OPPOSED-FLOW FLAME SPREADING IN REDUCED GRAVITY

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Introduction

Experimental results obtained in drop towers and in Space Shuttle based experiments coupled with modelling efforts are beginning to provide information that is allowing an understanding to be developed of the physics of opposed–flow flame spread at reduced gravity where the spread rate and flow velocity are comparable and of the role played by radiative and diffusive processes in flame spreading in microgravity [1–6]. Here we describe one Space Shuttle based experiment on flame spreading in a quiescent environment, the Solid Surface Combustion Experiment, SSCE [7], one planned microgravity experiment on flame spreading in a radiatively–controlled, forced opposing flow environment, the Diffusive and Radiative Transport in Fires Experiment, DARTFire [8], modelling efforts to support these experiments, and some results obtained to date.

SSCE Apparatus

The SSCE apparatus consists of a sealed container, approximately 0.039 m^3 in volume, that is filled with a mixture of specified O_2 and N_2 percent by volume at a prescribed pressure. The test specimens are either ashless filter paper (thin fuel), 0.165 mm thick, 10 cm long, and 3 cm wide, or polymethylmethacrylate (PMMA; thick fuel), 0.318 cm thick, 2 cm long, and 0.635 cm wide. One end of the sample is ignited using an electrically–heated nichrome wire.

For the thin fuel, three 0.127 mm Pt/Pt–Rh thermocouples are positioned along the sample centerline. The first is embedded in the sample 5 cm from the ignition end of the sample, the second is located 2.3 mm above the sample but 2.54 cm farther from the ignitor, and the third is located 7.0 mm above the sample directly over the first. For the thick fuel, one one thermocouple is positioned in the gas, and two in the solid, one at the surface and one in depth. Two orthogonal views of the experiment are recorded using 16 mm cine–cameras operating at 24 frames/s.

SSCE Results

Four experiments for the ashless filter paper samples have been run to date, three at $50\%O_2/50\%N_2$ by volume at 1.5 atm (STS–41, October 1990), 1.0 atm (STS–40/SLS–1, June 1991), 2.0 atm (STS–43, August 1991), and one at $35\%O_2/65\%N_2$ at 1.5 atm (STS–50/USML–1, July 1992). Figure 1 shows four frames from the side–view film for 50% O_2 at 1.5 and 1.0 atm. Just after the ignitor wire is heated, ignition from nitrocellulose on the wire results in a bright orange flash that subsides once the flame spreads away from the ignitor wire. The flame is spreading from left to right, and the time for each frame is the time after the first flame–like image appears on the film.

As the flame spreads, the soot radiation level in the tail of the flame decreases in both flames, and the lower pressure flame becomes entirely blue. Additionally, the flame elongates early in the spread process as the leading edge propagates faster than the trailing edge. Even though the soot radiation changes with time and the flame elongates just following ignition, the leading–edge spread rate is almost fixed immediately after the flame leaves the ignitor. The spread rates for the first three experiments are 0.358, 0.454, and 0.547 cm/s for 1.0, 1.5, 2.0 atm, respectively, at 50% O_2, and for the 35% O_2 experiment it is 0.092 cm/s at 1.5 atm.

Thermocouple traces, as a function of location in the flame, for the surface and gas temperatures, and the net heat flux to the solid [6] are shown in Fig. 2. The leading edge of the flame is at x=0, which is fixed at the location of the peak net heat flux. The surface temperature increases rapidly as the flame is approached and then reaches a relatively steady temperature, which indicates the region of pyrolysis. The temperature then rises, and as the tail of the flame passes the thermocouple, the temperature quickly decreases until the residual char increases in temperature again as fresh oxygen, which diffuses to the surface while products diffuse away, results in surface oxidation.

Steady–State Modelling

Flame spread modelling is used to support the experimental effort. A comprehensive, steady–state, mathematical model developed along with the experimental program has been presented elsewhere [3,4]. The conservation equations in the gas for mass, fuel, oxygen, x and y momentum, and energy, including finite–rate chemistry, and the energy and mass conservation equations in the solid, including finite–rate, endothermic pyrolysis, are solved for the steady–state spread rate and distribution of field variables. For the thin fuel, radiation from CO_2 and H_2O is considered [4], but the radiation fed back to the surface is generally assumed to balance that reradiated from the surface so that a direct radiative coupling between the gas and the solid is not presently considered [5].

