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An estimate of the correction applied to radiant flame measurements due to attenuation by atmospheric CO_2 and H_2O

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Abstract

A narrow band statistical model has been used to estimate the uncertainty introduced into radiative heat flux measurements from fires which is attributable to attenuation by atmospheric H_2O and CO_2. The flames were assumed to be soot-dominated with blackbody emission characteristics. The ambient surroundings near the flames were assumed to be homogeneous with the total pressure being fixed at one atmosphere. Atmospheric CO_2 concentrations were held constant at 0.04 kPa and the water vapor concentrations varied between 0.55–5.63 kPa based on temperature and relative humidity. The remaining partial pressures were accounted for by O_2 and N_2. Correlations to estimate atmospheric attenuation are given over a range of conditions that include path length (10–200 m), ambient temperature (19–35°C), source temperature (1000–1600°C) and relative humidity (0.25–1.0) as parameters. The results of these calculations indicate that, over this range **of** conditions, the radiant flux can be attenuated by as much as 42%.

1. Introduction

The effect of radiant attenuation by atmospheric species on heat **flux** measurements from flames is well established. The fraction of attenuated radiation between a fire and a detector is a function of, among other factors, the radiant source (temperature and emitting species concentrations), atmospheric conditions (tem-

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perature and absorbing species concentrations, relative humidity) and the absorption path length. A series of controlled experiments which investigated the radiant output of fires were performed at Factory Mutual Research Corporation (FMRC) and the National Bureau of Standards **(NBS,** now NIST) in the mid to late 1970's and early 1980's **[1–8].** More recently, the radiative characteristics of large-scale liquid pool fires have been studied at the Fire Research Institute of Japan (FRI) [9–11] and the University of Poitiers (UP) **[12,13].** Additionally, field measurements of the radiative output from the Kuwait oil field fires were performed in 1991 [14].

When radiation passes through a field containing molecular species such as H_2O and CO_2, the intensity is attenuated due to absorption and the resulting measurement (intensity, heat flux) is lower than the source emissive power. Attempts have been made to minimize the effects of attenuation by sighting radiometers through N_2 purged tubes [1]. In most cases, however, the effects of atmospheric attenuation were not taken into account.

Attenuation is not always a significant effect. The studies performed at FMRC, **NIST,** FRI and UP focused primarily on fires using moderately or heavily sooting fuels; the emissive power of these flames is often taken to be proportional to a blackbody. Koseki and Yumoto [9] have shown that flame emissivity approaches $\varepsilon = 1$ for increasing pool sizes. The absorption of radiation that occurs in the relatively narrow spectral absorption bands of H_2O and CO_2 does not significantly attenuate the total radiative heat flux from a blackbody emitter over short path lengths. This was acknowledged by Modak and Croce [4] who, in a study of square PMMA pool fires (0.025–1.22 m on a side), estimated that under the worst case conditions atmospheric absorption did not exceed 8% for a path of 3 4 pool diameters.

Two circumstances in which attenuation of radiative emission by atmospheric H_2O and CO_2 may not be negligible are (1) non-sooting flames and *(2)* soot dominated flames in which measurements occur over long path lengths. In non-sooting flames emission from molecular gases, primarily H_2O and CO_2, dominates the radiant output. Since these gases are also the principal atmospheric absorbers, radiative attenuation can be significant, even over short path lengths. Alternatively, for measurements of large-scale fires it is not always possible to place a heat flux gauge close to the source [14]. For moderate to long measurement path lengths, attenuation by atmospheric H_2O and CO_2 can be significant even for heavily sooting flames with blackbody emission characteristics.

The total heat release rate (HRR) of a fire can be estimated from measurements of the radiant heat flux at a distance, **L,** from the fire. For distances greater than four diameters from the pool center, a fire can be treated approximately as a point source with the radiative power being expressed as **[14,15]:**

$$\dot{Q}_{\mathrm{rad}} = 4\pi L^2 \dot{q}''. \tag{1}$$

If atmospheric attenuation is significant, Eq. (1) will under predict the radiant heat release rate based on measured values of q''. Therefore, to account for atmospheric

attenuation, the transmittance should be included:

$$\dot{Q}_{\mathrm{rad}} = \frac{4\pi L^2 \dot{q}''}{\tau}. \tag{2}$$

The radiant fraction of a fire, defined as

$$\chi_{\mathrm{r}} = \frac{\dot{Q}_{\mathrm{rad}}}{\dot{Q}_{\mathrm{tot}}}, \tag{3}$$

takes on similar values for most hydrocarbon fuels at a given pool diameter [10,16–18]. In this expression $\dot{Q}_{\mathrm{tot}}$ is the total heat release rate. Combining **Eqs.** (2) and (3) gives

$$\mathrm{Qtot} = \frac{\mathrm{Qrad}}{\chi_{\mathrm{r}}} \propto \frac{\dot{q}''}{\chi_{\mathrm{r}}\tau}. \tag{4}$$

