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SOLID INFLAMMABILITY BOUNDARY AT LOW SPEED (SIBAL)

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This research program is concerned with the effect of low-speed, concurrent flow on the spreading and extinction processes of flames over solid fuels. The primary objective is to verify the theoretically predicted extinction boundary, using oxygen percentage and flow velocity as coordinates. In particular, we are interested in the low-speed quenching limits and the existence of the critical oxygen flammability limit. Detailed flame spread characteristics, including flame spread rate, flame size, and flame structure are sought. Since the predicted flame behavior depends on the inclusion of flame and surface radiation, the measured results will also be used to assess the importance of radiative heat transfer by direct comparison to a comprehensive numerical model.

This project passed the Science Concept Review (SCR) in 1996. As a result, the experiment continues on the flight definition path, and is currently scheduled to be performed in the Space Station Combustion Integrated Rack (CIR). We present an overview of recent and ongoing work, including selected experimental and theoretical topics.

GLOVEBOX EXPERIMENTS

The SIBAL project took advantage of an opportunity to perform a Microgravity Glovebox space experiment in order to determine some long-duration burning behavior. The Forced Flow Flame Spread Test (FFFT) consisted of a test module, which was a miniature, low-speed wind tunnel; a hand-held control box; and individual fuel sample assemblies. The test module was a metallic duct with an inlet section, where air velocity measurements were made, and an outlet section where the fan that moves the air was located [1].

Flat sheets of paper fuel of different thicknesses were burned. Due to limitations in the size of this experiment, none of the flames reached steady state. General observations of flame spread rate, temperatures, and appearance were obtained, however. The flames were wide, dim, and mostly blue (see fig. 1 for an example). The wide flames were due to small airflow speed, and the dim blue flame color was due to slow oxygen transport. Flame spread rates increased as the flow speed increased, and were inversely proportional to sample thickness.

FLAME SPREAD MODEL

The model has been described in detail elsewhere [2] so only the broad features are presented here. The steady, Navier-Stokes equations are solved together with conservation of energy and reacting species. A one-step, second-order chemical reaction is assumed. Gas and solid phase radiation are included, and the gas properties are evaluated as a function of temperature.

The model was solved in two dimensions. A comparison is made with experiment in fig. 1. The fuel consumption rate contours are plotted next to the flame. These contours are the best indicator of the blue visible flame in models with one-step kinetics. In order to achieve the best agreement with experimental data, Grayson et al. [3] used $w_F = 0.1$ mg/s cm^3 to represent the edge of the blue flame (minimum visible reaction rate) in related solid-fuel flame-spread modeling, and the same value is used here. The curvature of the visible flame is in good agreement with that of the computed reaction rate contour, even though the computed flame is steady while the observed flame did not yet reach steady state.

In concurrent-flow flame spread, however, it is well-known that in order to have a system for which the two-dimensional approximation is valid requires an excessively wide sample. Specifically, such a formulation applies for cases where the fuel is substantially wider than the flame length. This is a difficult condition to meet even for relatively small, concurrent-flow flames. Rather than attempt to build an experiment for which the two-dimensional approximation is valid, we instead developed a three-dimensional model. It is only in the initial stages, and additional work is forthcoming. While being more computationally intensive, this model can now examine the effect of varying fuel width on flame characteristics. The most obvious advantage for using a three-dimensional formulation is that the exact geometry of the experiment can be modeled.

FLAME RADIATION STUDIES

Because of the reduction of convection, radiation becomes an important heat transfer mechanism in microgravity flames. The accuracy and the affordability of computation models for radiation that can be coupled to the flame analyses are of general interest.

We have applied a variety of radiation models to a one-dimensional low-stretch diffusion flame with carbon dioxide and water vapor as the radiation participating media [4]. These include gray-gas, optical-thin, wide-band, narrow-band and spectral line weighted sum of gray gases (SLWSGG) models. Both the accuracy (in term of the radiative source, i.e., the divergence of radiative heat flux) and the relative computational times are compared. Computed results of the radiative source distribution for wide-band, narrow-band and SLWSGG show reasonable agreement with each other. Results from the optical-thin and gray-gas models with Planck mean absorption coefficient are shown to underestimate the self-absorption and overestimate the emission substantially for the low stretch flame. On the other hand, the relative computational times can be different by several orders of magnitude, the most time consuming being the narrow-band model.

Since the narrow-band model yields the more accurate spectral information among these models and is now affordable for one-dimensional flames, several computations have been carried out recently to study low-stretch flames. The narrow-band model was incorporated into a solid-fuel diffusion flame (PMMA) to investigate the flammability boundary as a function of ambient oxygen percentage and stretch rate and to study the effect of gas versus solid surface radiation [5]. In [6], a detailed account of the radiation absorption (self and across species) and emission are given including the contribution of MMA fuel vapor.

More recently, the narrow-band model has been combined with detailed chemical kinetics in the study of the flammability limit of hydrogen/oxygen gaseous diffusion flames at low pressure [7]. We have chosen an ambient pressure of 1.013 kPa with carbon dioxide as the diluent. The conditions studied are particularly relevant to Mars exploration. Fig. 2 shows the computed maximum flame temperature as a function of stretch rate with and without flame radiation. It is obvious from this figure that radiation is very important at low stretch rates. There are large drops of flame temperature at low stretch rates due to radiative losses and the flame temperature curve exhibits a peak at an intermediate stretch rate. Although this trend has been shown previously with simplified models (either simplified kinetics or simplified radiation treatment or both), the present results with the narrow-band model and detailed kinetics are expected to be more accurate quantitatively.

