

# Flame Spread over Thin Solid Fuels in Partially Premixed Atmospheres

P. D. RONNEY\*

Department of Mechanical Engineering, University of Southern California, Los Angeles, CA

J. B. GREENBERG

Faculty of Aerospace Engineering, Technion, Israel Institute of Technology, Haifa 32000, Israel

Y. ZHANG and E. V. ROEGNER

Department of Mechanical and Aerospace Engineering, Princeton University, Princeton, NJ

Experiments on flame spread rates ( $S_f$ ) over thin solid fuels in oxidizing atmospheres to which gaseous fuel is added reveal a large increase in  $S_f$  for some gaseous fuels. The most to least effective fuels tested are, in order,  $H_2$ , CO, hydrocarbons, and  $NH_3$ . From these experiments it is inferred that, unlike nonpremixed flame spread, the finite-rate kinetics of the gaseous fuel have a dominant influence on  $S_f$  even far from extinction conditions. A simple model developed to account for the effect of the gaseous fuel on  $S_f$ , while still retaining the framework of deRis's model of  $S_f$  for infinite-rate kinetics of the solid fuel vapors, shows good qualitative and fair quantitative agreement with experimental data. Furthermore, it is shown that for some fuels, e.g., CO, the gaseous products of partial combustion produce a more combustible environment than the fresh atmosphere; the practical implications of this finding for modeling fires in enclosures are discussed.

## NOMENCLATURE

$B_p$	frequency factor of premixed fuel + $O_2$ chemical reaction
$d$	transport zone thickness = $\alpha_g/V$
$D_p$	premixed flame Damköhler number = $\rho_g B_p Y_{n\nu} / 2M_n s$
$E_p$	activation energy of premixed fuel + $O_2$ chemical reaction
$F$	heat flux to unit width of fuel bed
$g$	acceleration of gravity
$H$	transfer number = $[\tau_x - \tau_i + \alpha_1 - \alpha_2 + \alpha_2 \alpha_H] / (L/Q_n)$
$k_g$	gas thermal conductivity
$L$	latent heat of vaporization of solid fuel
$Le$	Lewis number = ratio of thermal to mass diffusivity
$M$	molecular weight
$q''$	heat flux per unit area of premixed flame sheet
$Q$	heat release per unit mass of fuel

$s$	strain rate
$S_f$	flame spread rate
$S_L$	premixed gas laminar burning velocity
$T$	temperature
$T_{ad}$	adiabatic flame temperature of gas mixture
$T_f$	temperature at nonpremixed flame
$T_p$	temperature at premixed flame
$V$	opposed flow velocity
$x$	coordinate parallel to fuel bed
$X$	mole fraction
$y$	coordinate perpendicular to fuel bed
$Y$	mass fraction
$Y_{n\nu}$	solid fuel vapor mass fraction at fuel surface = $[H - (\alpha_1 - \alpha_2)] / (1 + H)$

## Greek Symbols

$\alpha_1$	$Y_{O_{2z}} / (v_n Y_{n\nu})$
$\alpha_2$	$v_p Y_{p_{2z}} / (v_n Y_{n\nu})$
$\alpha_2$	coupling function (Eq. 2 only)
$\alpha_g$	gas mixture thermal diffusivity
$\alpha_H$	$[(Y_{p_{2z}} Q_p) / (Y_{n\nu} Q_n)] / \alpha_2$
$\beta$	$\tau_x - \tau_i + L/Q_n$
$\delta$	Dirac function

\* Corresponding author.

Presented at the Twenty-Fifth Symposium (International) on Combustion, Irvine, California, 31 July–5 August 1994.

- $\chi$  compressed coordinate (see Eq. 7b)  
 $\phi$  gas-phase equivalence ratio =  $(Y_{p\infty}/Y_{ox\infty})\nu_p$   
 $\nu$  stoichiometric oxidant to fuel mass ratio  
 $\theta_p$   $E_p C_p / R Y_{nv} Q_n$   
 $\Theta_p$  nondimensional activation energy of premixed flame =  $E_p / RT_p$   
 $\rho$  density  
 $\tau$  temperature nondimensionalized by  $Y_{nv} Q / C_p$   
 $\tau_s$  solid fuel thickness  
 $\omega$  chemical reaction rate

### Subscripts

- $g$  gas mixture (temperature-averaged property)  
 $n$  pertaining to nonpremixed fuel or condition at nonpremixed flame front  
 $ox$  pertaining to oxidant  
 $p$  pertaining to premixed fuel or condition at premixed flame front  
 $s$  solid fuel  
 $v$  pertaining to vaporization condition at solid fuel bed surface  
 $\infty$  condition in ambient atmosphere

### INTRODUCTION

Flame spread over thermally thin solid fuels is useful for studying the behavior of more complex two-phase nonpremixed flames, such as building fires, because solid-phase heat conduction can be neglected. One aspect of flame spread which has not been studied previously is "partially premixed" flame spread, where gaseous fuel is present in the oxidizing atmosphere. The study of partially premixed flame spread has practical value because in building fires, combustion may occur under poorly ventilated conditions, causing the air to become partially depleted of oxygen and to contain combustible gases such as fuel vapors,  $H_2$ , or CO. Subsequent fire spread could occur at varying oxygen and gaseous fuel content. The potential significance of flame spread under these conditions has been noted previously [1]; for example, in underventilated propane-air nonpremixed flames, combustion products contained typically 9% hydrocarbons, 2.2% CO,

and 1.5%  $H_2$ . The most readily observable and practically important characteristic of flame spread is the spread rate ( $S_f$ ).  $S_f$  is also commonly predicted by flame spread theories [2, 3]. Consequently, this work focuses on studying the effect of gaseous fuel addition to the ambient atmosphere on  $S_f$  for thin solid fuels.