This expression demonstrates that neglecting the contribution of atmospheric attenuation will lead to an under prediction of the heat release rate of a fire based on heat **flux** measurements. Conversely, if one wishes to estimate the radiant heat flux based on a known set of fire parameters, Eqs. (2) and *(3)* can be rearranged to give

$$\dot{q}'' = \frac{\chi_r \dot{Q}_{\mathrm{tot}} \tau}{4\pi L^2} \tag{5}$$

which is consistent with the approach outlined in Refs. [15,16]. Results from the large-scale *(2* m < D < 30 m) liquid pool fires at **UP,** FRI and elsewhere indicate that radiation blockage by smoke produced from the fire increases with pool diameter. This has the effect of reducing the radiative fraction, χ_{r} [15,16]. The present analysis, however, does not address this issue.

Quantitative approaches have been proposed to account for the attenuation of flame radiation by atmospheric gases [15,16] and smoke [19]. Babrauskas [15] published atmospheric transmittance charts for a range of blackbody source temperatures and ambient conditions. In this report, however, no analytical expressions were provided to calculate transmittance and the path length was limited to 14 m. In some instances, radiative flux gauges must be situated at much greater distances from the emitting source. In a study of radiant emission from the 1991 Kuwait oil field fires, Evans et al. [14] located radiometers as far as 200m from the fires.

Mudan and Croce [16] proposed the use of emissivity charts published by Hottel and Sarofim [20] to calculate atmospheric attenuation by H_2O and CO_2. One drawback to this method is the indication that the H_2O emissivity charts have significant errors for source temperatures above 900°C and that the partial pressure correction is temperature dependent [21]. **A** preferable approach for calculating emissivity is the three-parameter curve fit provided by Modak [22] for H_2O and CO_2. However, these correlations are limited to situations in which the partial pressure of the absorbing species is greater than 0.11 kPa (0.001 atm) and the product of the path length and the partial pressure is less than 606.8 kPa-m (6 atmm). This range of partial pressures is suitable for fire product species, however the ambient CO_2 partial pressure is lower than the limit prescribed by the model. Additionally, for water vapor partial pressures in the order of a few kPa, the upper limit of the pressure path

length product limits the range of path lengths over which the model can be applied. A need therefore exists for analytic expressions to estimate the radiant attenuation by atmospheric H_2O and CO_2 at low absorbing species partial pressures and long path lengths. The purpose of this study was to calculate the magnitude of radiant attenuation by atmospheric H_2O and CO_2 for large scale, luminous fires using a 1-D model, and to provide correlations that permit corrections to be made to experimental heat flux measurements.

2. Simulated conditions

It was assumed that the fires were large (optically thick) and had soot-dominated emission behavior. Therefore, fire conditions were approximated as a blackbody emission source characterized by temperatures between 1000°C and 1600°C. This range includes the 927–1227°C (1200–1500 K) range of "Schmidt Temperatures" prescribed by de Ris [23] for turbulent hydrocarbon flames. The "Schmidt Temperature" is the temperature at which a blackbody source placed behind a flame is set so that it neither adds nor subtracts from the measured radiance. Atmospheric conditions were characterized by CO_2 concentration, ambient temperature and relative humidity. The conditions were chosen based on reported weather patterns [24] in Kuwait City and Tokyo, which are representative of conditions under which the oil field and the FRI measurements were performed, respectively. Figs. 1a and b show the average monthly temperature and relative humidity for these cities. The total pressure was assumed constant at 101.3 kPa (1 atm) and the atmospheric CO_2 concentration was fixed at 0.04 kPa. This CO_2 concentration is equivalent to 395 μL/L (ppm), which is slightly higher than the value of approximately 365 μL/L (ppm) reported for 1998 by Thoning and Tans [25]. Changing the CO_2 concentration to 350 μL/L (ppm) has a minimal effect, reducing the total attenuation by less than 0.1%. Based on available data [26], the average monthly barometric pressure in Tokyo varies by less than 1% from 101.3 kPa (1 atm). Therefore the assumption of 101.3 kPa (1 atm) total pressure and 0.04 kPa CO_2 concentrations should produce reasonable results. Water vapor was the only other absorbing species considered and its concentration was characterized by temperature and relative humidity. The water concentration was varied from 0.55 kPa at 19°C and $\phi = 0.25$–5.63 kPa at 35°C and $\phi = 1.0$. The remainder of the atmosphere consisted of O_2 and N_2, with mole fractions of 0.21 and 0.79 respectively. In all of the simulations, the atmosphere surrounding the fire was considered homogeneous. One consequence of this condition is a step change in temperature and species concentrations between the fire and its surroundings. A schematic of the arrangement is shown in Fig. 2.

