

SOLID SURFACE COMBUSTION EXPERIMENT: THICK FUEL RESULTS¹

561-25
02 7398

ROBERT A. ALTENKIRCH
Washington State University
Pullman, Washington

and

Subrata Bhattacharjee¹, Jeff West¹/Lin Tang²/Kurt Sacksteder³/Michael A. Delichatsios⁴
¹San Diego State University, San Diego, California/ ²Washington State University, Pullman, Washington
³NASA Lewis Research Center, Cleveland, Ohio/ ⁴Factory Mutual Research, Norwood, Massachusetts

Introduction

In the Solid Surface Combustion Experiment (SSCE), a series of five experiments for flame spread over a thin cellulosic fuel and thick polymethylmethacrylate in a quiescent O_2/N_2 oxidizing environment was conducted. Results from the five cellulosic experiments, and the supporting modeling and ground-based effort, are reported elsewhere (refs. 1-7). For the thin fuels, the spread rate, following ignition, rapidly adjusts to a steady value. Radiation heat transfer is a dominant phenomenon in the spread process at microgravity. While classical theory based on conduction arguments alone predicts the spread rate to be independent of pressure for spread over thin fuels (ref. 8), the spread rate in microgravity increases with increasing pressure. The increase is due to a decrease in the diffusion length scale with increasing pressure and a concomitant decrease in the optical depth of the flame and hence a decrease in the radiative heat loss from the flame as well. The result is an increase in flame temperature, and spread rate, with pressure. In the absence of radiation, classical theory for infinitely-fast, gas-phase kinetics predicts that the spread rate is independent of opposing flow velocity, but in the low flow environment the flame encounters in an initially quiescent, microgravity environment in which the opposing flow is eventually equivalent to the spread rate, the spread rate decreases with a decrease in opposing flow speed, due to the enhancement of radiative heat losses at the low flows.

It is well known that the propagation speed of a flame spreading over a thick fuel bed in an opposing flow environment depends on the strength and character of the opposing flow (refs. 9-11). Building on the understanding of the spread of a flame over a thin fuel, in which forward heat transfer through the solid is suppressed, we report here results from the SSCE for the more practical thick fuel configuration for quiescent flame spread in microgravity (ref. 12). This configuration has not been investigated to any great extent, experimentally, because the slow spread rates, much slower than those for a thin fuel, result in a need for substantial experimental time, time that is difficult to obtain in Earth-bound facilities such as drop towers.

Here we describe the results of experiments for spread over polymethylmethacrylate, PMMA, samples in the microgravity environment of the Space Shuttle. The results are coupled with modelling in an effort to describe the physics of the spread process for thick fuels in a quiescent, microgravity environment and uncover differences between thin and thick fuels. A quenching phenomenon not present for thin fuels is delineated, namely the fact that for thick fuels the possibility exists that, absent an opposing flow of sufficient strength to press the flame close enough to the fuel surface to allow the heated layer in the solid to develop, the heated layer fails to become "fully developed." The result is that the flame slows, which in turn causes an increase in the relative radiative loss from the flame, leading eventually to extinction. This potential inability of a thick fuel to develop a steady spread rate is not present for a thin fuel because the heated layer is the fuel thickness, which reaches a uniform temperature across the thickness relatively rapidly.

Experiment

The experiment apparatus was largely the same used for cellulosic sample experiments (ref. 12): a 39 liter chamber filled before flight with the test atmosphere, two cine cameras providing top and side perspectives of the PMMA samples, and a data acquisition and control computer. Three Shuttle missions were conducted with quiescent test atmospheres consisting of mixtures

¹ Work funded under NASA Contract NAS3-23901. Manuscript based on "Quiescent Flame Spread Over Thick Fuels in Microgravity", to appear in the *Twenty-Sixth Symposium (International) on Combustion* (ref. 15).