### APPROACH

To study possible influences of finite-rate kinetics, gaseous fuels having wide ranges of characteristic chemical reaction rates ( $\omega_p$ ) were employed. Also, effects of Lewis numbers of premixed fuel and oxidant were studied since previous work [4-6] shows that Le has important effects on  $S_f$  and flame temperature. Consequently, we employed  $H_2$ , CO,  $CH_4$ ,  $C_3H_8$ , and  $NH_3$  fuels in  $O_2$ - $N_2$  atmospheres; here  $Le_p \approx 0.3, 1.0, 0.9, 1.7,$  and  $0.8$ , respectively, and  $Le_{ox} \approx 1.0$ .  $H_2$  was chosen because at fixed temperature its characteristic  $\omega_p$  is larger than those of CO or hydrocarbon fuels. CO was chosen because of its practical importance to partially premixed flame spread which could occur in building fires.  $CH_4$  and  $C_3H_8$  were chosen as representative hydrocarbon fragments, with different  $Le_p$ , which could result from pyrolysis of nearby solid fuel beds.  $NH_3$  was chosen because of its low characteristic  $\omega_p$ . For CO fuel,  $O_2$ -He and  $O_2$ - $CO_2$  atmospheres were employed to study  $Le_{ox}$  effects; here  $Le_p \approx 1.3$  and  $0.6$ , respectively.

Table 1 shows some characteristics of these fuels. The heat release per mole of  $O_2$  consumed is similar for all fuels but  $S_L$  in fuel-air mixtures at fixed  $T_{ad}$  varies substantially. This indicates that  $\omega_p$  varies widely for these fuels, since  $\omega_p \sim S_L^2$  [7]. Thus, differences in  $S_f$  between different fuels at similar oxygen mole fraction ( $X_{ox\infty}$ ) is probably due to finite-rate kinetics rather than thermal effects.

We employ downward flame spread, where buoyant convection opposes flame spread. Upward flame spread is not employed because in this case convective and diffusive transport are concurrent. Consequently, fuel area exposed to hot combustion products increases with time, causing accelerating rather than steady flame spread [8]. Also, an opposing flow velocity ( $V$ )

TABLE 1  
Characteristics of the Reactants Employed in This Study<sup>a</sup>

Fuel	Heat Release per mole of O <sub>2</sub> Consumed (kcal/mol)	$S_L$ , Lean, 1750 K, (cm/s)	$S_L$ , Rich, 1750 K, (cm/s)	$B_p$ (cm <sup>3</sup> mol <sup>-1</sup> sec <sup>-1</sup> )	$E_p$ (kcal/mol)
H <sub>2</sub>	115	82 [20]	210 [20]	$6.7 \times 10^{17}$ [24]	26.1 [24]
CO	135	7 [21]	40 [21]	$1.1 \times 10^{16}$ [*]	40 [25]
CH <sub>4</sub>	96	17 [22]	7.3 [22]	$2.4 \times 10^{16}$ [25]	48.4 [25]
C <sub>3</sub> H <sub>8</sub>	105	17 [22]	14 [22]	$8 \times 10^{15}$ [*]	40 [25]
NH <sub>3</sub>	101	2.0 [23]	3.5 [23]	$4.9 \times 10^{14}$ [26]	39.1 [26]

<sup>a</sup> Values of  $S_L$  reported are for fuel-air mixtures with equivalence ratios corresponding to  $T_{ad} = 1750$  K. In Ref. 21, the CO contained 1.5% H<sub>2</sub> and 1.35% H<sub>2</sub>O. For values of  $B_p$  marked by [\*], no rate expressions which are first order in fuel and oxidant (as required by the model [17]) could be found; hence, values were chosen to give correct value for  $S_L$  of lean mixtures at  $T_{ad} = 1750$  K using the expression below Eq. 9.

is not imposed because theory [2] and experiment [9] indicates that  $V$  affects  $S_f$  only slightly for thermally thin fuels (except near extinction). While buoyancy imposes  $V \approx 1.5(g\alpha_g)^{1/3}$  [2, 10], detailed computations [11] show that free and forced convection have similar influences on flame spread over thin fuels.

## EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental apparatus was similar to that employed previously [4]. Ashless filter paper samples were burned in a 37-L chamber filled with the desired atmospheres by partial pressures. A criterion for transition between thermally-thin and thermally thick flame spread [12] indicates that our experiments are characterized as thermally thin. The chamber was sufficiently large that less than 2% of the initial oxygen was consumed during the tests. The fuel samples were held in 5 cm wide clamps to inhibit edge-burning effects. Tests showed that 5 cm was sufficiently wide to ensure that heat losses to the clamp did not affect  $S_f$ . An array of type S thermocouples of 50- $\mu$ m wire diameter was attached to this clamp to enable measurement of flame temperature profiles. The thermocouple voltages were measured, recorded and corrected for radiation losses by a microcomputer-based data acquisition system. The thermocouple response time (typically 50 ms) was adequate for the current purposes. The flames were ignited by coiled nichrome wires coated with nitrocellulose and spread downward for 30 cm.  $S_f$  was inferred

from video records of the spreading process. The estimated uncertainties in  $S_f$ , temperature, oxidant mole fraction ( $X_{ox\infty}$ ) and total pressure are 3%, 5%, 1%, and 0.5%, respectively.

## EXPERIMENTAL RESULTS

### Spread Rates

Figure 1 shows the effect of gaseous fuel on  $S_f$  for CO, CH<sub>4</sub>, and C<sub>3</sub>H<sub>8</sub> fuels in O<sub>2</sub>-N<sub>2</sub> atmospheres for several fixed values of equivalence ratio ( $\phi$ ) and  $X_{ox\infty}$ . For fixed  $\phi$ , the highest and lowest values of  $X_{ox\infty}$  shown correspond to the gas-phase lean flammability limit and the nonpremixed-flame extinction limit, respectively. In all cases gaseous fuel increases  $S_f$  at fixed  $X_{ox\infty}$  (that is, replacing inert with fuel increases  $S_f$ ), especially for CO fuel. Tests in CO-O<sub>2</sub>-CO<sub>2</sub> and CO-O<sub>2</sub>-He atmospheres (not shown) indicated that this behavior was qualitatively similar at other values of  $Le_p$  and  $Le_{ox}$ .