Fig. 3 gives the flammability map using carbon dioxide diluent and stretch rate as coordinates. First, without radiation, the extinction boundary is monotonic with respect to stretch rate. From the trend of the computed boundary, there is no apparent low-stretch limit: when carbon dioxide dilution level is increased, the flame can still be made flammable at lower stretch rates. Furthermore, it is seen that the adiabatic system would cease to be flammable only when the carbon dioxide dilution is beyond 90% (obtained by extrapolating stretch rate to zero). With radiation, low-stretch quench limits exist and the trend of the extinction boundary is altered. This behavior helps to define an absolute carbon dioxide dilution level above which a flame can not exist at any stretch rate. The existence and the determination of this dilution level can be important from the point of view of fire safety. For the present diffusion flame at 1.013 kPa and an upstream temperature of 300 K, this dilution level is 81%, equal from both the fuel and the oxygen sides.

LOW-PRESSURE TUNNEL

We are constructing a combustion tunnel for use in normal gravity both to provide data for comparison to the model as well as to give guidance in the design of the ultimate space experiment. This vertical wind tunnel, measuring 11 cm x 11 cm, can be operated at reduced pressure to better simulate a flame burning in microgravity. The fuel, automatically supplied from a roll, will be fed in at the exact rate so that the flame will be fixed in space. Infrared and ultraviolet flame emissions will be imaged using video cameras and corresponding filters.

A central issue in this experiment is the choice of fuel. Mechanically, the fuel must be rollable both before and after combustion. Scientifically, the fuel must be well-characterized and burn in a uniform manner. These concerns are addressed by using a custom-woven fabric fuel, consisting mostly of pure cotton threads, but with some fiberglass threads woven in to provide support after combustion. The detailed specifications of the fuel are still being determined. In fact, the low-pressure tunnel will be used to refine the fuel properties to yield the optimal mechanical and scientific properties desired.

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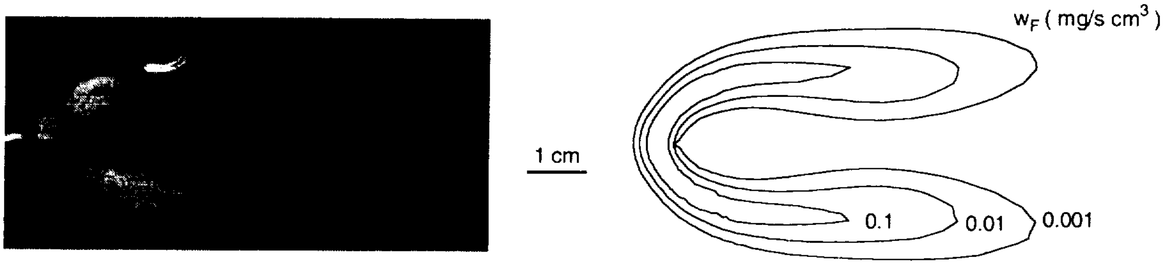
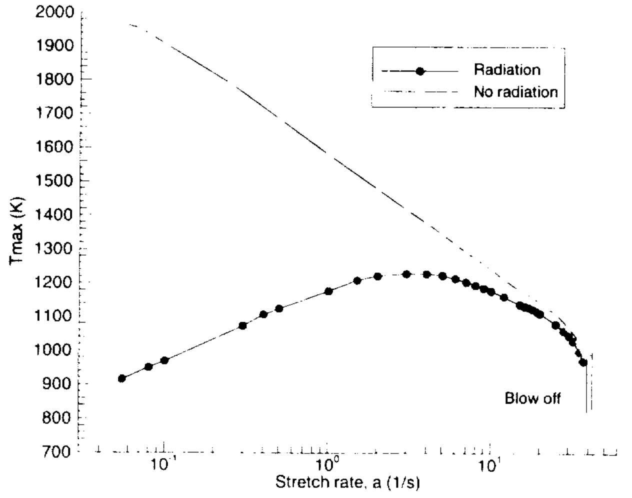


Figure 1. Concurrent-flow combustion of a paper sheet (half-thickness area density = 1.0 mg/cm^2): comparison of visible flame to numerically predicted fuel consumption rate contours. Flow is from left to right at 2 cm/s. Note that the flame is still shrinking in size, while the model results are steady.



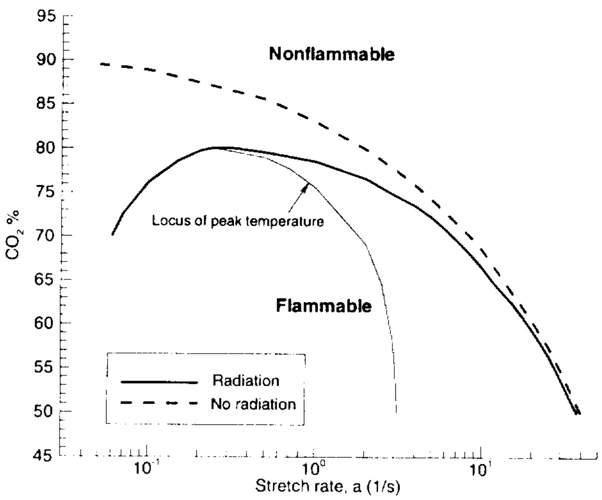


Figure 2. (Left) The maximum flame temperature of H_2/O_2 diffusion flames as a function of stretch rate (fuel side) at a total pressure of 1.013 kPa and 50% CO_2 dilution (same on the fuel and the oxygen sides), with and without the consideration of flame radiation.

Figure 3. (Right) Flammability boundary of $H_2/O_2/CO_2$ opposed-jet diffusion flame with and without the consideration of flame radiation. Total pressure: 1.013 kPa; upstream temperature: 300K.