

FIELD MODELLING OF SURFACE FLAME SPREAD OVER CHARRING MATERIALS

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SUMMARY

The application of field models to the simulation of smoke movement in fire scenarios is becoming increasingly commonplace as the underlying database of validation and experience grows. However the application of field models to flame spread, and their consequent use in fire scenarios, is in its infancy. In this paper a hierarchy of flame spread models are presented as implemented in the field modelling code, SOFIE. Increasing sophistication of the models reduces the reliance upon empirical data, whilst conversely, the greater the reliance upon empirical data, the more applicable the model to real world materials.

INTRODUCTION

The application of field models to the simulation of smoke movement in fire scenarios is becoming increasingly commonplace as the underlying database of validation and experience grows. When the fire source can be well defined, such as in a design fire, then field models can be expected to provide reasonable simulations of the resulting smoke movement remote from the actual source itself, even if detailed phenomena in the near field are poorly resolved.

The application of field models to flame spread, and their consequent use in fire scenarios, is however only in its infancy. Flame spread is a consequence of direct convective and indirect radiative heat transfer, therefore quantitative simulations of flame spread can only be achieved once the local gas temperature can be accurately predicted. This places an inherent reliance upon the fundamental sub-models employed to represent the gas phase turbulent combustion phenomena. Despite this limitation there has been some progress regarding the development of flame spread models and their coupling to field models, for example ^{1,2,3,4,5}.

Flame spread models may be broadly categorised as either being based upon a mass loss rate model dependent upon local material properties, described through, for example, an Arrhenius type rate expression, or based upon empirical data derived from, for example, cone calorimeter experiments ⁶. The latter models offer the advantage of being able to be applied to a wide range of real world materials, though are less able to take account of any local temporal variations in incident heat flux. Conversely the former class of models, by requiring the solution of both energy and mass transport with the solid material, are readily able to account for the detailed spatial and temporal variation of incident heat flux, but are constrained by the range of materials to which they may be applied.

FLAME SPREAD MODELS

Three different flame spread models have been developed within the field modelling code, SOFIE (Simulation of Fires in Enclosures), specifically developed at Cranfield for compartment fire predictions ⁷.

Heat of Gasification

The simplest model is based upon an empirically determined heat of gasification and an ignition delay correlated by the net incident heat flux, the model is described in detail in Aksit et al ³. The model was demonstrated to reproduce, to a satisfactory level, the flame spread in a plywood lined enclosure, figure 1. Such models may well have a role where detailed resolution of the flame spread phenomena is not required, but some account of the increase in surface area over which volatiles are release is required. The attraction of the model is its inherent simplicity. The disadvantage is the considerable empirical input required.

Cone Calorimeter

The next model is an attempt to take into account the time dependent variation of the physical properties of a specific material during the pyrolysis phase, whilst still relying upon empirical data. In this case the heat release rate for a material is obtained from standard cone calorimeter tests and in effect is a generalisation of the simple heat of gasification model, whereby the heat of gasification is now a function of time. This model is described in detail in Aksit et al. ⁸. The approach capitalises on the wealth of materials data available from the now standard cone calorimeter tests and offers a feasible approach for simulating flame spread over real world materials. Figure 2 illustrates some typical cone calorimeter data for plywood at three different incident heat fluxes and figure 3 the corresponding mass loss rates. Time to ignition is correlated against an integral of the incident heat flux, once achieved the surface element is assumed to follow an appropriate interpolated curve corresponding to the incident heat flux at the time of ignition.

Differential Pyrolysis

The previous models are characterised by empirically determining the time to ignition and the subsequent rate of heat release without the need for discretising the interior of the combustible material. Whilst this has a clear advantage for complex materials and geometries the models rely upon the concept of an ‘ignition temperature’ or ‘time to ignition’ correlated by incident heat flux. The more fundamental and rigorous approach has been investigated by a number of authors, for example Yan and Holmstedt ¹ and Novozhilov et al. ⁴, in which one or more equations are solved within the solid material itself for the transport of mass and energy. Such recent studies have attempted to predict charring flame spread over plane surfaces using CFD. These have incorporated the rate of flame spread over the solid fuel using much simplified pyrolysis models. However, given the nature of solid material gasification, the implementation of such models, with an acceptable accuracy, requires time and length scales at most of order 0.1s and 0.1mm respectively ⁴. Extending these models to

the simulation of flame spread in arbitrary 3D geometries, which themselves have large dimensions, necessitates an expensive computational task in both resources and time.

The approach adopted here is based upon the description of solid pyrolysis proposed by Kung⁹. However, instead of modelling the pyrolysis mechanisms as an Arrhenius controlled reaction rate, a simplified method based upon a prescribed ignition temperature is adopted. This approach may be considered to be an energy based, differential pyrolysis model.