To illustrate differences between gaseous fuels, Fig. 2a shows how  $\phi$  affects  $S_f$  for all five fuels at fixed  $X_{ox\infty}$ . The most to least effective fuels for spread rate enhancement are H<sub>2</sub>, CO, hydrocarbons and NH<sub>3</sub>. The ranking is nearly the same as their  $S_L$  at fixed  $T_{ad}$  (Table 1); the fuel with lowest  $S_L$  (NH<sub>3</sub>) has almost no effect on  $S_f$ . Moreover, the ranking does not correlate with  $Le_p$  or heat release (Table 1). These results suggest that  $\omega_p$  substantially affect  $S_f$ .

To explore the role of kinetics,  $S_f$  was measured with and without 0.5 mol. % CF<sub>3</sub>Br

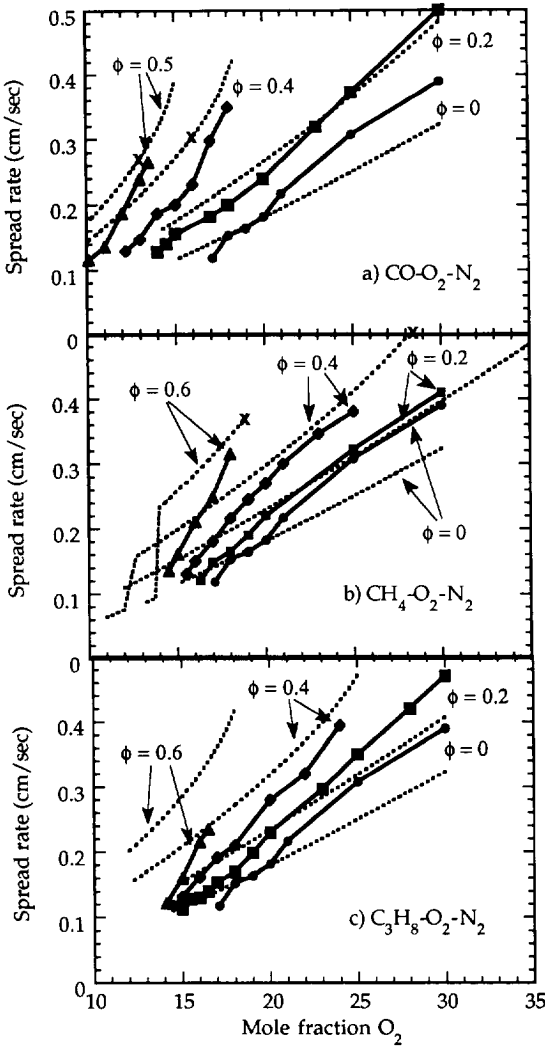


Fig. 1. Effect of oxidant mole fraction and gaseous fuel addition on flame spread rate over a solid fuel bed of nominal thickness 165  $\mu\text{m}$  (density 0.092  $\text{g}/\text{cm}^2$ ) at 1 atm pressure. Solid lines and data points: experiment; dashed lines: theoretical predictions. X = Composition corresponding to the estimated flammability limit for the gas-phase only (see text). (a) CO fuel in  $\text{O}_2\text{-N}_2$  atmospheres. (b)  $\text{CH}_4$  fuel in  $\text{O}_2\text{-N}_2$  atmospheres. (c)  $\text{C}_3\text{H}_8$  fuel in  $\text{O}_2\text{-N}_2$  atmospheres.

added (Fig. 2b), which is known [13] to reduce  $S_L$  and thus  $\omega_p$  in many practical flames. This amount of  $\text{CF}_3\text{Br}$  had almost no effect on  $S_f$  for cases with no fuel or with  $\text{CH}_4$  fuel, a modest effect for CO, and a substantial effect for  $\text{H}_2$ . This further indicates the importance of  $\omega_p$  on  $S_f$  for partially premixed flame

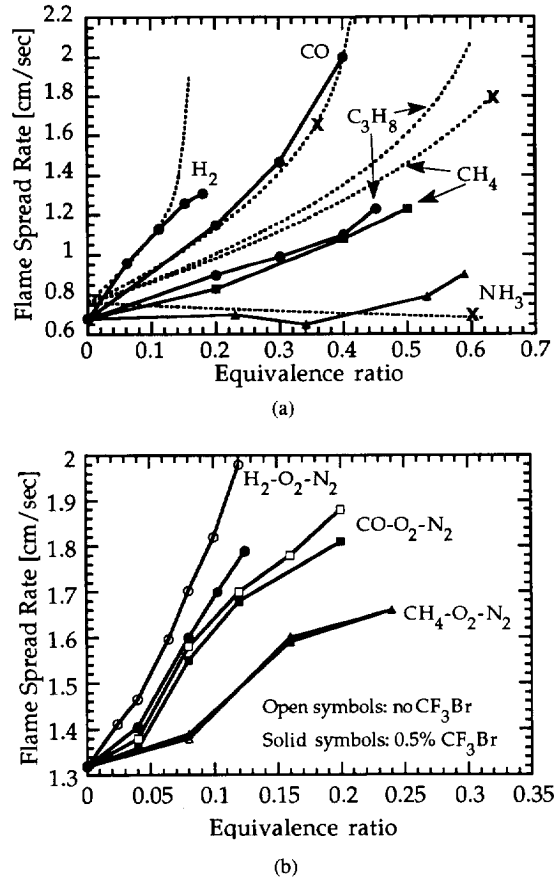


Fig. 2. Effect of gaseous-fuel equivalence ratio on  $S_f$  for nominal fuel bed thickness 51  $\mu\text{m}$  (density 0.0185  $\text{g}/\text{cm}^2$ ). (a) 18%  $\text{O}_2$  in  $\text{N}_2$  at 1 atm pressure, showing effect of fuel type and comparison between experiments (solid lines and data points) and theoretical predictions (dashed lines). X = Composition corresponding to the estimated flammability limit for the gas-phase only. (b) 25%  $\text{O}_2$  in  $\text{N}_2$  at 0.4 atm pressure, showing effect of addition of a flame inhibitor ( $\text{CF}_3\text{Br}$ ).

spread, since  $\text{H}_2$  provides the most increment to  $S_f$ , and thus decreasing  $\omega_p$  (due to  $\text{CF}_3\text{Br}$  addition) would have the most impact on  $S_f$  for  $\text{H}_2$ .