Some computed results are compared to experimental results for the 50% O_2, 1.5 atm experiment in Fig. 3. The character of the gas–phase temperature at the leading edge of the flame is predicted well, but the trailing edge of the flame is too far from the surface, with little or no curvature toward the surface, to provide agreement with experiment. Because the leading edge of the flame is responsible for establishing the spread rate, reasonable agreement between measured and predicted spread rate is obtained, the measured values, given above, for the 50% O_2 experiments being 0.358, 0.454, 0.547 cm/s for 1.0, 1.5, 2.0 atm, respectively, compared to predicted values of 0.360, 0.417, 0.450 cm/s. Both the measured and predicted spread rates increase with pressure; without gas–phase radiation, the predicted spread rate, which is approximately a factor of two higher than experiment (0.704 cm/s) at 1.0 atm, is almost independent of pressure, although it declines slightly with an increase in pressure.

For thin fuels, radiative effects are important at low opposing flow velocities, decreases in flow velocity causing a decrease in spread rate and possible extinction [9]. As the flow velocity is increased, the effects of radiation become unimportant, with extinction at high flow velocities occurring via blowoff. While thick fuel experiments have not been completed yet, modelling of flame spread over thick fuels has progressed, although the effects of radiation have been confined to surface reradiation [10]. For these fuels, surface radiative effects are important for all flow velocities because as the flow velocity is increased from very low values to very high values, the radiative effects compared to the conduction effects do not decrease as they do for thin fuels.

DARTFire Experiment

Experimental and modelling results, obtained in conjunction with the SSCE, show that radiative effects are important in low–velocity, opposed–flow flame spreading at reduced–gravity. Although in the SSCE the opposing flow is not controlled, because the environment is quiescent, it is, in flame–fixed coordinates, the spread rate. In the DARTFire experiment, which is described in a recently–developed Science Requirements document [8], the fuel surface is subjected to various levels of an external radiative flux, and the flame spreads into a low–velocity, forced–flow boundary layer. Such a configuration will allow determination of those environments that lead during flame evolution to sustained spreading or extinction and development of a clear understanding of the interaction between the flow and radiation fields at reduced gravity.

Unsteady Modelling

More recently, the steady–state model has been extended to include unsteady effects [11,12] that allows flame characteristics to be computed from ignition onward. While the spread rates measured in the SSCE are steady, which is understandable because the flow field around the leading edge of the flame is established by the flame itself and is relatively fixed independent of flame location, the trailing edge of the flame exhibits some unsteady behavior. For DARTFire, the flame spread is inherently unsteady because the flame spreads into a thinning boundary layer in which the flow field changes with flame position.

Conclusions

Results of gas and surface temperature and spread rate measurements in flame spread over a thin cellulosic fuel in a 50% O_2/50% N_2 quiescent environment obtained aboard recent missions of the Space Shuttle show steady spreading, and, when coupled with steady–state modelling, the importance of radiation. Spread rate increases with pressure through the effects of pressure on gas radiation, the optical depth of the lower pressure flames and the attendant heat loss being greater than at higher pressure. Computed results agree with experimental results near the leading edge of the flame, but additional refinement of the model is needed in order to describe accurately the trailing edge of the flame and more accurately the coupling of gas and surface radiative processes. Development of an experiment in which the radiative and flow environment will be carefully controlled is proceeding as well as the development of unsteady flame spread models.

Acknowledgements

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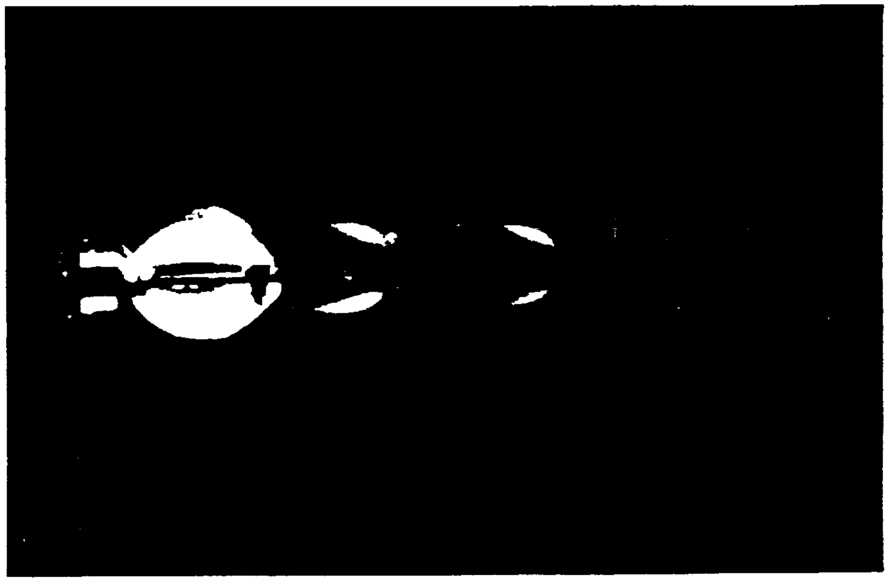