of O_2/N_2 at 70% O_2 /1 atm pressure (STS-54), 50% O_2 /1 atm (STS-63), and 50% O_2 /2 atm (STS-64). In each flight two PMMA samples, 25.4 mm long x 6.35 mm wide x 3.18 mm thick were imbedded in an aluminum structure, with one large face exposed to the chamber atmosphere in the plane of the structure surface. The bottom and side faces of the samples were insulated from the structure. A resistively-heated Kanthol wire for ignition was imbedded 1.6 mm from one end. Three type R thermocouples were installed for each sample: one each in the gas-phase, at the fuel surface, and imbedded in the fuel. The thermocouples above and below the surface were at different distances from the surface of the two samples to provide a reconstructed five-point temperature profile. In 70% O_2 , 0.127 mm diameter thermocouple wire was used throughout. For the 50% O_2 tests, 0.076 mm wire was used for the surface and imbedded thermocouples and 0.025 mm wire in the gas phase.

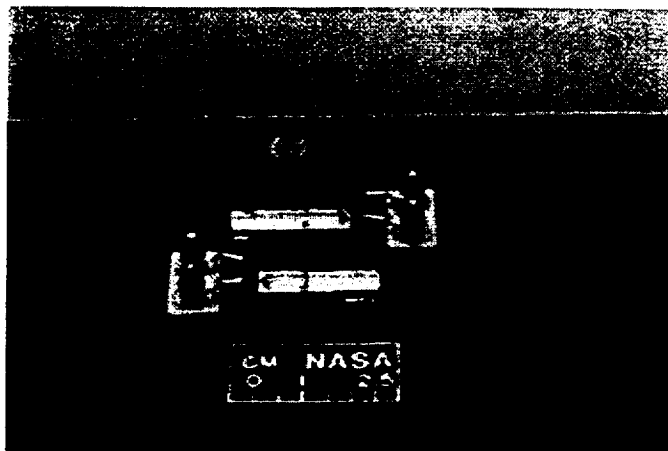


Figure 1 Samples and sample holder for PMMA samples.

spreading flames, measured using image analysis software (ref. 5), with time are shown. The flattened portions of these plots are associated with the flames encountering the gas-phase thermocouples, which glow brightly and partly obscure the dim flame images. The size of the gas-phase thermocouples was initially chosen to match that of earlier experiments with thin, cellulosic fuels (ref. 6). Following the first experiment at 70% O_2 , when it was found that thermocouples of that size influence the spread process for a portion of the experiment, presumably because of the low flame temperatures due to substantial radiative heat loss from the flame, computed to be as much as 60% of the heat released, Earth-bound near extinction experiments were conducted to determine if the use of smaller thermocouples would be less intrusive, which it was found to be. As a result, for subsequent flight experiments, the smallest thermocouples that could be physically installed were used. Once the flames pass the thermocouple, they resume a trajectory of gradually decreasing slope, i.e., a decreasing spread rate. The flame in 70% O_2 , 1 atm was beginning to escape the thermocouple when it was quenched by the experiment's computer.

Modelling

The mathematical model employed has been reported elsewhere (refs. 2,6,7,13), so only a brief description is presented here. Unsteady, dimensionless, two-dimensional conservation equations in the gas for energy, momentum, fuel, oxygen, and nitrogen are expressed in a generic format. An ignition source term is applied to a portion of the solid and gas near the interface and at the location of the experimental igniter. A Planck mean absorption coefficient, $a_{p,GB}$, calculated from the method of Global Energy Balance (refs. 2,7), considering CO_2 , H_2O , methylmethacrylate vapor, and the temperature distribution in the flame accounts for reabsorption of radiation. Typical values of $a_{p,GB}$ range from 2 to 4 m^{-1} . Feedback of gas radiation to the fuel surface, surface reradiation, and three-dimensional radiation effects due to the finite width of the sample are included.

In addition to the conservation equations, the equation of state for density, a square-root dependence of viscosity and thermal conductivity in the gas on temperature, and a pyrolysis formula based on negligible surface regression, constant solid density, and first-order kinetics (ref. 14) are used to complete the formulation. Property values are listed elsewhere (ref. 15).

