attenuated by the absorbing water vapor. The double integration must be performed for each gray gas. Thereafter, the summation over all K gray gases in Eq. (3) is carried out to determine the total radiative flux according to Eq. (4).

With the exception of the exponential absorption term, $e^{-\kappa_k r}$, the volumetric exchange factor $(\overline{S_{flame}S_{fuel,j}})_k$ is identical to the classical configuration factor $F_{i,j}$ used for predicting radiative exchange between diffuse surfaces in the absence of a radiatively participating intervening medium. Analytical expressions for the radiative configuration factor $F_{i,j}$ for commonly encountered surface-to-surface exchange configurations are tabulated in the literature (Siegel and Howell, 2002). The accuracy of the evaluation of the volumetric exchange factor was verified by comparing the numerical integration of Eq. (3) for the limiting transparent intervening medium case ($\kappa_k \rightarrow 0$) to results from published analytical expressions for the radiation configuration factor for identical geometric scenarios. Validation under this $\kappa_k \rightarrow 0$ condition was conducted for both the $\phi = 0$ and 30 degree flame configurations for a flame height $H = 1$ m. It was found that for 10^{11} integration points the difference between numerical integration and analytical result was less than 1%.

This favorable comparison for the non-absorbing limiting case demonstrates the accuracy of the numerical integration of Eq. (3), if only for the transparent intervening medium case. The convergence characteristics of the numerical integration for the case of finite radiation attenuation ($\kappa_k \neq 0$) were also investigated. For a single gray gas ($K = 1$) of gray gas absorption coefficient $\kappa_1 = 5 \text{ m}^{-1}$, it was found that the value of $(\overline{S_{flame}S_{fuel,j}})_k$ ceased to change for a spatial discretization exceeding 10^{10} integration points for both $\phi = 0$ and 30 deg. Increasing computer precision (to the so-called "long double" precision) yielded no change to eight significant figures in the value of the volumetric exchange factor. The results suggest a convergent solution free of round-off error, lending confidence in the accuracy of the volumetric exchange factor for finite gray gas absorption coefficient. Based on the results of the validation exercise, 10^{11} integration points were used in all simulations reported here. The calculation of the volumetric exchange factor for all strips on the fuel bed required approximately 12 hours of computation time for each of the 20 gray gases. In practice, $(\overline{S_{flame}S_{fuel,j}})_k$ was evaluated for all gray gases simultaneously using parallel computing, after which the summation of Eq. (4) was performed to determine the local radiant flux incident on the fuel.

RESULTS AND DISCUSSION

Simulations were performed for 2 flame heights, $H = 1$ and 10 m, with corresponding fuel bed lengths of $L = 10$ and 100 m, respectively. Vertical ($\phi = 0$ deg) and angled ($\phi = 30$ deg) flames were explored. Two flame temperatures were

investigated, $T_f = 1000$ K and 1500 K. These 2 flame temperatures were selected based on wildland fire measurements of Butler et al. (2004a), where temperatures (using unshielded thermocouples) as high as 1200°C were reported. All simulations were conducted with and without environmental water vapor in the intervening medium between flame and fuel bed. For those predictions including water vapor, a uniform mole fraction of 3.5% H_2O was imposed, corresponding to a worst-case scenario relative humidity of 100% at a temperature of 300 K. Again, an isothermal, radiatively black flame with maximum temperature $T_f = 1500$ K radiating to an environment characterized by 100% relative humidity represents the upper bound on the influence of environmental water vapor on attenuation of flame radiation in wildland fires.

Figure 2 illustrates the variation in predicted local incident radiant flux with position along the fuel bed for flame height $H = 1$ m with and without the effect of radiation attenuation by 3.5% environmental water vapor. Figure 2a illustrates the effect of varying flame temperature and flame angle, and Figure 2b shows the influence of flame height. The trends for all cases are qualitatively similar.