A narrow band statistical model (RADCAL) was used to simulate the radiative emission from the fire and absorption by atmospheric gases [27]. This model has been used extensively in the heat transfer and combustion communities. RADCAL solves the equation of radiative transfer along a line of sight for an absorbing–emitting medium containing a mixture of gases and soot. The model calculates the

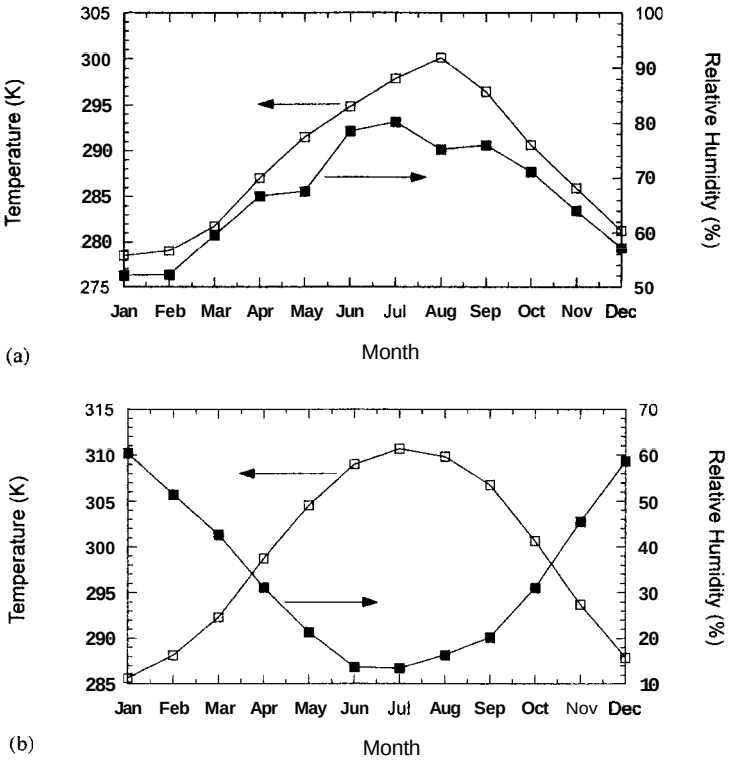

Fig. 1. (a) Monthly average temperature and relative humidity for Tokyo, Japan. (b) Monthly average temperature and relative humidity for Kuwait City, Kuwait.

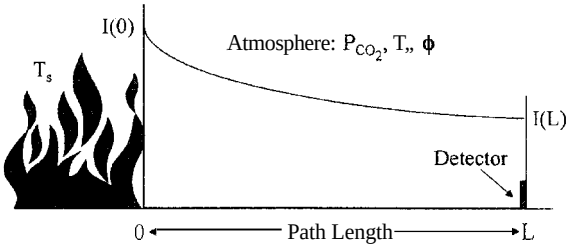

Fig. 2. Schematic of model configuration.

spectral absorption coefficient for a gaseous mixture through the use of narrow-band radiation models. The line of sight can be divided into a series of homogeneous, isothermal segments and the radiant spectral intensity incident upon an area is calculated. The transmittance was calculated as the ratio of the spectrally integrated

intensity at a distance, L, from the fire versus the spectrally integrated intensity at $L = 0$

$$\tau = \frac{I(L)}{I(0)} = \frac{\int_{\lambda_1}^{\lambda_2} i_\lambda(L)\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} i_\lambda(0)\,\mathrm{d}\lambda} = \frac{\int_{\lambda_1}^{\lambda_2} \tau_\lambda i_\lambda(0)\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} i_\lambda(0)\,\mathrm{d}\lambda}, \tag{6}$$

where i_λ is the spectral intensity at a distance, L, from the fire and τ_λ is the spectral transmittance of the gases along the path. While the model is valid for wavelengths up to 200 μm, the spectral range that was used for these calculations was limited to $\lambda = 0.4$–$10.8\,\mu\mathrm{m}$. This range was wide enough to account for 96–99% of blackbody emission for the temperature range 1000–1600°C.

