

GRAY GAS WEIGHTING COEFFICIENTS FOR ARBITRARY GAS-SOOT MIXTURES

J. D. FELSKE and T. T. CHARALAMPOPOULOS

Department of Mechanical and Aerospace Engineering, State University of New York at Buffalo, Amherst,
NY 14260, U.S.A.

(Received 16 February 1982 and in final form 3 May 1982)

Abstract—A method is developed for determining the gray gas weighting coefficients for gas-soot mixtures from the coefficients which separately model the soot behavior and the behavior of the gases. Representations for both the emissivity and absorptivity are achieved. The approach is shown to be accurate over wide ranges of temperature, pathlength and soot concentration.

NOMENCLATURE

a_i	gray gas weighting coefficient—soot emissivity;
a'_i	gray gas weighting coefficient—soot absorptivity;
A_{ij}	total band absorbance;
ΔA_k	band overlap factor;
b_j	gray gas weighting coefficient—gas emissivity;
b'_j	gray gas weighting coefficient—gas absorptivity;
B_{ij}, B_k	gray gas weighting coefficient—gas-soot mixture emissivity;
B'_{ij}	gray gas weighting coefficient—gas-soot mixture absorptivity;
c_0	constant;
C_2	second Planck constant;
E_λ	Planck function;
f_v	volume fraction of soot;
k_{sm}	mean absorption coefficient for soot [m^{-1}];
$k_{s\lambda}$	spectral absorption coefficient for soot [m^{-1}];
K_{ij}, K_k	gray gas absorption coefficient—gas-soot mixture emissivity [m^{-1}];
K'_{ij}	gray gas absorption coefficient—gas-soot mixture absorptivity [m^{-1}];
L	pathlength [m];
P	pressure [atm.];
T	temperature [K];
T_m	temperature of the medium [K];
T_0	source temperature [K].

ϵ	emissivity;
λ	wavelength;
σ	Stefan-Boltzmann constant;
$\psi^{(3)}$	pentagamma function.

Subscripts

c,	carbon dioxide;
g,	gas;
s,	soot;
T,	gas-soot mixture;
w,	water vapor.

Superscript

\sim ,	sum of gray gases representation.
----------	-----------------------------------

INTRODUCTION

GRAY gas weighting coefficients for gas-soot mixtures have been determined by several investigators under certain conditions [1–5]. In refs. [1–3] the weighting factors for the soot were required to be equal to those for the gas at all temperatures. Although this requirement allows zonal heat transfer computations to be performed more efficiently, it can introduce significant errors since the weighting factors for gas and soot have somewhat different dependencies on temperature [4]. In ref. [4, 5] weighting factors for specific gas-soot mixtures were determined directly from mixture emissivities. Although a wide range of temperature was modelled, the weighting factors were determined for only two ratios of water vapor to carbon dioxide partial pressures and for only four different soot concentrations.

The purpose of the present study is to develop a simple analytical framework within which gray gas weighting coefficients for arbitrary gas-soot mixtures may be accurately determined from the coefficients which separately model the soot and the mixture of gases. In addition to providing a simple formulation for arbitrary mixtures, the present approach has the advantage of allowing the two different types of species to be modelled separately. Hence, when different types of soot need to be considered (because the combustion

Greek symbols

α	absorptivity;
β_j	gray gas absorption coefficient—gas emissivity [m^{-1}];
β'_j	gray gas absorption coefficient—gas absorptivity [m^{-1}];
γ_i	gray gas absorption coefficient—soot emissivity [m^{-1}];
γ'_i	gray gas absorption coefficient—soot absorptivity [m^{-1}];

of different fuels is being modelled) the gray gas weighting coefficients for the new gas-soot mixture may be determined simply by remodelling the soot and combining these results with the known behavior for pure gas mixtures. The constraint of having to directly model specific gas-soot mixtures [4, 5] is thereby removed.

ANALYSIS

Emissivity

The total emissivity of a gas-soot mixture may be written in general as [6]

$$\varepsilon_T = \varepsilon_s + \sum_{i,j} [\bar{E}_{\lambda ij} / (\sigma T_m^4)] e^{-\bar{\kappa}_{s,ij} L} A_{ij} - \sum_k \frac{\bar{E}_{\lambda k}}{\sigma T_m^4} e^{-\bar{\kappa}_{s,k} L} \Delta A_k \quad (1)$$

where ij denotes the i th band of the j th gas species, ΔA_k is the reduction in band absorptance due to band overlap in the k th spectral region, and ε_s is the total emissivity of the soot (as if no gases were present). The barred quantities indicate an appropriate mean value of the quantity for the particular gas band. By introducing the following approximation to equation (1), the desired result may then be obtained directly—no additional approximations are required.