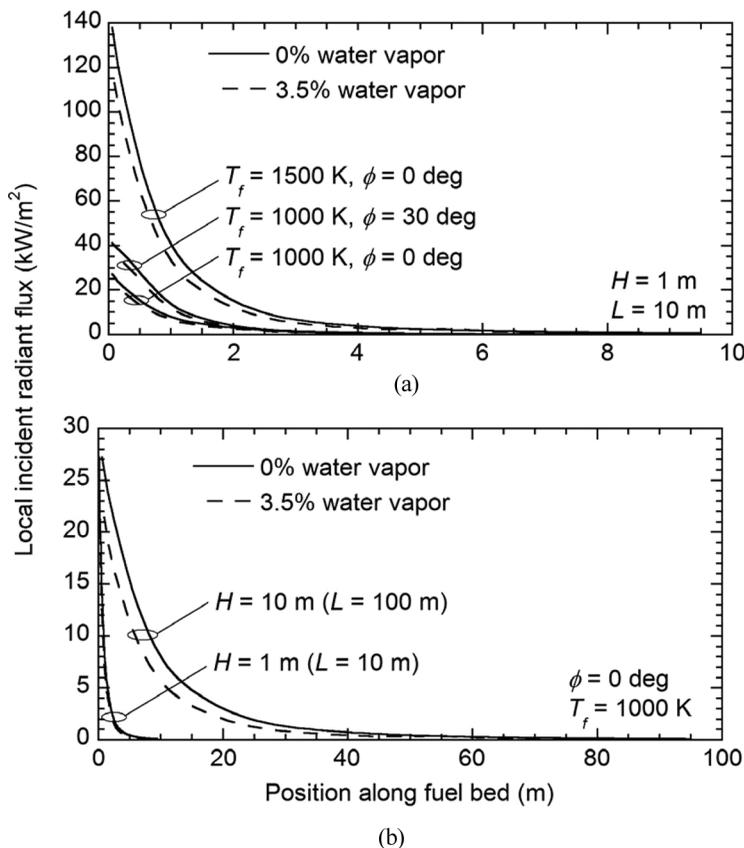


Figure 2 Predicted local incident radiant flux along the fuel bed for cases with and without water vapor absorption.

As expected, the highest radiant flux incident on the fuel bed is at the base of the flame, where the flame is viewed most intensely by the fuel bed. The local radiant flux drops dramatically with increasing distance along the fuel bed. Further, the magnitude of the incident flux is considerably higher for the hotter flame, and the local radiative flux is higher for the angled flame.

The influence of water vapor is to attenuate the radiation incident on the fuel bed. At the base of the flame where the radiant flux is the highest, absorption by environmental water vapor reduces the radiant flux incident on the fuel bed by 9% for the $T_f = 1000$ K flame, and 13% for the $T_f = 1500$ K flame. The greater influence of water vapor at higher T_f is due to the fact that the spectral emission from the hotter flame is concentrated more heavily in the spectral regions corresponding to the infrared absorption bands of water vapor. As the flame angle increases from $\phi = 0$ deg, the flame occupies a greater field of view for all locations along the fuel bed. Whereas the reduction in incident flux at the base of the flame for the $\phi = 0$ deg case was 9%, the flux there is reduced by only 5% for the $\phi = 30$ deg case. This may be explained by the fact that the average path length for radiation between flame and fuel bed is smaller for angled flames and consequently, there is less attenuation by water vapor.

The effect of flame height is shown in Figure 2b, where local incident flux predictions for $H = 1$ and 10 m (with $L = 10$ and 100 m, respectively) are plotted for the vertical flame configuration for $T_f = 1000$ K. The differences in flux magnitude very near the base of the flame are not significantly different for the two different flame height simulations. This is not surprising, since the region near the flame base "sees" little of the flame beyond the 1 m height, and is therefore exposed to nearly the same radiative environment in both cases. Farther from the flame base along the fuel bed, however, the longer flame yields higher incident flux magnitudes produced by the effect of the additional flame height for $H = 10$ m. The attenuation of radiation by water vapor is more significant for the longer flame, due to the fact that radiation from the longer flame must, on average, traverse greater distance of absorbing medium before reaching the fuel.