The calculations performed here were an attempt to model the measurement of a radiometer placed at a fixed location relative to a flame. Since the simulation is one dimensional, no attempt was made to determine the effect of varying the position of a radiometer relative to the flame except by varying the path length between the flame and the instrument. It is assumed that the radiometer has a flat spectral response and a wide view angle. This simulation considers radiation directed along a single line of sight such that the relative size of the fire has a small influence on the actual incident flux. This view factor effect becomes negligible with increasing distance.

3. Results

The measurement path length was varied from 10–200 m; this range was chosen to simulate the conditions from studies performed on the 1991 Kuwait oil fires [14]. Over a path of this length, significant attenuation of the initial radiant intensity can occur. Generally, conditions of low flame temperature, combined with high air temperature and high relative humidity produce the greatest attenuation. Blackbody emission (represented by i_λ in Eq. *(6))* is a strong function of temperature, while atmospheric transmittance (τ_λ) is independent of the radiant source temperature. The net result is that the total, or integrated, transmittance (τ) calculated using **Eq.** (6) is a weak function of the radiant source temperature. Fig. **3** plots the intensities, $i_\lambda(L)$ for path lengths of $L = 0$ and 200 m, source temperatures of $T_s =$ 1000°C and $T_s = 1200$°C, an ambient temperature of $T_a = 27$°C, and a relative humidity of $\phi = 0.25$. This figure demonstrates the dependence of i_λ on T_s, however the ratio $\tau_\lambda = i_\lambda(L)/i_\lambda(0)$ is the same at each temperature. For a fixed atmospheric condition, a higher fraction of incident radiation will be absorbed from a source at a low temperature than one at a high temperature on an integrated basis. At the same time, higher atmospheric temperatures and relative humidity values result in higher water vapor concentrations, this leads to increased absorption. This is shown in Fig. **4,** which plots the total transmittance, calculated from Eq. (6) as a function of path length for two blackbody source temperatures. This figure shows the attenuation for flame temperatures of 1000°C and 1200°C, the relative humidity of the surrounding air $\phi = 0.5$ and 1.0 and path lengths up to $L = 200$ m,

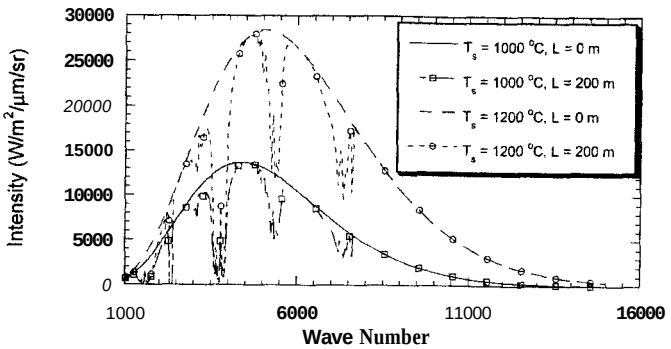

Fig. 3. Radiant intensity calculated from RADCAL [25] for the conditions $T_a = 27°C$, relative humidity $\phi = 0.25$, path length $L = 0$m. 200 m, and source temperature $T_s = 1000°C$, 1200°C.

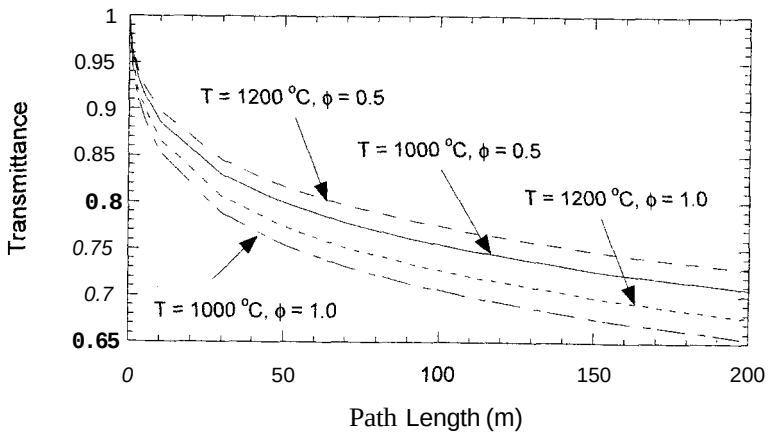

Fig. 4. Normalized radiant intensity, $I(L)/I(0)$, vs. path length for flame temperatures of 1000°C and 1200°C and ambient conditions of $T_a = 23°C$, $\phi = 0.5, 1.0$.

with the air temperature taken as *23°C.* The change in humidity from 0.5–1.0 doubles the partial pressure of water vapor in the atmosphere from 1.59 to 3.17 kPa, while the atmospheric CO_2 partial pressure was fixed at 0.04 kPa. The result of the change in humidity is reflected by the approximately 5% higher attenuation seen at 200 m for each flame temperature. The total transmittance is less sensitive to changes in source temperature. The remaining set of conditions produced similar results.