As suggested in refs. [7, 8], if a single mean value for the absorption coefficient of the soot is adopted (k_{sm}) for all of the bands, and if, in addition, its value is chosen such that $\varepsilon_s = 1 - \exp(-k_{sm} L)$, then the total emissivity of the gas-soot mixture may be written as

$$\varepsilon_T = \varepsilon_s + (1 - \varepsilon_s) \varepsilon_g \quad (2)$$

where ε_g is the total emissivity of the gases (as if no soot were present) and is given by

$$\varepsilon_g = \sum_{i,j} \frac{\bar{E}_{\lambda ij}}{\sigma T_m^4} A_{ij} - \sum_k \frac{\bar{E}_{\lambda k}}{\sigma T_m^4} \Delta A_k \quad (3)$$

The approximation given by equation (2) has been demonstrated to be accurate over three decades of pathlength for a given gas-soot mixture at a single temperature [8]. Since equation (2) marks the point of departure for the present study, its accuracy was investigated over a wider range of conditions. As discussed in detail in the next section, this approximation was always found to be reliable.

The desired sum of gray gases representation for the gas-soot mixture emissivity is of the form [4, 5]

$$\tilde{\varepsilon}_T = \sum_{k=1}^N B_k (1 - e^{-K_k L}) \quad (4)$$

where

$$B_k = B_k(T_m) \quad (5)$$

and

$$K_k = K_k(P_c, P_w, f_v) \quad (6)$$

in which P_c and P_w are the partial pressures of the carbon dioxide and water vapor and f_v is the volume

fraction of soot. The \sim is introduced to indicate quantities which are represented by the sum of gray gases model. In addition, to satisfy the optically thick limit,

$$\sum_{k=1}^N B_k = 1. \quad (7)$$

An important feature of the above representation is that the dependence of the total emissivity on temperature is to be carried entirely by the pre-exponential factor B_k . This type of representation is desired since it greatly reduces the computational requirements associated with determining the zonal interchange areas which arise when computing radiative heat transfer by the zone method [4, 5].

To achieve this representation from the individual sum of gray gases representations for the pure gas and pure soot emissivities, the individual representations must both be of the form defined by equation (4). That is, the emissivity of the gas mixture (in the absence of any soot) must be given by

$$\tilde{\varepsilon}_g = \sum_{j=1}^J b_j (1 - e^{-\beta_j L}) \quad (8)$$

where

$$b_j = b_j(T_m), \quad (9)$$

$$\beta_j = \beta_j(P_c, P_w) \quad (10)$$

and

$$\sum_{j=1}^J b_j = 1. \quad (11)$$

The emissivity of the soot (in the absence of any gases) must be given by

$$\tilde{\varepsilon}_s = \sum_{i=1}^I a_i (1 - e^{-\gamma_i L}) \quad (12)$$

where

$$a_i = a_i(T_m), \quad (13)$$

$$\gamma_i = \gamma_i(f_v) \quad (14)$$

and

$$\sum_{i=1}^I a_i = 1. \quad (15)$$

It is to be noted that the single gray gas representation of the soot emissivity which was used in deriving equation (2) from equation (1), $\varepsilon_s = 1 - \exp(-k_{sm} L)$, is not of the above form since $k_{sm} = k_{sm}(T, f_v)$ [7, 8]. Therefore, it must first be represented in this form in order to achieve the desired result. This is accomplished in a later section.

From equations (11) and (15) it is noted that

$$\begin{aligned} 1 &= \left(\sum_{i=1}^I a_i \right) \left(\sum_{j=1}^J b_j \right) \\ &= \sum_{i=1}^I \sum_{j=1}^J a_i b_j \end{aligned} \quad (16)$$

Then, by combining equations (2), (8), (11), (12), (15) and (16), it follows that the total emissivity of the gas-soot mixture may be written in the form of equation (4) as

$$\tilde{\varepsilon}_T = \sum_{i=1}^I \sum_{j=1}^J B_{ij}(1 - e^{-K_{ij}L}) \quad (17)$$

where

$$B_{ij} = a_i b_j \quad (18)$$

$$K_{ij} = \gamma_i + \beta_j. \quad (19)$$

Equations (17)–(19) thereby represent the emissivity of an arbitrary gas-soot mixture as a sum of gray gases in which the weighting factors (B_{ij} , K_{ij}) may be computed from those used to separately model the gas (b_j , β_j) and the soot (a_i , γ_i).