The set of equations and suitable boundary conditions are solved numerically using the SIMPLER algorithm (ref. 16). A 25.4 mm long sample of PMMA, with the same width and half-thickness dimensions as the experiment, is embedded flush with an inert surface, with the exception of the 70% O_2 environment for which the computational sample was 10 mm longer, for reasons that will be apparent below. The inert surface is used to direct the gas flow toward the reaction zone and to provide suitable boundary conditions for analysis. The downstream inert surface, behind the ignition end, is 4 cm long, and the upstream inert

A sliding-plate mechanism for flame quenching was deployed under computer control to preserve the fuel surface shape after flame spreading was complete. In STS-54, the flame arrival time at the sample end was estimated by the rise time to a threshold temperature at the thermocouple locations. In STS-64, the first sample quench time was computed using a higher threshold temperature, and the second sample was allowed to burn until the cine film was consumed. In STS-63, both sample were allowed to burn until the cine film was consumed, but the cameras were started 60 seconds after ignition in the second sample.

Experimental Results

For brevity, only flame position as a function of time data are presented here. These data allow a description of the phenomena involved to be developed. In Fig. 2, position of the

surface, toward which the flame is spreading, is 23.46 cm long (22.46 cm for 70% O₂). The computation is performed over a 30 cm long x 20 cm high domain. The ignition power input per unit volume is 2.2×10^8 W/m³, which when multiplied by the ignition volume results in 2.4 W of ignition power, approximately the experimental input. This power input is continued until flame ignition occurs, which is usually at approximately 1.8 s, at which time it is shut off.

Computations on several grids were performed to establish the level of refinement required for essentially grid-independent results, the grid chosen being 140 (x-nodes) x 52 (y-nodes), x being along the solid, y normal to the solid, with 8 y-direction nodes in the solid. Along the y-direction, the grid step size is 0.625 mm from the fuel surface into the gas to y=10 mm. After 10 mm a power-law variation for grid distribution to the top of the domain is used. The grid distribution along the x-direction consists of a step size of 1.74 mm from x=0 to x=4 cm (downstream inert surface), followed by a step size of 0.283 mm to x=6.54 cm (fuel sample), and then followed by a power-law variation to the right-hand-side of the domain (upstream inert surface). The time step ranged from 0.05 to 0.5 s, and the relative convergence criterion for all field variables was 0.005.

In Fig. 3, the experimental results are presented again for comparison to the computational results. The computations track the flame progression relatively well as the flame spreads from time zero and captures the fact that the spread rate decreases with time. As the computations are extended beyond the experimental time, the flame continues to spread at a decreasing rate until it reaches a maximum distance of progression, at which time the leading edge retreats as the flame shrinks in size and then extinguishes. This behavior was found for all three environments considered. For 70% O₂, the progression was beyond the 25.4 mm experimental sample length, and so computationally the sample was extended 10 mm as mentioned above.

Discussion

Previous results for thin cellulosic fuels in a quiescent, microgravity environment showed that the flame spread rate following ignition quickly adjusted to a fixed value (ref. 6,7). Here we find, however, that for the thick fuels, the spread rate continually decreases with time until eventually, computationally, the flame extinguishes. This behavior is somewhat understandable as described below.

Consider a region near the leading edge of the flame in which the thermal diffusion length is $L_g = \alpha_g / V_f$, V_f , the spread rate, being the velocity scale. Actually, the length over which heat is transferred is less than α_g / V_f because of radiation (ref. 3), the consequences of which will be evident later, but initially in the spread process radiation is unimportant until the flame evolves to sufficient size. Within the solid, there is a y-direction thermal scale for the heated layer depth of $\delta_y = \sqrt{\alpha_s \alpha_g / V_f^2}$, α_g / V_f^2 being the time the solid is heated from T_- to the vaporization temperature T_v and an x-direction scale of $\delta_x = \alpha_s / V_f$.