It is well known from theory [6-8] and experiment [9] that far from extinction, the reaction rate of solid fuel vapors with  $\text{O}_2$  ( $\omega_n$ ) does not affect  $S_f$ ,  $S_f$  being determined by mixing rather than reaction rates. Indeed, most analyses [2,3], presume reaction occurs instantaneously upon mixing of fuel and oxidant ( $\omega_n \rightarrow \infty$ ). However, the  $S_f$  data described above

show that even far from extinction,  $\omega_p$  affects  $S_f$  substantially. Consequently, a noteworthy conclusion is suggested:  $\omega_p$  substantially affects  $S_f$ , even at conditions where  $\omega_n$  does not affect  $S_f$ .

### Flame Structure

Visual observations (Fig. 3) showed that without gaseous fuel or with small quantities of gaseous fuel a single flame front exists. However, for cases where the increase in  $S_f$  due to gaseous fuel is substantial (higher gaseous fuel concentrations and fuels with higher  $\omega_p$ ), a second outer flame front is clearly visible, even when  $X_{\text{ox}\infty}$  is reduced to obtain the same  $S_f$  as a nonpremixed atmosphere having higher  $X_{\text{ox}\infty}$ .

Another indication of flame structure is provided by two-dimensional temperature maps (Fig. 4) generated from measured temperature histories using standard techniques [14]. Figure 4 shows two flames with the same diluent gas, pressure, and similar  $S_f$  but one with and one without premixed fuel. With premixed fuel the

flame is much taller and extends further from the fuel surface.

From temperature data a further indicator of flame structure, the profile of heat flux to the fuel bed per unit area, can be obtained. This can be estimated from  $k_g$  and  $dT/dy$  at the fuel surface. The temperature and gradient at the surface were estimated from parabolic fits to temperatures recorded by the three thermocouples closest to the fuel surface. Figure 5 shows that, consistent with previous studies [15], without gaseous fuel the heat flux is concentrated in a short length of fuel bed near the flame leading edge. With gaseous fuel, the heat flux is distributed over a noticeably greater length.

The data in Figs. 3–5 suggest that at conditions where the increase in  $S_f$  due to premixed fuel is substantial, the *reaction zones for consumption of solid fuel vapors and gaseous fuel are not merged*. If these zones were merged, similar temperature fields and heat flux profiles would be expected because these two flames have similar total heat flux to the fuel

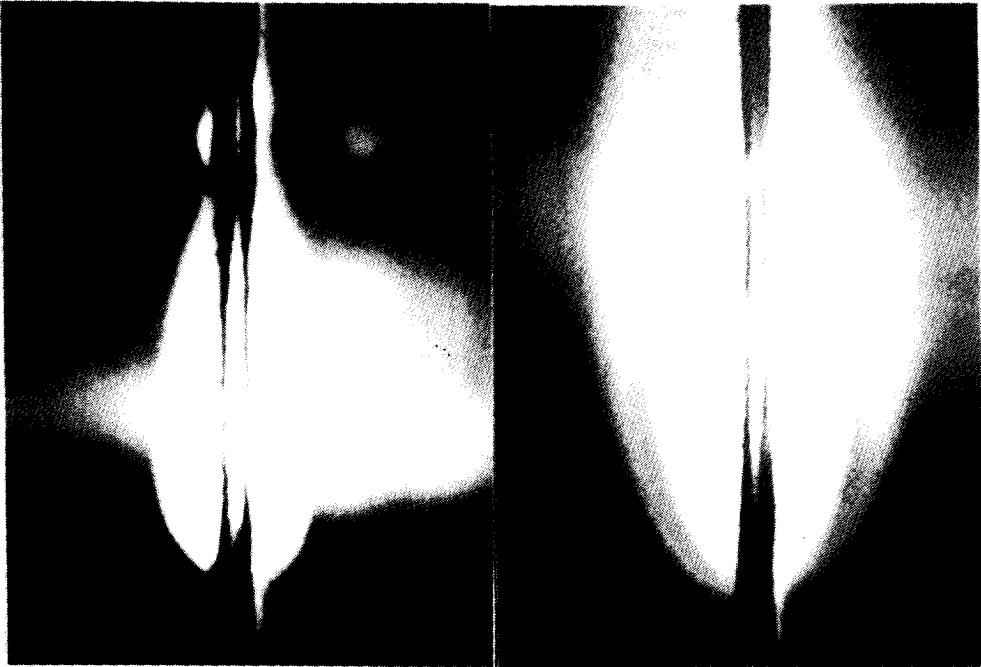


Fig. 3. Direct photographs of downward-spreading flames in  $\text{O}_2\text{-N}_2$  mixtures at 1 atm pressure with nominal fuel bed thickness  $51\ \mu\text{m}$ . Left: 27%  $\text{O}_2$ , no added CO,  $S_f = 1.35\ \text{cm/s}$ ; right: 22%  $\text{O}_2$ , 10% CO,  $S_f = 1.60\ \text{cm/s}$ . Field of view  $5\ \text{cm high} \times 3.5\ \text{cm wide}$  for each photograph.