Absorptivity

For a gas-soot mixture at temperature T_m which is irradiated by a gray or black source at temperature T_0 , the absorptivity is given by

$$\alpha_T(T_m, T_0) = \alpha_s(T_0) + \sum_{i,j} \frac{\bar{E}_{\lambda ij}(T_0)}{\sigma T_0^4} e^{-\bar{\kappa}_{s,ij}L} A_{ij}(T_m) - \sum_k \frac{\bar{E}_{\lambda k}(T_0)}{\sigma T_0^4} e^{-\bar{\kappa}_{s,k}L} \Delta A_k(T_m). \quad (20)$$

The total absorptivity of the pure soot, α_s , depends only on the source temperature since the spectral absorption coefficient for the soot is, to a good approximation, independent of temperature across the range of temperatures encountered in combustion systems [9]. Another consequence of this physical characteristic of the soot is that

$$\alpha_s(T_0) = \varepsilon_s(T_0). \quad (21)$$

Proceeding in the same manner which led to equation (2) from equation (1), one obtains the following approximate expression for the total absorptivity:

$$\alpha_T(T_m, T_0) = \alpha_s(T_0) + [1 - \alpha_s(T_0)]\alpha_g(T_m, T_0) \quad (22)$$

where

$$\alpha_g(T_m, T_0) = \sum_{i,j} \frac{\bar{E}_{\lambda ij}(T_0)}{\sigma T_0^4} A_{ij}(T_m) - \sum_k \frac{\bar{E}_{\lambda k}(T_0)}{\sigma T_0^4} \Delta A_k(T_m). \quad (23)$$

The accuracy of the above relationship is demonstrated in the next section.

The desired sum of gray gases representation for the absorptivity is then achieved in a manner analogous to that used in developing the expression for the emissivity. The result is

$$\tilde{\alpha}_T = \sum_{i=1}^I \sum_{j=1}^J B'_{ij}(1 - e^{-K'_{ij}L}) \quad (24)$$

where

$$B'_{ij}(T_m, T_0) = a'_i(T_0)b'_j(T_m, T_0) \quad (25)$$

and

$$K'_{ij}(f_v, P_c, P_w) = \gamma'_i(f_v) + \beta'_j(P_c, P_w) \quad (26)$$

in which the functions $a'_i(T)$, $\gamma'_i(f_v)$, $b'_j(T_m, T_0)$ and $\beta'_j(P_c, P_w)$ are the gray gas weighting coefficients used in modelling the pure soot and pure gas absorptivities

$$\tilde{\alpha}_s = \sum_{i=1}^I a'_i(1 - e^{-\gamma'_i L}) \quad (27)$$

and

$$\tilde{\alpha}_g = \sum_{j=1}^J b'_j(1 - e^{-\beta'_j L}). \quad (28)$$

As a consequence of equation (21), $\tilde{\alpha}_s(T) = \tilde{\varepsilon}_s(T)$ and hence the weighting coefficients for the soot absorptivity are the same as for the soot emissivity

$$a'_i(T) = a_i(T) \quad (29)$$

$$\gamma'_i(f_v) = \gamma_i(f_v). \quad (30)$$

In modelling the gas absorptivity, the gray gas absorption coefficients are generally taken to be the same as for the emissivity modelling

$$\beta'_j(P_c, P_w) = \beta_j(P_c, P_w) \quad (31)$$

while the coefficients $b'_j(T_m, T_0)$ are determined by fitting to data [14].