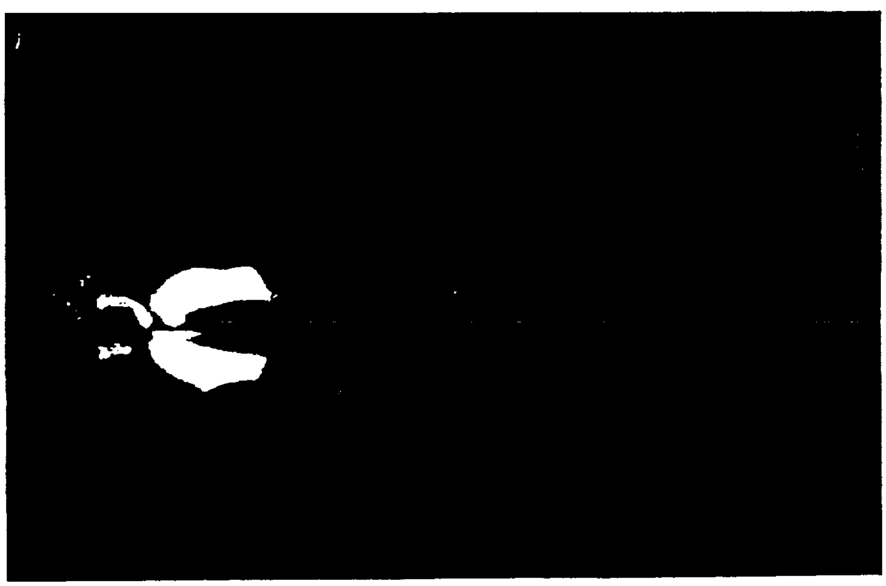

Fig. 1. Four frames from 16 mm film of flame spread over ashless filter paper in the SSCE at 50% O_2 at 1.5 atm (top) and 1.0 atm (bottom). Times are time from the first appearance of a flame–like image on the film.

