

Detailed Modeling of Flame Spread Processes over Solid: Progress and Prospect

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Flame spread over solid surface has been a research topic in combustion and fire science for more than thirty years. A spreading flame involves many interactive sub-processes: fluid flow, heat and mass transfer, solid thermal decomposition, gas-phase chemical kinetics and multi-dimensionality. To make a flame-spreading problem 'tractable' theoretically, a number of simplifying approximations are normally made. This often limits the usefulness of the model results. With the increase of computational capability, more detailed processes can be included. With impetus from the NASA's microgravity combustion program, considerable progress has been made in modeling small-scale laminar flame spread over solids over the past dozen years. In this talk, some of the advances made will be reviewed, the possible applications of current models will be discussed and future research that can extend the capability of the present day models will be mentioned.

Much progress has been made on the fluid mechanics of flames. Right now, unsteady, three-dimensional laminar flows can be computed for a spreading flame [1,2]. We can distinguish, for example, both the qualitative and the quantitative differences between a buoyancy-driven upward spreading flame and a purely forced concurrent-flow spreading flame [3]. The confidence in computational flow capability also permit us to go into regimes where we do not have data, i.e. making predictions before experiment. For example, we have been able to predict the trend of flame behavior in low-speed forced flow in microgravity. The low-speed extinction phenomena [4-6] and the tendency of a flame to go upstream if ignited in the middle of a fuel sample [7] are but two successful examples among many.

Flame radiation has been known to be important in fires for a long time [8]. Conventional wisdom is that radiation is important only when the fire reaches certain size and the major radiation source is from soot. In microgravity convection is reduced, radiation becomes important (non-dimensionally) even when the flame is small and blue in color. As a matter of fact, radiation alters the qualitative behavior of flame in the low convection regime and is responsible to the low-speed quenching phenomena. Instead of treating radiation in an ad hoc way as in the past (e.g. assuming 40% of heat release is from radiation), recent effort has been to compute radiation in a more rigorous manner. Since radiation is coupled directly to the flame structure, both have to be computed interactively. The effort so far has been for gaseous radiation (CO₂, CO and H₂O) [9]. Although the computation of the concentrations of these gaseous species is reasonably straight forward, the computation of their radiation characteristics, being spectral, is a challenge, especially in multi-dimensional situations.

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Finite rate chemical kinetics has not been included in early upward flame spreading models. However, chemical kinetics plays several very important roles that we will discuss next. Referring to the schematics in Fig. 1, a flame stabilization zone is located upstream. This zone has a characteristic dimension $\sim \alpha/u$ where α is the thermal diffusivity of the gas and u is the characteristic velocity in this region (buoyant induced or forced). This region can be very small compared with the overall length of the flame, but it plays the critical role of anchoring the rest of the flame. In this zone both the stream-wise and the cross stream-wise heat conduction are important (hence boundary layer approximation is not valid). Together with finite rate chemical kinetics, this zone determines whether a flame can exist (i.e. extinction limit).

Finite rate kinetics can also be important at the flame tip zone. The flame tip is open because it loses heat to the solid. This quenched opening allows un-reacted fuel or reaction intermediates to escape from the flame and to accumulate elsewhere; thus creating the potential for flashover. The flame tip can be thought as the location of the 'local' flammability limit zone. If the condition is right, a flame tip may cease to advance, i.e. flame growth may stop [10].

Thus far only one-step finite-rate global kinetics has been included in the concurrent flame spread models [1-6]. Attempt to use quasi-global kinetics has been made in opposing flame spread [11].

Next, we will discuss the possibilities for application of the current flame spread models and the longer-term research needs.

Potential application of the current detailed flame spread models:

- (1) They can be used to study the limiting mechanism(s) of fire growth. What are needed to confine a fire to a small size? This may be achieved through material modifications or a change of the surrounding atmosphere. The current models, properly amended, can help to provide clues.
- (2) Suppression of incipient fires. If the suppressant mechanism is primarily thermal in nature (e.g. water and CO₂), the models we have so far can be used study the most effective way to apply the suppressant.
- (3) The model can be used to estimate the amount of escaped pyrolysate.
- (4) With un-burnt fuel vapor added to the ambient, the model can be used to study the acceleration of flame spread and its transition to flashback.