ACCURACIES OF EQUATIONS (2) AND (22)

The accuracy of the approximate relation for the emissivity, equation (2), was investigated over wide ranges of temperature, pathlength and soot concentration for two sets of partial pressures of water vapor and carbon dioxide. The absorption coefficient of the soot was taken to be inversely proportional to wavelength

$$k_{s,\lambda} = c_0 f_v / \lambda \quad (32)$$

where c_0 is a constant which was set equal to 5.0. Based upon the above $k_{s,\lambda}$, the total emissivity of the soot is given by [6]

$$\varepsilon_s = 1 - \frac{15}{\pi^4} \psi^{(3)} \left[1 + \frac{c_0 f_v T_m L}{C_2} \right] \quad (33)$$

where $\psi^{(3)}$ is the pentagamma function. The band absorptances were computed according to the expression given in ref. [10] wherein the band parameters and correction factors were taken from refs. [11, 12]. Six bands for carbon dioxide were included (2.0, 2.7, 4.3, 9.4, 10.4, 15 μm) as well as five bands for water vapor (1.38, 1.87, 2.7, 6.3 μm , rotational). The reduction in band absorptance ΔA_k due to band overlap in the 2.7 μm region was computed according to [13]; in the 15 μm region, ΔA_k was computed according to ref. [12].

Table 1 indicates the percentage differences between the exact emissivity given by equation (1) and the

approximate emissivity as computed from equation (2). The average differences over the range of pathlengths $0.015 \leq L \leq 15$ m are listed along with the maximum deviations over the same range. The agreement is seen to be excellent for all combinations of temperature and soot concentration. Computations for $P_c = 0.1$ atm, $P_w = 0.2$ atm, $P_{total} = 1.0$ atm show similar agreement.

The accuracy of the approximate relation for the absorptivity, equation (22), was assessed by considering three different source temperatures ($T_0 = 600$, 1200 and 1800 K) in conjunction with the same ranges of temperature, pathlength and gas and soot concentrations used in the assessment of the emissivity relation. Table 2 indicates the percent differences between the exact absorptivity, equation (20), and the approximate absorptivity, equation (22), for a source temperature of 1200 K. The agreement is seen to be excellent for all combinations of soot concentration

and temperatures of the medium. Similar accuracy is exhibited at the same source temperature when $P_c = 0.1$ atm, $P_w = 0.2$ atm, $P_{total} = 1$ atm and for a source temperature of 1800 K with either set of partial pressures. For $T_0 = 600$ K, the errors are approximately twice those observed at the higher temperatures.

SUM OF GRAY GASES MODEL FOR SOOT

Although gray gas weighting coefficients are available for various mixtures of carbon dioxide and water vapor [1, 4, 14], corresponding coefficients for soot have only been given at a single temperature [1] using a three gray gas representation. In the present study a two gray gas representation has been achieved in fitting the emissivity (absorptivity) given by equations (12)–(15) over wide ranges of temperature, pathlength and soot concentration.

Table 1. Percentage differences* between the exact [equation (1)] and approximate [equation (2)] expressions for the total emissivity of H_2O-CO_2 -soot mixtures $P_c = P_w = 0.1$ atm; $P_{total} = 1.0$ atm

f_v	T_m (K)									
	600	800	1000	1200	1400	1600	1800	2000	2200	2400
10^{-8}	†0.37	0.37	0.50	0.70	0.95	1.20	1.46	1.70	1.55	1.70
	‡1.70	1.72	2.12	2.90	3.80	4.73	5.60	6.30	5.80	6.40
10^{-7}	1.90	1.56	1.60	1.82	2.10	2.30	2.40	2.50	1.84	1.82
	7.30	5.60	4.80	4.40	4.50	5.10	5.40	5.50	4.00	4.00
10^{-6}	3.20	2.25	1.90	1.70	1.60	1.50	1.40	1.22	0.85	0.75
	7.70	5.05	3.50	2.60	2.50	2.60	2.50	2.30	1.50	1.40
10^{-5}	1.60	1.04	0.82	0.70	0.58	0.48	0.40	0.32	0.23	0.18
	4.00	2.45	1.62	1.12	0.93	0.84	0.74	0.64	0.48	0.40

* Percentage difference = $100 \times [\text{equation (1)} - \text{equation (2)}]/\text{equation (1)}$.
† Average percentage difference for the range of geometric pathlengths $0.015 \leq L \leq 15.0$ m.
‡ Maximum percentage difference in the range of geometric pathlengths $0.015 < L \leq 15.0$ m.