A correlation was fit to the calculations to permit approximate corrections for heat flux measurements. The correlation gives the transmittance as a function of path length, flame temperature, atmospheric temperature and relative humidity. The

Table 1
Constants to calculate coefficient a_n using **Eq.** (8). These values are valid over the following ranges: $T = 19°C-35°C$, $T_s = 1000°C-1600°C$, $\phi = 0.25-1.0$

n	C_{1n}	C_{2n}	C_{3n}	C_{4n}
0	1.486	-2.003×10^{-3}	4.68×10^{-5}	-6.052×10^{-2}
1	1.225×10^{-2}	-5.900×10^{-5}	1.66×10^{-6}	-1.759×10^{-3}
2	-1.489×10^{-4}	6.893×10^{-7}	-1.922×10^{-8}	2.092×10^{-5}
3	8.381×10^{-7}	-3.823×10^{-9}	1.0511×10^{-10}	-1.166×10^{-7}
4	-1.685×10^{-9}	7.637×10^{-12}	-2.085×10^{-13}	2.350×10^{-10}

transmittance was fit to a fourth order polynomial

$$\tau = \frac{I(L)}{I(0)} = a_0 + a_1 L + a_2 L^2 + a_3 L^3 + a_4 L^4, \tag{7}$$

where L is the distance from the source to the detector (m). The coefficients a_n were fit to a linear function of atmospheric temperature (T_a), flame temperature (T_s), and humidity (ϕ):

$$a_n = C_{1n} + C_{2n} T_a + C_{3n} T_s + C_{4n} \phi. \tag{8}$$

Values for each parameter are listed in Table 1. The temperatures used to calculate a_n have units of Kelvin. The correlation outlined in **Eqs.** (7) and (8) fits the calculations to within 2% over the entire range in conditions that were considered.

Based on the data in Fig. 1 and Ref. [14], an estimate of the atmospheric transmittance can be made from Eqs. (7) and (8) for the average conditions of Kuwait City during the month of February. Using an air temperature of $T_a = 15°C$ (288 K) and a relative humidity of $\phi = 51\%$, and assuming **a** "Schmidt" flame temperature of $T_s = 1023°C$ (1300 K), the transmittance for a 200m path is $\tau = 0.75$. De Ris recommends a range in "Schmidt" temperatures of $T_s = 927-1227°C$ (1200–1500K), the lower of these temperatures being associated with soot-dominated flames [23]. According to the same reference, increasing fire size leads to a slight reduction in "Schmidt Temperature". From Fig. 4 and Eqs. (7) and (8), it can be seen that the total transmittance is relatively insensitive to the source temperature, T_s. This can also be inferred from the magnitude of the coefficients in Table 1. The calculated total transmittance values for source temperatures of $T_s = 927°C$ and 1127°C, keeping other conditions fixed, are $\tau = 0.74$ and 0.76, respectively. The nominal transmittance value of $\tau = 0.75$, calculated for the conditions prescribed in Ref. [14] implies that the burning rate could have been underpredicted by as much as 33% based on Eq. (5). Uncertainty in the value of χ_r can be large, particularly when the fuel composition and the effects of smoke blockage are unknown. Nevertheless, atmospheric attenuation can have a significant impact on the measured radiation from a fire and the results shown here provide a simple method for incorporating these effects into the analysis.

4. Conclusions

Calculations have been performed to estimate the attenuation of radiant heat output from a fire by atmospheric H_2O and CO_2 using a narrow band radiation model and a simplified 1-D approach. The calculations were performed over a wide range of temperatures and water vapor concentrations that simulate a variety of fire and ambient surrounding conditions. An analytic expression is provided to calculate atmospheric transmittance for path lengths between 10–200m. The expression is in good agreement with the band model calculations over the entire range of conditions. This correlation has an advantage over other existing methods of calculating atmospheric transmittance because it does not rely on graphical data.

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