Longer-term Research needs:

- (1) More detailed chemical kinetics information for the combustion of solids is needed. This include both the solid thermal decomposition processes and the oxidizing kinetics of the pyrolysis gases. Global chemical kinetics used in the current models is empirical in nature and can not be expected to yield quantitatively accurate predictions. In view of the progress made in gaseous and liquid fuel combustion with detailed kinetics, effort should be made to increase

- the kinetics data base for selected solid fuels and to incorporate the more detailed kinetic information into the model (not a trivial task!).
- (2) Solid phase processes also may include charring and bubbling. The remaining fuel after flame passage often smolders. Whether these events should be incorporated into the model may depend on their importance to the particular problem.
 - (3) Efficient radiation computation scheme and solid radiation data are needed. Rigorous computation of flame radiation in multi-dimensional flame is very time consuming. The computational time for the radiation part can exceed that for the combustion part by a large margin. While computational radiation heat transfer is not normally the expertise of the combustion/fire researchers, we can help by letting our colleagues in radiation know what is our need and by improving the interactive computational scheme between the radiation part and the flame part. It also interesting to know that there is little spectral radiation data on solid surface, especially at elevated temperature and in burning conditions. An initial effort has recently made on thin cellulosic fuels but much more are needed [12].
 - (4) Clearly soot production and soot radiation affect flame spread. Soot is of interest to the general combustion community not just in fire. It is expected that detailed soot formation model, of similar (or higher) complexity as those of the large hydrocarbons, may appear in the near future and can, in principle, be incorporated in future fire models.
 - (5) When the small flame grows to a larger size, downstream portion of flame may become unsteady and go through laminar- turbulent transition. How to incorporate this transitional part into the model clearly will remain to be a long-term challenge.

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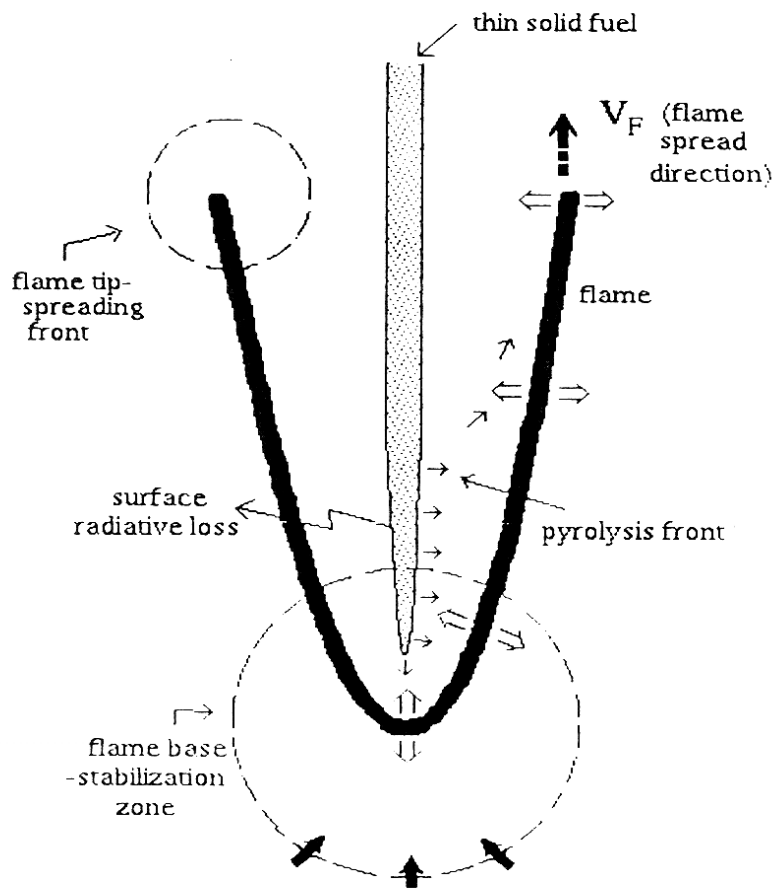


Figure 1. Schematic of a spreading flame in a concurrent flow