Table 2. Percentage differences* between the exact [equation (20)] and approximate [equation (22)] expressions for the total absorptivity of H_2O-CO_2 -soot mixtures. $T_0 = 1200$ K; $P_c = P_w = 0.1$ atm; $P_{total} = 1.0$ atm

f_v	T_m (K)									
	600	800	1000	1200	1400	1600	1800	2000	2200	2400
10^{-8}	†0.55	0.62	0.66	0.70	0.72	0.74	0.76	0.78	0.41	0.44
	‡2.18	2.48	2.72	2.90	3.00	3.08	3.16	3.22	1.84	1.97
10^{-7}	1.30	1.48	1.67	1.82	1.95	2.06	2.16	2.26	1.31	1.42
	2.80	3.24	3.86	4.40	4.83	5.20	5.56	5.90	4.48	4.80
10^{-6}	1.23	1.42	1.60	1.70	1.85	1.95	2.03	2.10	1.67	1.74
	1.72	1.96	2.30	2.60	2.83	3.03	3.22	3.40	3.50	3.65
10^{-5}	0.54	0.61	0.66	0.70	0.70	0.70	0.70	0.70	0.62	0.61
	0.86	0.94	1.03	1.12	1.18	1.22	1.24	1.27	1.27	1.30

* Percentage difference = $100 \times [\text{equation (20)} - \text{equation (22)}]/\text{equation (20)}$.
† Average percentage difference for the range of geometric pathlengths $0.015 \leq L \leq 15.0$ m.
‡ Maximum percentage difference in the range of geometric pathlengths $0.015 \leq L \leq 15.0$ m.

Table 3. Percentage differences* between the exact [equation (33)] and approximate [equations (12) and (34)–(37)] expressions for the soot emissivity (absorptivity)

f_v	$T_m \text{ or } T_0$ (K)									
	600	800	1000	1200	1400	1600	1800	2000	2200	2400
10^{-8}	† – 7.44	– 7.05	– 6.23	– 5.18	– 3.47	– 2.66	– 1.26	0.20	1.72	3.30
	‡ – 11.75	– 9.07	– 8.34	– 7.02	– 5.37	– 3.55	– 2.85	– 4.02	– 5.27	7.78
10^{-7}	– 9.55	– 6.96	– 5.26	– 3.95	– 2.84	– 1.83	– 0.86	0.08	1.04	2.00
	– 13.30	– 8.80	– 7.83	– 6.31	– 4.53	– 2.70	– 2.46	– 3.60	4.26	6.54
10^{-6}	– 7.98	– 5.10	– 3.40	– 2.33	– 1.50	0.90	0.38	0.12	0.60	1.10
	– 13.50	– 8.70	– 7.32	– 5.62	– 3.70	– 1.80	– 2.08	0.26	4.85	7.12
10^{-5}	– 6.02	– 3.16	– 1.72	– 0.95	– 0.54	– 0.32	– 0.22	– 0.18	– 0.17	– 0.16
	– 13.6	– 8.10	– 6.20	– 4.45	– 2.73	– 1.30	– 1.70	2.38	4.12	5.90

* Percentage difference = $100 \times [\text{equation (33)} - \text{equation (12)}] / \text{equation (33)}$.

† Average percentage difference for the range of geometric pathlengths $0.005 \leq L \leq 50$ m.

‡ Maximum percentage difference in the range of geometric pathlengths $0.005 \leq L \leq 50$ m.

To find the values of $a_i(T)$ and $\gamma_i(f_v)$, optimization techniques [15] were employed in which an objective function was minimized subject to several constraints. The objective function was selected to be the sum over all pathlengths (for a fixed T and f_v) of the squares of the differences between ϵ_s and $\tilde{\epsilon}_s$ (equivalently, α_s and $\tilde{\alpha}_s$). The constraints were that the coefficients had to be positive and that the a_i had to sum to unity. Thirty-one pathlengths were chosen from 0.005 m to 50.0 m. For the ranges $600 \leq T \leq 2400$ K and $10^{-8} \leq f_v \leq 10^{-5}$ the $a_i(T)$ and $\gamma_i(f_v)$ determined by the optimization yielded an average deviation in predicted emissivity (absorptivity) of about 1.6%. The numerical values for $a_i(T)$ and $\gamma_i(f_v)$ were then put into analytical form by fitting them with various functions. Several representations of varying degrees of accuracy were achieved [16]. The simplest representations which also provided reasonable accuracy were found to be

$$a_1(T) = 1.447 - (7.943 \times 10^{-4})T + (7.977 \times 10^{-8})T^2 \quad (34)$$

$$a_2(T) = 1 - a_1(T) \quad (35)$$

and

$$\gamma_1(f_v) = \exp(13.70 + 1.001 \ln f_v), \quad (36)$$

$$\gamma_2(f_v) = \exp(14.83 + 0.9951 \ln f_v). \quad (37)$$

Table 3 indicates the percentage differences between the exact expression for the soot emissivity (absorptivity), equation (33), and the sum of gray gases representation [equations (12) and (34)–(37)]. The average differences over the range of pathlengths $0.005 \leq L \leq 50$ m are listed along with the maximum deviations over the same range. The simple two gray gas representation is seen to be quite good for temperatures greater than 800 K. For the usual range of flame temperatures ($1400 \leq T \leq 2000$ K) the agreement is excellent. Figure 1 depicts the agreement graphically for a soot concentration of $f_v = 10^{-6}$, typical of gaseous diffusion flames.