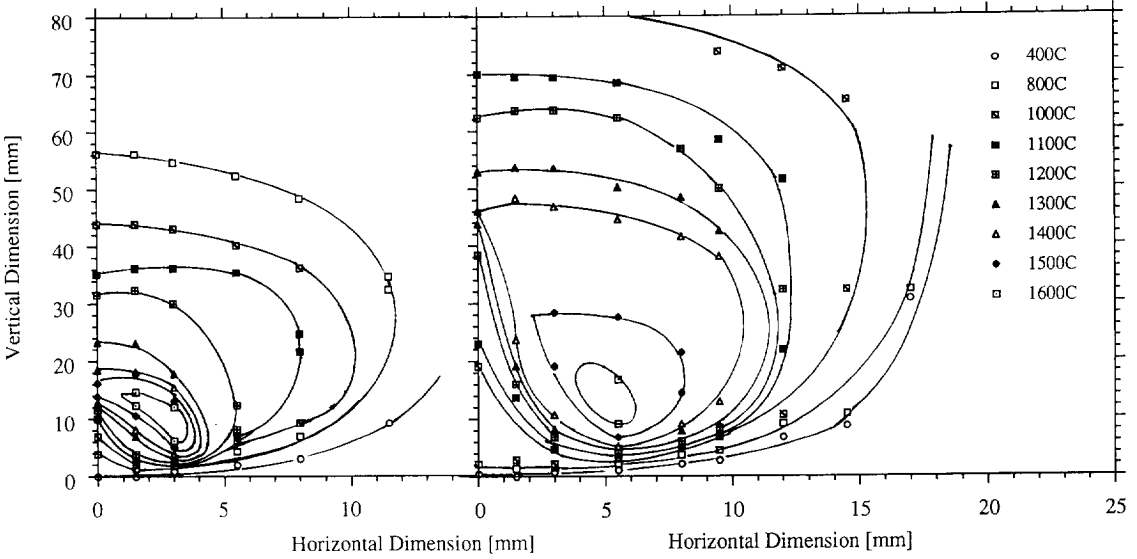


Fig. 4. Temperature maps of steady downward flame spread over a thin solid fuel bed of nominal thickness 51  $\mu\text{m}$  in  $\text{O}_2\text{-N}_2$  mixtures at 0.5 atm pressure. Left: 27%  $\text{O}_2$ , no added CO,  $S_f = 1.30$  cm/s; right: 22%  $\text{O}_2$ , 10% CO,  $S_f = 1.54$  cm/s. Note expanded horizontal scale.

bed (since  $S_f$  is similar), thermal and transport properties (since CO,  $\text{O}_2$ , and  $\text{N}_2$  have similar properties), and peak temperatures.

**Modeling**

Based on experimental evidence that (1)  $\omega_p$  substantially affects  $S_f$ , even when  $\omega_n$  does not and (2) the reaction zones for premixed and nonpremixed flames are not necessarily merged, a simple semiquantitative model of the effect of premixed fuel on  $S_f$  is proposed.

Because of the simplified geometrical and chemical assumptions, this model should be considered a tool for conceptual understanding and a guide for more detailed calculations rather than a predictive tool.

The model (Fig. 6) retains the deRis [2] model of a nonpremixed flame with  $\omega_n \rightarrow \infty$  that touches the fuel bed at  $x = 0$  (i.e.,  $x_n = 0$ ) and adds a thin semi-infinite premixed flame sheet, located at  $x = x_p < 0$  upstream of the nonpremixed flame, whose heat release rate per unit area ( $q''$ ) depends on  $\omega_p$ . For semiinfinite sources Thomas [16] showed that the heat flux to the fuel bed ( $F$ ) due to this pre-

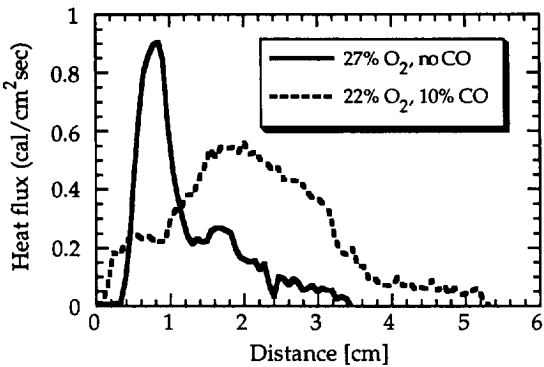


Fig. 5. Heat flux to the fuel bed for the same tests as shown in Fig. 4.

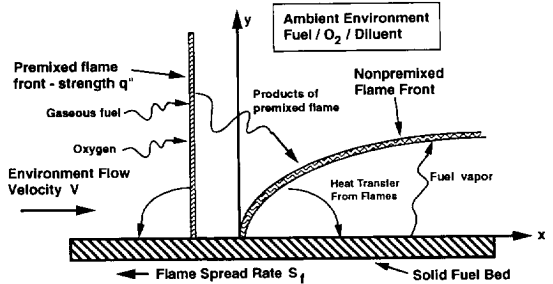


Fig. 6. Configuration of proposed model of flame spread with gaseous fuel.

mixed flame sheet is<sup>1</sup>

$$F = \frac{2}{\pi} \frac{k_g}{\rho_g C_{pg}} \frac{q''}{V}. \quad (1)$$

This model requires a flame separation ( $x_n - x_p$ ) of order  $d$ ; a merged-flame model is presented later.  $F$  modifies the boundary condition of the deRis model [2] on the fuel surface at  $x < 0$ , which, after nondimensionalization, becomes (see deRis's Eq. 8)

$$\begin{aligned} b \frac{\partial \alpha_2}{\partial x} &= \frac{\partial \alpha_2}{\partial y} + F^* \delta(x_n - x_p); \\ b &\equiv \frac{\rho_s C_{ps} \tau_s S_f}{k}; \\ F^* &\equiv \frac{2}{\pi} \frac{q''}{\rho_g Q_n V}. \end{aligned} \quad (2)$$

(For analytical convenience, we have assumed that all the heat flux to the fuel bed due to the premixed flame occurs at  $x = x_p$ .) The classical analysis can be retraced with this modification to yield, using Delichatsios's [3] exact solution and redimensionalizing,

$$\begin{aligned} S_f &= \frac{\pi}{4} \frac{k}{\rho_s C_{ps} \tau_s} \frac{T_f - T_v}{T_v - T_x} \\ &\times \left( 1 + \frac{8}{\pi^2} \exp\left((x_n - x_p) \left(\frac{\pi}{8} - 1\right)\right) \right. \\ &\left. \times \frac{q''}{\rho_g V C_{pg} (T_f - T_v)} \right). \end{aligned} \quad (3)$$

To estimate  $q''$  and  $x_p$  we employ the asymptotic analysis of partially premixed flames in stagnation-point flow by Hamins et al. [17]. This analysis considers a nonpremixed flame at  $x = 0$  coupled to a premixed flame that adjusts  $x_p$  so that  $q''$  (which depends strongly on its temperature ( $T_p$ ) through the Arrhenius term in  $\omega_p$ ) is commensurate with the temperature and concentration gradients at that location.