See Color Plate F-2

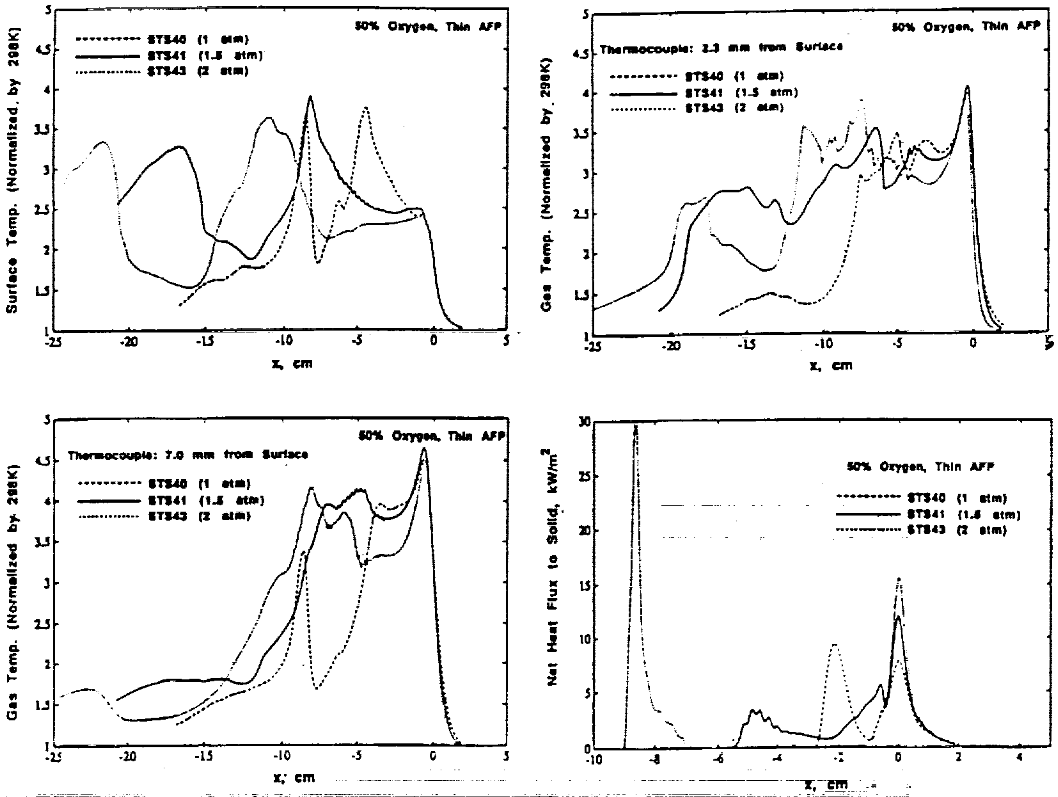

Fig. 2 Measured temperature and heat flux profiles for spread over ashless filter paper in the SSCE at 50% O_2.

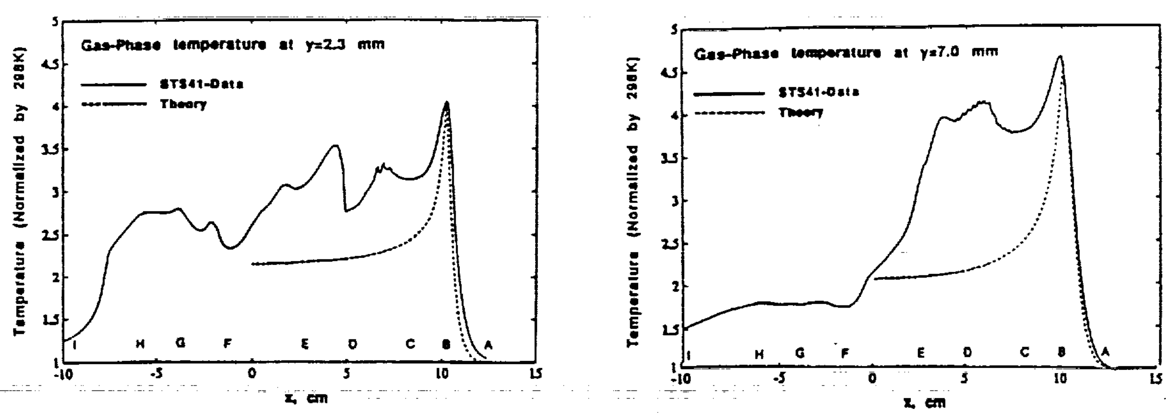

Fig. 3. Comparison between measured and computed temperatures for spread over ashless filter paper in the SSCE at 50% O_2 and 1.5 atm.

COMMENTS

Question (Howard R. Baum, NIST): The role of gas phase radiation in these problems may indeed be important. However, while the local emission can be roughly approximated in a 2-dimensional simulation, the feedback to the condensed phase is inherently 3-dimensional. This is due to the limited width of the fuel sample and the rapid decay of the temperature and combustion product species in the lateral direction.

Answer: Dr. Baum's points are well-taken, and, as he indicates, there are two separate issues to address here. In some earlier preliminary work (1,2), we found that the Planck mean absorption coefficient as defined here is not particularly sensitive to sample width. Values from "two-dimensional" computations, which have a 3-D aspect to them in that lines of sight throughout a 2-pi steradian solid angle are considered in calculating fluxes on the computational domain, do not change much as the sample width is reduced to a range in which we are interested, as long as some physically reasonable temperature and species profiles are used in the lateral direction when radiation loss from the sides of the flame is considered. Consequently, the "two-dimensional" radiation model for the gas-phase emission appears to be a reasonable approximation.

In considering radiation feedback to the surface though, which we have not done here but have rather taken the feedback to balance the surface reradiation, 3-D effects are inherent. While the 2-D model accounts for reasonable overall radiative loss from the gas-phase, the fraction of gas radiation fed back to the surface depends on the details of how the radiation loss though the sides of the flame is treated. We plan to address this inherent 3-D effect in an approximate way in future 2-D computations.

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