At the flame leading edge, an approximate steady-state energy balance on the solid gives

$\rho_s c_s (T_v - T_-) V_f \delta_y \approx \lambda_g (B - r) \Delta h_v / c_g - \epsilon_s \sigma (T_v^4 - T_-^4) \delta_x$ where the first term on the right-hand-side is the heat conduction from the flame to the fuel upstream through the gas and solid (refs. 17,18), and the second is the radiative loss from the surface in which the x-direction length in the solid has been taken to be larger than that in the gas for now. B is the transfer number, and r is the stoichiometric fuel-air ratio. For a thin fuel, in which δ_y is τ , δ_y / δ_x is small such that upstream conduction in the solid is negligible, and δ_x is L_g because the heat conduction is through the gas, we get a steady solution for V_f as long as the heat conducted from the gas exceeds the heat lost by radiation, i.e.,

$$2V_f \approx \frac{\lambda_g (B - r) \Delta h_v}{c_g \rho_s c_s (T_v - T_-) \tau} + \sqrt{\left(\frac{\lambda_g (B - r) \Delta h_v}{c_g \rho_s c_s (T_v - T_-) \tau} \right)^2 - \frac{4\epsilon_s \sigma (T_v^4 - T_-^4) \alpha_g}{\rho_s c_s (T_v - T_-) \tau}} \quad (1)$$

When radiation is neglected, Eq. (1) gives the de Ris-Delichatsios formula (refs. 8,17,18) except for a factor of $\pi/4$. As mentioned above, experiments for thin cellulosic samples in a quiescent, microgravity environment yield a steady spread rate for those environments in which the flame spreads.

Assuming slow variations from one steady state to another, the unsteady counterpart of the above energy balance is obtained by

adding the term $\frac{d}{dt} \rho_s c_s (T_v - T_\infty) \delta_y \delta_x$ to the left-hand-side in which we use the same steady-state length scales as an approximation. For the thin fuel again, with $\delta_x = L_g$ and $\delta_y = \tau$, the unsteady term divided by the convective term gives $(1/V_f) \frac{d}{dt} \frac{\alpha_g}{V_f}$ so that the time scale becomes α_g / V_f^2 , which is of the order of 1 to 10 s for the spread rates measured (ref. 6).

For the thick fuel, with $\delta_x = \alpha_g / V_f$, the time scale is α_g / V_f^2 . With $\alpha_g \cong 10^{-3} \alpha_k$ and the spread rate approximately two orders of magnitude, or more, smaller than for the thin fuel, the time scale can be more than an order of magnitude larger than that for a thin fuel, large to the extent that the flame is unable to adjust to a steady state as the in-depth heated layer in the solid near the leading edge continues to grow with time. From the approximate energy balance for the thick fuel, neglecting the radiative loss, we get, early in the spread process, that $V_f \propto 1/\sqrt{t}$ where the proportionality factor is inversely proportional to B . That is, for higher oxygen concentrations, V_f decreases initially more rapidly. Once this decrease takes place, the flame seeks to adjust to a steady state such that the V_f dependence on t changes and is a function of the environment.

Steady spread over PMMA in a quiescent, microgravity environment should exist if the fuel, or heated layer in the solid, is thin enough as it exists for thin cellulosic samples. Steady-state computations, in which the unsteady term in the computational model is dropped, and the steady computations carried out in flame-fixed coordinates as described elsewhere (refs. 6,7), except that the above solid-phase model for PMMA used here is employed, show that for thicknesses of and below 0.05 mm for 50% O₂/1 atm and 0.2 mm for 100% O₂/2 atm, steady spread for PMMA of the same width as the experimental samples is obtained. For these computations, a domain approximately 111 cm long and 89 cm high with a 90x50 non-uniform grid in the gas and 10 grid lines in the solid was used. The relatively large domain is needed to allow the oxygen field to develop. The computed spread rates for these limiting thicknesses are approximately 2 and 1 mm/s, respectively. These thicknesses are comparable to the thickness of 0.083 mm for which cellulosic samples gave steady spread rates in an O₂ percentage as low as 35% at 1 atm (ref. 6).