COMPUTATIONS FOR H₂O–CO₂–SOOT MIXTURES

To demonstrate the approach for computing properties of gas-soot mixtures, the sum of gray-gases representation for H₂O–CO₂ mixture emissivities given in ref. [14] was combined according to equations (17)–(19) with the sum of gray gases representation for soot given above. The results were then compared to the total emissivities computed from equation (1). In order to separate discrepancies caused by the combining formula [equations (17)–(19)] from discrepancies caused by imperfect modelling of the pure gas and pure

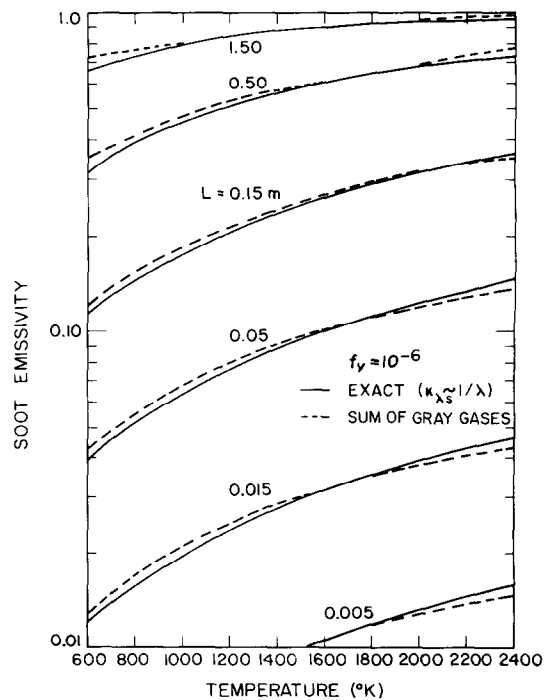


FIG. 1. Comparison of the sum of gray gases model of the soot emissivity [equations (12) and (34)–(37)], with the exact soot emissivity [equation (33)]: $f_v = 10^{-6}$.

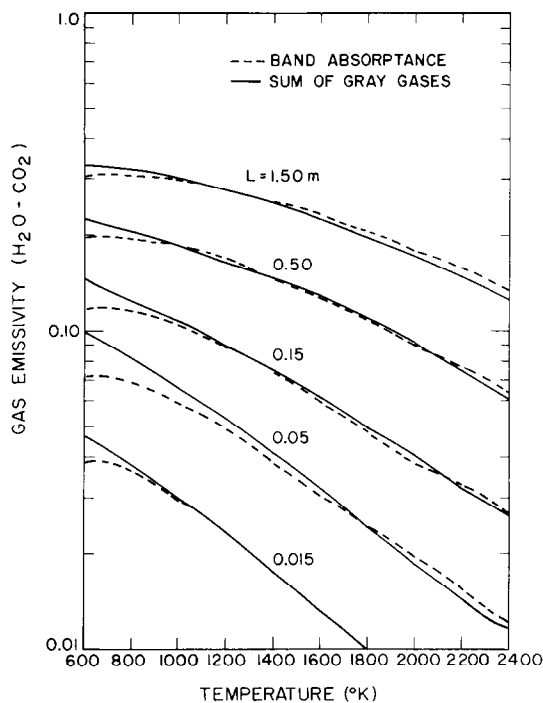


FIG. 2. Comparison of the sum of gray gases model of the $\text{H}_2\text{O}-\text{CO}_2$ emissivity [14] with the emissivity computed from band absorptances [equation (3)]: $P_c = P_w = 0.1$ atm; $P_{\text{total}} = 1.0$ atm.