At lower strain rates or higher  $\omega_p$  the flame moves toward the incoming flow, thus to lower  $T_p$ . A single irreversible chemical reaction is assumed with  $\omega_p = B_p Y_p Y_{ox} \exp(-E_p/RT)$ . For asymptotically large  $\Theta_p \equiv E_p/RT_p$  the reaction zone is much thinner than  $d$ , thus convective transport across the reaction zone is negligible and  $q'' = -k((\partial T/\partial x)_{x=x_p^+} - (\partial T/\partial x)_{x=x_p^-})$ . Some algebra using Eqs. 5 and 20–23 in [17] shows that, after dimension-

$$q'' = \frac{1}{\sqrt{2\pi}} \sqrt{s \alpha_g} \rho_g Y_{nu} Q_n \exp\left(\frac{-x_p^2}{2}\right) \frac{\alpha_2 \alpha_H}{\chi_p}. \quad (4)$$

$\chi_p$  is a scaled value of  $x_p$  determined by solution of five equations for unknowns  $x_p$ ,  $\chi_p$ ,  $\tau_p$ ,  $y_{cp}$  and  $m$ :

$$\begin{aligned} 0.6307m^2 - 1.344m + 1 \\ = 4\pi \exp(x_p^2) \left( \frac{\chi_p \tau_p^2}{\alpha_2 \alpha_H \theta_p} \right)^2 D_p y_{oxp} \\ \times \exp\left(\frac{-\theta_p}{\tau_p}\right), \end{aligned} \quad (5)$$

$$\begin{aligned} m &= (\tau_x + \alpha_2 \alpha_H - \tau_p) / \alpha_2 \alpha_H; \\ y_{exp} &= (\alpha_1 - \alpha_2) - \chi_p (\alpha_1 - \alpha_2 + 1), \quad (6a, b) \\ \chi_p &= (\tau_x + \alpha_2 \alpha_H - \tau_p) / (1 - \beta - \alpha_2 \alpha_H); \\ \chi_p &= 1/2 \operatorname{erfc}(x_p / \sqrt{2}). \end{aligned} \quad (7a, b)$$

In the above  $s \approx V/d \approx 1.2(g^2/\alpha_g)^{1/3}$  is the characteristic strain rate, in the present case induced by buoyant flow [10]. In Ref. 17,  $s$  is presumed constant throughout the flow; since this is not the case in the current experiments, a more accurate model of partially premixed flame spread would require both detailed chemistry and hydrodynamics.

For fixed thermodynamic parameters and  $E_p$ , Eqs. 5–7 determine the effect of Damköhler number ( $D_p$ ) on  $q''$ . Numerical solutions show that  $q''$  typically changes by a factor of 3 over the applicable range of  $D_p$ . Thus since  $D_p \sim B_p/s$ , both chemical and hydrodynamic factors may influence  $S_f$  significantly.

A more powerful effect of  $D_p$  on  $S_f$  occurs because the separated-flame model breaks

<sup>1</sup> Equation 1 overestimates  $F$  somewhat because the real heat source has finite extent. However, the thermal transport zone thickness [2]  $d \approx 2\alpha_g/V \approx 1.3(\alpha^2/g)^{1/3} \approx 0.16$  cm for the conditions shown in Fig. 4. Since the orthogonal region of the premixed flame is about  $6d$ , it should have an effect similar to a semiinfinite source, especially considering that the flame structure near the leading edge controls  $S_f$  [15].

down and a merged-flame model is required when  $(T_f - T_p)/T_p \leq \Theta_p^{-1}$ , which occurs at low  $D_p$ . The impact of gaseous fuel on  $S_f$  seems to be greatly diminished for merged flames. Our merged-flame analysis is motivated by a model of Lewis number effects on flame spread [5] which showed that to leading order in  $1-\text{Le}^{-1}$ , these effects manifest themselves solely through their effect on  $T_f$ ; an analogous analysis (not shown) for added gaseous fuel assuming merged flames yields the same result if  $Y_{px}$  is small. Consequently for merged flames we estimate  $S_f = (\pi/4)(k_g/\rho_s C_{ps} \tau_s)[(T_f - T_v)/(T_v - T_\infty)]$ , where  $T_f$  is the flame temperature including contributions of both fuels [17]:

$$T_f = T_\infty + \left( T_v - T_\infty + \frac{Q_n - L}{C_p} + \frac{v_p Q_p}{v_n C_p} \frac{\phi}{1 - \phi} \right) \times \left( 1 - \left( 1 + Y_{px} \frac{v_p}{v_n} \frac{1 - \phi}{\phi} \right)^{-1} \right). \quad (8)$$

It is easily verified that  $X_p$  has much less effect on  $T_f$  than  $X_{ox}$  does, thus premixed fuel does not affect  $T_f$  and  $S_f$  significantly for merged flames (low  $D_p$ ).

As previously recommended [18] thermodynamic and transport properties were evaluated at  $(T_f + T_\infty)/2$ . Thermodynamic properties of cellulose were taken from [9]. Overall chemical reaction rate parameters were taken from literature values (Table 1). Based on the discussion above, the criterion for using the merged-flame analysis was chosen to be  $(T_f - T_p)/T_p < \theta_p^{-1}$ . Because of this there is a sudden drop in  $S_f$  seen in Fig. 1b at low  $X_{ox}$ . In reality this drop would occur gradually over a range of  $X_{ox}$ , which is consistent with the results shown in Figs. 1a-1c.