The mechanism causing the unsteady spread and eventual extinction for the thick fuel can be explained by comparing computed temperature and oxygen contours at several times during the unsteady spread process as shown from computations in Fig. 4. The thermal diffusion scale in the gas is α_g / V_f , as mentioned above, and for unit Lewis number this is the mass diffusion scale as well. However, the actual thermal length scale in the gas over which temperature changes occur is reduced because of the effects of radiation (ref. 3). The reduction increases as the spread rate decreases, and the effects of radiation become more pronounced while the mass diffusion scale increases. As a result, as the flame evolves over time for the thick fuel, the spread rate decreases with time, and the mismatch between the thermal length scale and the mass diffusion scale grows. Eventually, the diffusion rate of oxygen to the high temperature flame, proportional to $y_{O_2,\infty} / L_g$, is too small to sustain the flame, and the flame extinguishes. This behavior is evident in Fig. 4. While there are oxygen concentrations below which thin fuels are unable to support spreading flames, and this inability has been identified with the effects of radiation on the gas-phase chemical kinetics (ref. 2), and oxygen diffusion (ref. 19), apparently the spread rate for thin fuels is high enough that the flame spreads at a steady rate.

Conclusions

Experiments for flame spread over flat surfaces of thick fuels in microgravity show that the flame spread rate slowly decreases with time. Because the fuel is thick, the heated layer in the solid evolves in time. Spread rates are low enough that radiative effects are important, and they cause the distance over which temperature changes occur in the gas to be reduced over what it would be in the absence of radiation when the conduction and mass diffusion scales are comparable. In contrast, the distance over which oxygen must diffuse to reach the flame is unaffected by radiation. As a result, this distance grows in time as the flame slows, which results in a reduction of the diffusion rate to the flame to lead eventually to flame extinction. There appears to be a critical thickness below which steady spreading is obtained in microgravity. Below this thickness, the fuel is heated rapidly, and the spread rate remains high enough that any difference in the distance over which temperature changes and mass diffusion occur is unimportant in comparison to the thick fuels.

References

1. Bhattacharjee, S., Altenkirch, R.A., Srikantaiah, N., and Vedha-Nayagam, M. (1990). *Combustion Science and Technology* 69, 1-15.
2. Bhattacharjee, S. and Altenkirch, R.A. (1991). *Twenty-Third Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 1627-1633.

3. Bhattacharjee, S., Altenkirch, R.A., Olson, S.L., and Sotos, R.G. (1991). *Journal of Heat Transfer* 113, 670-676.
4. Bhattacharjee, S. and Altenkirch, R.A. (1992). *Twenty-Fourth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 1669-1676.
5. Bhattacharjee, S., Altenkirch, R.A., and Sacksteder, K. (1993). *Combustion Science and Technology* 91, 225-242.
6. Ramachandra, P.A., Altenkirch, R.A., Bhattacharjee, S., Tang, L., Sacksteder, K., and Wolverton, M.K. (1995). *Combustion and Flame* 100, pp. 71-84.
7. Bhattacharjee, S., Altenkirch, R.A., and Sacksteder, K. (1996). *Journal of Heat Transfer* 118, pp. 181-190.
8. de Ris, J.N. (1969). *Twelfth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 241-252.
9. Wichman, I. S., Williams, F., A., and Glassman, I. (1982). *Nineteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 835-845.
10. Fernandez-Pello, A.C., Ray, S.R., and Glassman, I. (1981). *Eighteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 579-587.
11. Williams, F.A. (1977). *Sixteenth Symposium (International) on Combustion*, The Combustion Institute, Pittsburgh, pp. 1281-1294.
12. Vento, D., Zavesky, R., Sacksteder, K., and Altenkirch, R.A. (1989). *The Solid Surface Combustion Space Shuttle Experiment Hardware Description and Ground-Based Test Results*, NASA TM 101963.
13. Bullard, D.B., Tang, L., Altenkirch, R.A., and Bhattacharjee, S. (1993). *Adv. Space Res.* 13-7: 171-184.
14. Lengelle, G. (1970). *AIAA J.* 8: 1989-1986.
15. West, J., Tang, L., Altenkirch, R.A., Bhattacharjee, S., Sacksteder, K., and Delichatsios, M.A. (1997). *Quiescent Flame Spread Over Thick Fuels in Microgravity*, *Twenty-Sixth Symposium (International) on Combustion*, The Combustion Institute, in press.
16. Patankar, S.V. (1980). *Numerical Heat Transfer and Fluid Flow*, Hemisphere, New York.
17. Delichatsios, M.A. (1993). *Comb. Flame* 95: 336-339.
18. Delichatsios, M.A. (1994). *Comb. Flame* 99: 601-609.
19. Olson, S.L. (1990). *Comb. Sci. Technol.* 76: 233-249.