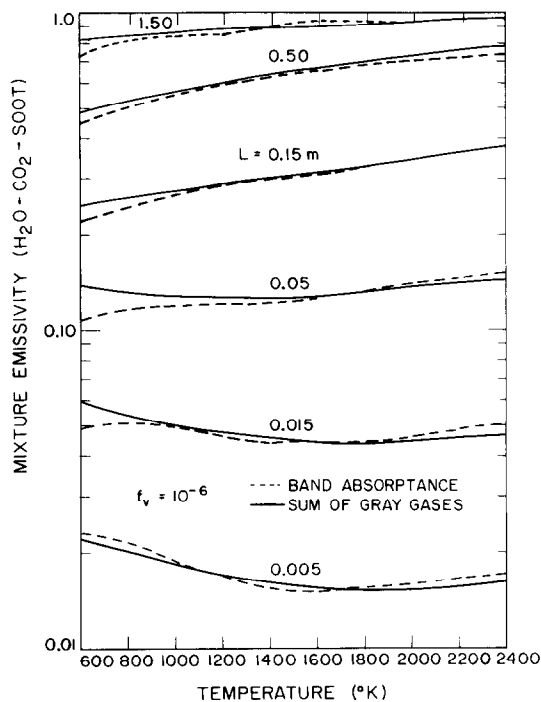


FIG. 4. Comparison of the sum of gray gases model of the $\text{H}_2\text{O}-\text{CO}_2$ -soot mixture emissivity [equation (17)] with the emissivity computed from the band absorptance formulation [equation (1)]: $f_v = 10^{-6}$; $P_c = P_w = 0.1$ atm; $P_{\text{total}} = 1.0$ atm.

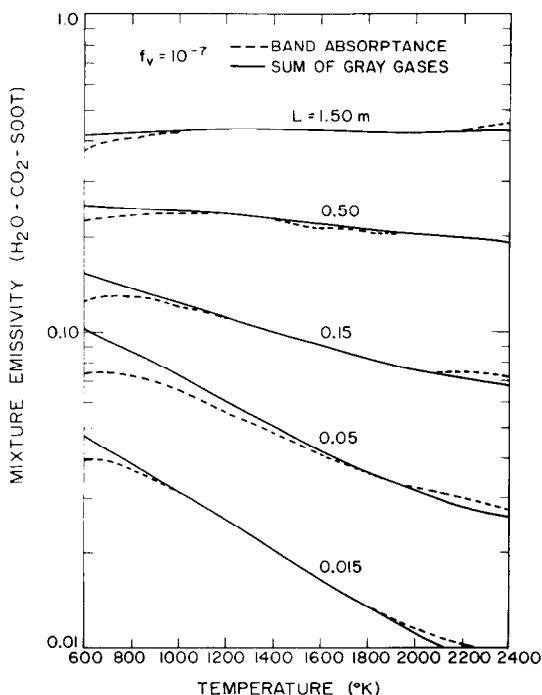


FIG. 3. Comparison of the sum of gray gases model of the $\text{H}_2\text{O}-\text{CO}_2$ -soot mixture emissivity [equation (17)] with the emissivity computed from the band absorptance formulation [equation (1)]: $f_v = 10^{-7}$; $P_c = P_w = 0.1$ atm; $P_{\text{total}} = 1.0$ atm.

soot emissivities, the total emissivities of the gases without soot were computed according to ref. [14] and compared with equation (3). These results are given in Fig. 2 where it is seen that deviations occur at temperatures less than 1000 K and at pathlengths greater than 1.5 m.

Results for the total emissivities of $\text{H}_2\text{O}-\text{CO}_2$ -soot mixtures are given in Figs. 3 and 4 for soot concentrations of $f_v = 10^{-7}$ and 10^{-6} respectively. The sum of gray gases representation, equation (17), is seen to yield emissivities which are essentially the same as those predicted using equation (1) whenever the individual sum of gray gases representations for both gases and soot are accurate. This is as it should be since the only approximation introduced into the analysis was equation (2)—whose accuracy has been demonstrated.

Acknowledgements—This research was supported by grants from the S.U.N.Y. Research Foundation (Faculty Research Fellowship) and the National Science Foundation (ENG-7825053).