The local influence of flame radiation absorption by water vapor for the cases presented in the foregoing sections is summarized in Figure 3. Here, the attenuation effect is expressed as a fractional reduction in local radiant flux resulting from absorption by environmental water vapor. To facilitate the presentation of data for both flame heights studied, the data are plotted as a function of normalized position along the fuel bed, x/L , where x is the coordinate along the fuel bed measured from the base of the flame. For all cases the fractional attenuation is lowest near the base of the flame where the magnitude of the incident flux is highest, and increases with increasing distance along the fuel bed.

It should be recognized, that although the fractional influence is higher farther from the flame, Figure 2 indicates that the local incident flux decreases rapidly in this direction. Thus, the percentage reduction in local radiant flux is highest in regions where the radiant flux is low. It is again observed that the relative effect of water vapor absorption is greater for increasing flame temperature, flame height, and for more nearly vertical flames. As outlined previously, this is explained by the greater average path-length through which the flame radiation must pass before arriving at the fuel bed for these scenarios.

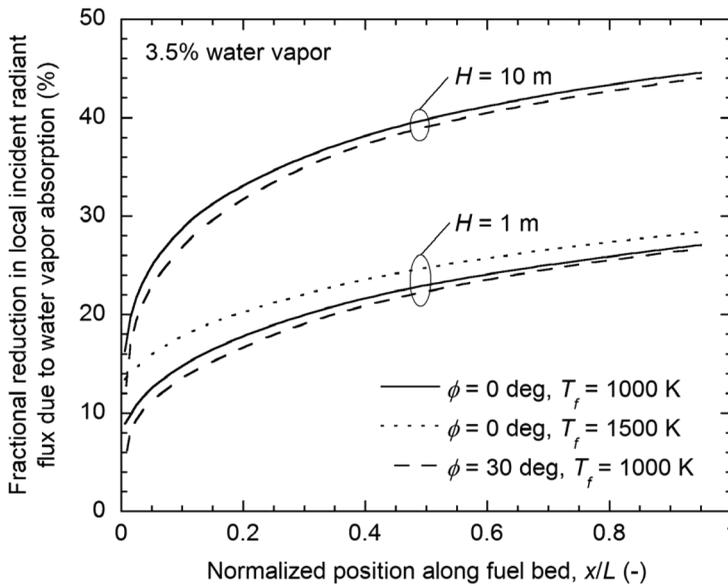


Figure 3 Fractional reduction in local incident radiant flux due to water vapor absorption as a function of normalized position along the fuel bed for all cases studied.

The foregoing sections have presented the modest effect of absorption by environmental water vapor on the *local* radiative flux incident on the fuel bed. Of interest is the aggregate effect of radiation absorption by water vapor on the total heat transfer to the fuel bed, found by summing the local incident flux spatially over the entire fuel bed area:

$$Q_{flame \rightarrow fuel} = \sum_j q_{flame \rightarrow fuel, j} A_j \quad (5)$$

Here, $Q_{flame \rightarrow fuel}$ is the total radiant heat transfer emitted by the flame that is incident on the entire fuel bed. Evaluation of Eq. (5) reveals that absorption by environmental water vapor reduces the total radiative heat transfer incident on the fuel bed by 13.5%, 16.7%, and 11.9%, respectively, for the $H = 1$ m flame for $\phi = 0$ deg at $T_f = 1000$ K and 1500 K, and $\phi = 30$ deg at $T_f = 1000$ K. The reduction in incident radiant transfer for the $H = 10$ m flame is 26.7% and 25.1% at $T_f = 1500$ K for flame angles of $\phi = 0$ deg and $\phi = 30$ deg, respectively. Again, these data are for extreme, idealized conditions (isothermal black flames, 100% relative humidity). As observed and explained previously, environmental water vapor has less influence for lower-temperature flames and for angled flames. Its effect is probably negligible for flames shorter than 1 m in height, although growing in significance for taller flames.

CONCLUSIONS

Predictions have been made for radiative transfer from black, isothermal, planar flame incident on a horizontal fuel bed maintained at 300 K. The effect of flame

inclination, flame temperature, and flame height were explored for cases with and without absorption by environmental water vapor in the intervening air (at 300 K). Even under the most adverse conditions, absorption by water vapor has a rather modest effect on the local radiant flux from flame to fuel. The effect is more pronounced for larger flames at higher flame temperatures, and less pronounced for angled flames.

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