SSCE PMMA Flame Position Composite STS-54, STS-63, STS-64

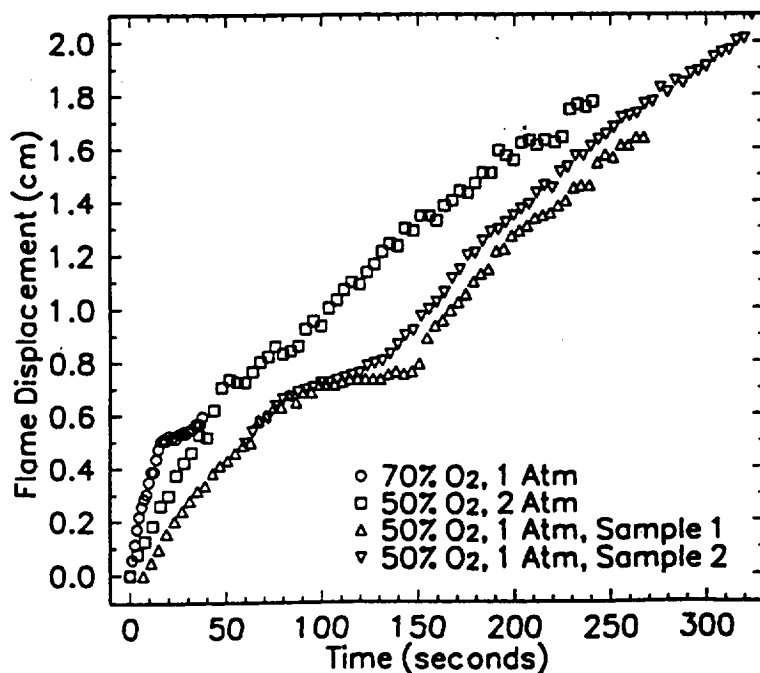
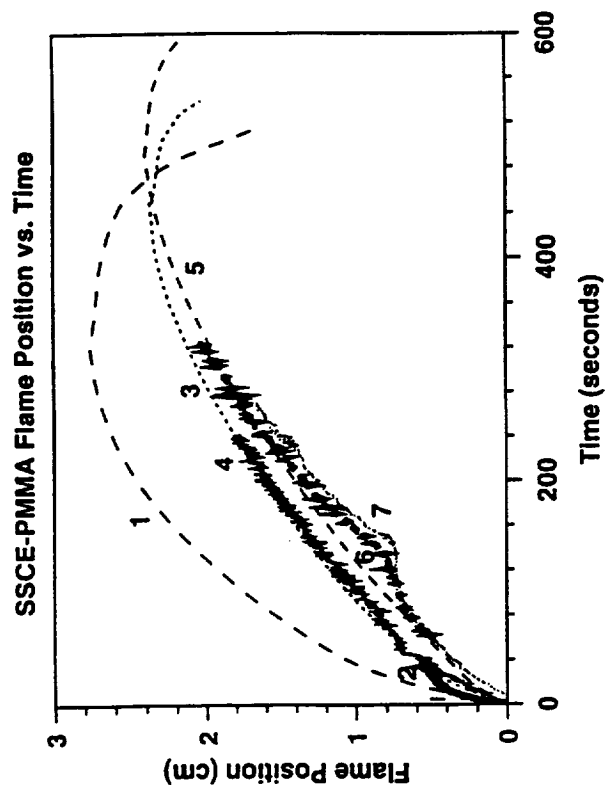