Figures 1a-1c and 2a show comparisons of predicted and experimental values of  $S_f$ . The agreement is reasonable considering the simplicity of the model employed. Note that for  $\text{NH}_3$ ,  $\omega_p$  is sufficiently low that separated flames are never predicted; thus  $S_f$  is not increased by  $\text{NH}_3$ —actually  $S_f$  decreases because the high  $C_p$  of  $\text{NH}_3$  reduces  $T_f$ .

For  $\text{CO-O}_2\text{-He}$  and  $\text{CO-O}_2\text{-CO}_2$  atmospheres agreement between model and experiment (not shown) was poor. This may be because the above models assume all Lewis numbers are unity, which is reasonable for  $\text{CH}_4$ ,  $\text{CO}$ ,  $\text{NH}_3$ , and  $\text{O}_2$  in  $\text{N}_2$  but not in  $\text{He}$  or  $\text{CO}_2$ . We are not aware of an analysis of partially-premixed flames for general  $\text{Le}$  and different kinetic parameters of the two fuels which could extend the model proposed here.

From Eqs. 16 and 21 in Ref. 17, the flame separation distance  $\chi_n - \chi_p$  can be estimated, where  $\chi_n = (\alpha_1 - \alpha_2)/(1 - \alpha_1 - \alpha_2)$ . For the premixed case in Fig. 3, this is predicted to be 0.15 cm, which is close the visible separation ( $\approx 0.2$  cm) seen therein.

At large  $X_p$ , the atmosphere is flammable. If buoyancy-induced strain is the loss mechanism that prevents gas flammability at low  $X_p$ , then a criterion for flammability, valid for  $\text{Le}_p \approx 1$  is [19]

$$\frac{s\alpha_g}{S_L^2} < \frac{\pi}{4} \exp\left(\frac{-\theta_{ad}}{2} \left(1 - \frac{T_\infty}{T_{ad}}\right) \left(1 - \frac{1}{\text{Le}_p}\right)\right); \quad \theta_{ad} \equiv \frac{-E_p}{RT_{ad}}, \quad (9)$$

where  $S_L$  is the unstrained planar burning velocity at  $\text{Le}_p = 1$ , estimated from  $S_L^2 = 2(B_p/M_p)(k_g/C_p)\theta_{ad}^{-2}Y_{px}(1 - \phi)\exp(-\theta_{ad})$  [7]. The predicted flammability limits for cases where  $\text{Le}_p \approx 1$  are shown in Figs. 1a, 1b, and 2. The reasonable agreement between prediction and experiment suggests that the kinetic parameters employed herein are representative of these fuels and that the model of buoyancy-induced strain is applicable.

### Practical Perspective

In many fires in enclosures such as building, combustion occurs at underventilated conditions. In such cases much of the oxygen is partially oxidized to  $\text{CO}$  rather than fully oxidized to  $\text{CO}_2$ . Since our experiments show that  $\text{CO}$  may substantially increase  $S_f$ , it is relevant to assess how  $S_f$  differs for flame spread in fresh ( $\text{CO}$ -free) versus partially combusted atmospheres. To illustrate this, Fig. 1a is redrawn in Fig. 7 with the ordinate changed to



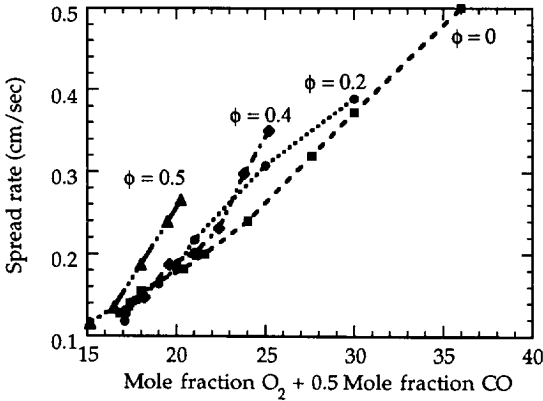


Fig. 7. Replot of Fig. 1a showing the effect of the total oxygen content as  $O_2$  equivalent ( $X_{O_2} + 0.5X_{CO}$ ) on spread rate.

$X_{O_{2e}} + 1/2X_{COe}$ —the ambient oxygen atom mole fraction as  $O_2$  equivalent. Figure 7 reveals a remarkable result:  $S_f$  is *greater* when a given number of oxygen atoms are present in the form of CO rather than  $O_2$ —by as much as 50% for 21%  $O_2$  in  $N_2$  with no CO versus 14%  $O_2$  and 14% CO ( $\phi = 0.5$ ). This result is also predicted by our model (Fig. 1a). Furthermore, the effective oxygen index (the lowest value of  $X_{O_{2e}} + 1/2X_{COe}$  which supports flame spread) is about 15% at  $\phi = 0.5$  versus 17% at  $\phi = 0$ . Hence, *partially combusted atmospheres containing CO as the product of partial oxidation provide higher spread rates and lower minimum oxygen indices than fresh atmospheres*. Moreover, these data do not even consider that  $T_x$  (thus  $S_f$ ) will be higher in partially oxidized atmospheres due to the heat release associated with partial oxidation.

## CONCLUSIONS

Experiments on flame spread over thin solid fuels in an oxidizing environment to which gaseous fuel is added reveal considerably increased spread rates in some cases. These results are interpreted in terms of finite-rate kinetics of the gas-phase fuel in what is normally considered an infinite-rate kinetics (transport-limited) problem. Experimental results were compared to a simple analytical model which includes finite-rate gaseous-fuel kinetics for an assumed (based on experimental evidence) configuration of premixed and

nonpremixed flames. The comparison is encouraging and indicates the importance of the flame configuration near the leading edge. Detailed numerical calculations which incorporate more detailed hydrodynamic and chemical models are needed. The results may have significance to modeling fires in buildings because  $S_f$  is higher and minimum oxygen indices are lower when a given quantity of oxygen is present as (for example)  $2O_2 + 2CO$  rather than  $3O_2$ . Since CO or hydrocarbons may appear as combustion intermediates in underventilated fires, these intermediates could yield larger fire growth rates than those expected based on fresh atmosphere properties. Consequently for modeling building fires in which combustion intermediates may be present, caution should be used when extrapolating data on spread rates and extinction conditions obtained in pure air.