REFERENCES

1. T. R. Johnson and J. M. Beer, The zone method analysis of radiant heat transfer: a model for luminous radiation, Fourth Symp. on Flames and Industry, paper no. 4, pp. 37-43. The Institute of Fuel, London (1972).
2. T. R. Johnson and J. M. Beer, Radiative heat transfer in furnaces: further development of the zone method of

- analysis, *Proc. 14th Int. Symp. Combust.*, pp. 639–649 (1973).
3. T. R. Johnson, T. M. Lowes and J. M. Beer, Paper 11: Comparison of calculated temperatures and heat flux distributions with measurements in the IJmuiden furnace, *J. Inst. Fuel* **39**, 39–51 (1974).
 4. P. B. Taylor and P. J. Foster, The total emissivities of luminous and non-luminous flames, *Int. J. Heat Mass Transfer* **17**, 1591–1605 (1974).
 5. P. B. Taylor and P. J. Foster, Some gray gas weighting coefficients for CO_2 - H_2O -soot mixtures, *Int. J. Heat Mass Transfer* **18**, 1331–1332 (1975).
 6. J. D. Felske and C. L. Tien, Calculation of the emissivity of luminous flames, *Combust. Sci. Tech.* **7**, 25–31 (1973).
 7. W. W. Yuen and C. L. Tien, A simple calculation scheme for the luminous flame emissivity, *16th Symp. (Int'l) Combust.*, pp. 1481–1486 (1977).
 8. J. DeRis, Fire radiation—a review, *Proc. 17th Int. Symp. Combust.*, pp. 1003–1016 (1979).
 9. S. C. Lee and C. L. Tien, Optical constants of soot in hydrocarbon flames, *18th Int. Symp. Combust.*, pp. 1159–1166 (1981).
 10. J. D. Felske and C. L. Tien, A theoretical closed form expression for the total band absorptance of infrared-radiating gases, *Int. J. Heat Mass Transfer* **17**, 155–158 (1974).
 11. D. K. Edwards and A. Balakrishnan, Thermal radiation by combustion gases, *Int. J. Heat Mass Transfer* **16**, 25–40 (1973).
 12. A. T. Modak, Exponential wide band parameters for the pure rotational band of water vapor, *J. Quantive. Spect. Radiat. Transfer* **21**, 131–142 (1979).
 13. J. D. Felske and C. L. Tien, Wide band characterization of the total band absorptance of overlapping infrared gas bands, *Combust. Sci. Tech.* **11**, 111–117 (1975).
 14. T. F. Smith and Z. F. Shen, Evaluation of coefficients for the weighted sum of gray gases model, *20th Nat. Heat Transfer Conf.*, ASME Paper No. 81-HT-55 (1981).
 15. K. A. Afimiwala, Program package for design optimization, Dept. Mechanical Engineering, State University of New York at Buffalo, Amherst, New York (1974).
 16. T. T. Charalampopoulos, The total emissivity of the hydrocarbon particulates expressed as the sum of gray gases with an application to a rectangular parallelepiped enclosure, M.S. Thesis, Part II, State University of New York at Buffalo, Amherst, New York (1981).

COEFFICIENTS DE PONDERATION DES GAZ GRIS POUR DES MELANGES ARBITRAIRES GAZ-SUIE

Résumé—On développe une méthode pour déterminer les coefficients de pondération des gaz gris pour des mélanges gaz-suie, à partir des coefficients qui représentent séparément le comportement des suie et celui des gaz. On obtient des représentations à la fois pour l'émissivité et l'absorptivité. On montre que cette approche est précise sur de larges domaines de température, de longueur de parcours et de concentration de suie.

EINFLUSSKOEFFIZIENTEN DER GRAUEN GASSTRAHLUNG FÜR BELIEBIGE GAS-RUSSMISCHUNGEN

Zusammenfassung—Es wird ein Verfahren entwickelt zur Bestimmung der Einflußkoeffizienten der grauen Gasstrahlung für Gas-Ruß-Mischungen aus den Koeffizienten, die im einzelnen das Verhalten des Rußes und des Gases wiedergeben. Sowohl die Emissions- als auch die Absorptionskoeffizienten können dargestellt werden. Es wird gezeigt, daß das Verfahren über einen weiten Bereich von Temperatur, Weglänge und Rußkonzentration genau ist.

ВЕСОВЫЕ КОЭФФИЦИЕНТЫ СЕРОГО ГАЗА ДЛЯ СМЕСЕЙ ГАЗА И САЖИ ПРОИЗВОЛЬНОГО СОСТАВА

Аннотация—Разработан метод определения весовых коэффициентов газа и сажи по коэффициентам, характеризующим сажу и газ в отдельности. Получены выражения для излучательной и поглощательной способности газа. Установлена точность предложенного метода в широком диапазоне температур, длин пробега и концентраций сажи.