Figure 2 The progress of spreading-flame position over burning PMMA samples. The flame in 70% O₂, 1 atm (circles) appears retarded by the thermocouples (0.127 mm wire). The position of the 50% O₂, 2 atm flame (squares) is obscured by the glowing thermocouple at about 50 s after ignition (0.025 mm wire), but flame progress is unaffected. Data from the other 50% O₂, 2 atm flame (not shown) is indistinguishable from the first until it is quenched by the computer at about 70 s after ignition. Two flames in 50% O₂, 1 atm (triangles) show distinguishable thermocouple influence: the flame encountering the thermocouple 3 mm above the fuel surface (sample 1) follows a delayed trajectory similar to its companion encountering the thermocouple 1 mm above the surface.



- 1. 70% O₂, 1 atm, computational
- 2. 70% O₂, 1 atm, experimental
- 3. 50% O₂, 2 atm computational
- 4. 50% O₂, 2 atm, experimental
- - - 5. 50% O₂, 1 atm computational
- 6. 50% O₂, 1 atm, experimental
- - - 7. 50% O₂, 1 atm, experimental

Figure 3 Computed and experimental (from Fig. 2) flame position as a function of time.

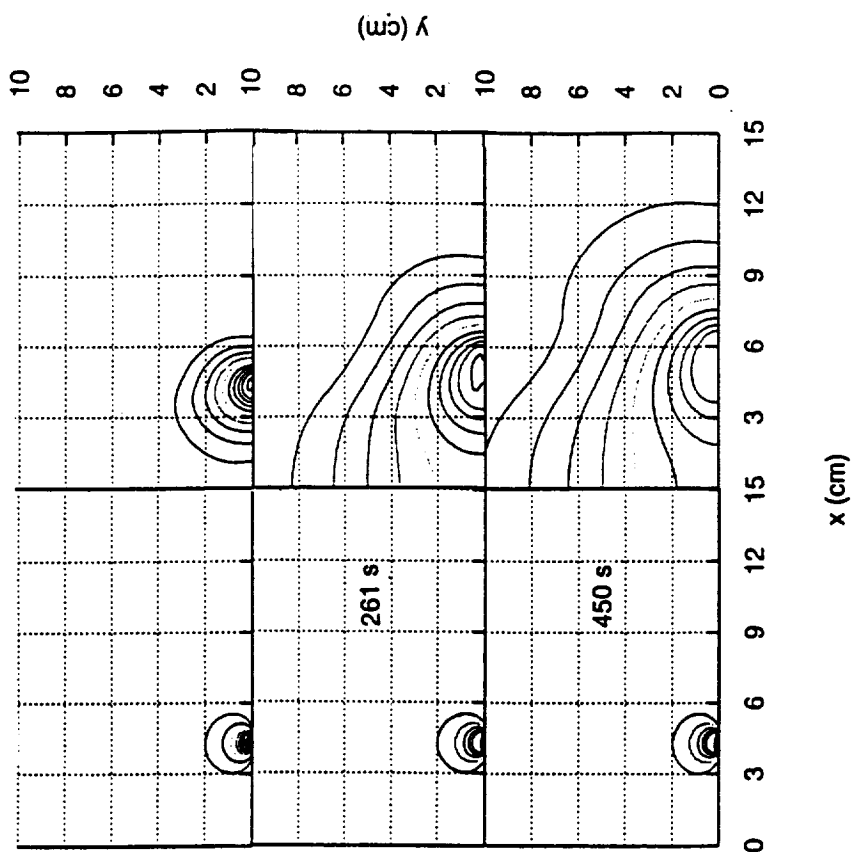


Figure 4 Computed temperature (left-hand-side) and oxygen (right-hand-side) contours for 50% O₂/2 atm ($y_{O_2} = 0.533$) for three different times during the spread process. The outermost oxygen contour is for $y_{O_2} = 0.45$, and the temperature contours are from 450 K to 1350 K for 48 s to 1050 K at 261 and 450 s. The thickness of the region over which oxygen diffuses grows with time such that the high temperature contours find themselves in a region in which the flux of oxygen is decreasing with time.