*This work was supported by the National Science Foundation through a Presidential Young Investigator Award to PDR.*

## REFERENCES

1. Beyler, C. L., *Combust. Sci. Technol.* 39:287 (1984).
2. deRis, J. N., *Twelfth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1969, pp. 241–252.
3. Delichatsios, M. A., *Combust. Sci. Technol.* 44:257–267 (1986).
4. Zhang, Y., Ronney, P. D., Roegner, E. V., and Greenberg, J. B., *Combust. Flame* 90:71–83 (1992).
5. Greenberg, J. B., and Ronney, P. D., *Int. J. Heat Mass Transf.* 36:315–323 (1993).
6. Bhattacharjee, S., Seaton, D. and Altenkirch, R. A., Fall Technical Meeting, Combustion Institute, Western States Section, October 12–13, 1992, Berkeley, CA.
7. Williams, F. A., *Combustion Theory*, 2nd ed., Benjamin-Cummings, Menlo Park, CA, 1985.
8. Williams, F. A., *Sixteenth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1976, pp. 1281–1294.
9. Fernandez-Pello, A. C., Ray, S. R., and Glassman, I., *Eighteenth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1981, pp. 579–589.
10. Altenkirch, R. A., Eichhorn, R., and Shang, P. C., *Combust. Flame* 37:71–83 (1980).
11. West, J., Bhattacharjee, S. and Altenkirch, R. A., *Combust. Sci. Technol.* 83:233–244 (1992).
12. West, J., Bhattacharjee, S. and Altenkirch, R. A., Fall Technical Meeting, Combustion Institute, Western States Section, October 12–13, 1992, Berkeley, CA.

13. Gann, R. G., ed., *Halogenated Fire Suppressants*, ACS Symposium Series Number 16, American Chemical Society, 1975.
14. Frey, A. E., and Tien, J. S., *Combust. Flame* 26:257-267 (1976).
15. Bhattacharjee, S., and Altenkirch, R. A., *Twenty-Fourth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1993, pp. 1669-1676.
16. Thomas, P. H., *Combust. Sci. Technol.* 28:173-175 (1982).
17. Hamins, A., Thridandam, H., and Seshadri, K., *Chem. Eng. Sci.* 40:2027-2038 (1985).
18. Wichman, I. S., and Williams, F. A., *Combust. Sci. Technol.* 33:207-214 (1983).
19. Buckmaster, J., and Mikolaitis, D., *Combust. Flame* 47:191-204 (1982).
20. Dowdy, D. D., Smith, D. B., Taylor, S. C., and Williams, A., *Twenty-Third Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1990, p. 325.
21. Rogg, B., and Williams, F. A., *Twenty-Second Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1988, p. 1441.
22. Law, C. K., Zhu, D. L., and Yu, G., *Twenty-First Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1986, p. 1419.
23. Ronney, P. D., *Combust. Sci. Technol.* 59:123-141 (1988).
24. Mitani, T., and Williams, F. A., *Combust. Flame* 39:169-190 (1980).
25. Westbrook, C. K., and Dryer, F. L., *Combust. Sci. Technol.* 27:31-43 (1981).
26. Branch, M. C., and Sawyer, R. F., *Fourteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, 1972, pp. 967-974.

Received 1 December 1993; revised 31 May 1994

## Comments

C. Fernandez-Pello, *University of California, Berkeley, USA*. The addition of CO and hydrocarbons to the air to simulate flame spread under fire vitiated conditions is interesting and practical. I object, however, to the interpretation and correlation of your results. Vitiated conditions imply oxygen concentrations below that of air, and it is well established that under these conditions the analysis of deRis is not applicable. Furthermore, since the premixed flame generated ahead of the spreading flow by the combustion of the added hydrocarbons will consume part of the oxygen, the problem will be even worse. I didn't have a chance to determine in your presentation if the oxygen concentration was much higher than that of air, so that the deRis analysis would be applicable, but if that is the case the use of the term vitiated condition would be wrong. My concern is that we have gone a long way toward convincing the fire community of the limitations of the deRis analysis, and this work, if misinterpreted, would represent a step backward in the study of flame spread rather than a step forward.

*Authors' Reply*. Clearly there are limitations to the deRis model, and any interpretation of flame spread data should consider these. There was no suggestion in the current work that finite rate kinetics is not an important factor in flame spread. Our main message was that for conditions *not* close to extinction, where finite-rate kinetics of the nonpremixed flame does not affect the spread rate ( $S_f$ ), finite-rate kinetics of the gaseous fuel oxidation is still an important factor. The behavior of  $S_f$  could be explained *only* by employing a separated-flames model with finite-rate kinetics of the premixed flame.

It is inappropriate to view the leading premixed flame simply as an entity that depletes the atmosphere of  $O_2$ , thus reducing the Damköhler number (Da) and encouraging extinction. In reality, the premixed flame increases the ambient temperature on the oxidizer side of the nonpremixed flame. What determines the temperature (and thus Da) at the nonpremixed flame front is the total enthalpy of the stoichiometric mixture of gaseous reactants with the solid fuel vapors. Adding

gaseous fuel increases this total enthalpy and thus nonpremixed flame temperature (although by relatively little in most cases, as discussed in the text.)

Our use of the term "vitiating" may have caused some misunderstanding. We did not limit our exploration to atmospheres that could be produced by burning fuels in air, since in some applications a higher initial O<sub>2</sub> concen-

tration may exist. While we make no claim whether flame spread in air is near the high-Da limit, we note that data by Fernandez-Pello *et al.* (Ref. 9 in the paper) show that for weak opposed flow in air,  $S_f$  is near its infinite-kinetics value. Therefore we believe the results may have some relevance to building fires in air.