The model is based upon the solution of the one dimensional, time dependent, heat conduction equation, modified to include the pyrolysis process. The progress of the solution can be divided into three distinct stages, controlled by two parameters, the prescribed ignition temperature, and the time varying 'char-depth' in an individual control volume.

The first stage can be identified as a pre-heating stage, determined solely by the time dependent heat conduction equation. The key concept of the overall modelling approach is based upon an ignition temperature. When an individual control volume reaches the ignition temperature then it is assumed that that volume commences to pyrolyse, at this point the second stage is reached.

During the second stage the differential energy transport equation is modified to account for the endothermic pyrolysis reaction. Furthermore, the temperature of the pyrolysing control volume is held fixed at the ignition temperature. The balance between the incident heat flux and that conducted further into the solid material determines the mass loss rate from the control volume, interpreted as a char depth, based upon a heat of reaction for the pyrolysis process. Only a small fraction of the pyrolysing control volume is gasified in a single time step, however if it is assumed that the material is either virgin or fully charred, then a local char depth within an individual control volume can be defined. When the char depth reaches the limit of the control volume then that control volume is defined to be completely charred and the second stage ends.

The third stage for the now charred control volume is the solution of the one-dimensional, time dependent, heat conduction equation for the charred material. The differential energy transport equation is modified to account for the heat transfer between the heated char and the volatiles as they flow out through the char. Therefore in general there will be a region of fully charred control volumes (stage III), followed by a single pyrolysing cell (stage II), followed by virgin material (stage I). The three regimes are solved in a simultaneous manner for all solid control volumes.

Figure 4 presents a comparison of the three flame spread models for a vertical sheet of material (plywood) with a line burner as ignition source at the base. The scenario is based upon that of Delichatsios et al.¹⁰. In general all three models give good agreement with the experimentally recorded mass loss rate. More detailed analysis reveals that the rate of flame spread is less accurately predicted. Clearly all three models offer a viable approach to modelling flame spread over charring materials though further development is required before they can be reliably applied in a real world fire scenario.

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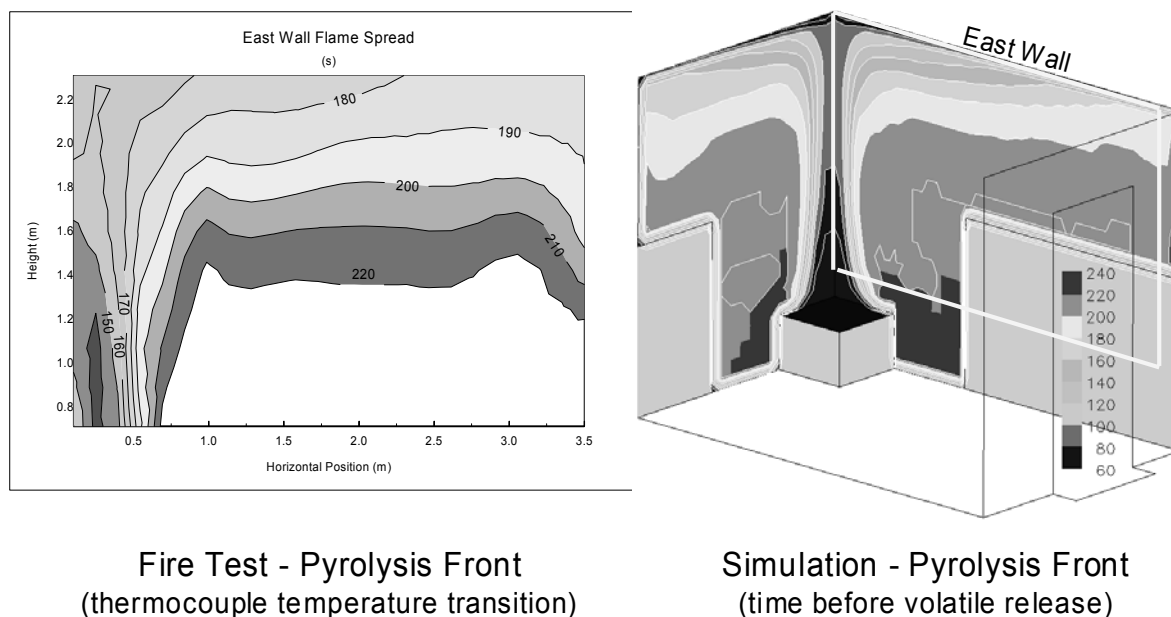


Figure 1: Flame spread in a plywood lined compartment. Time to ignition

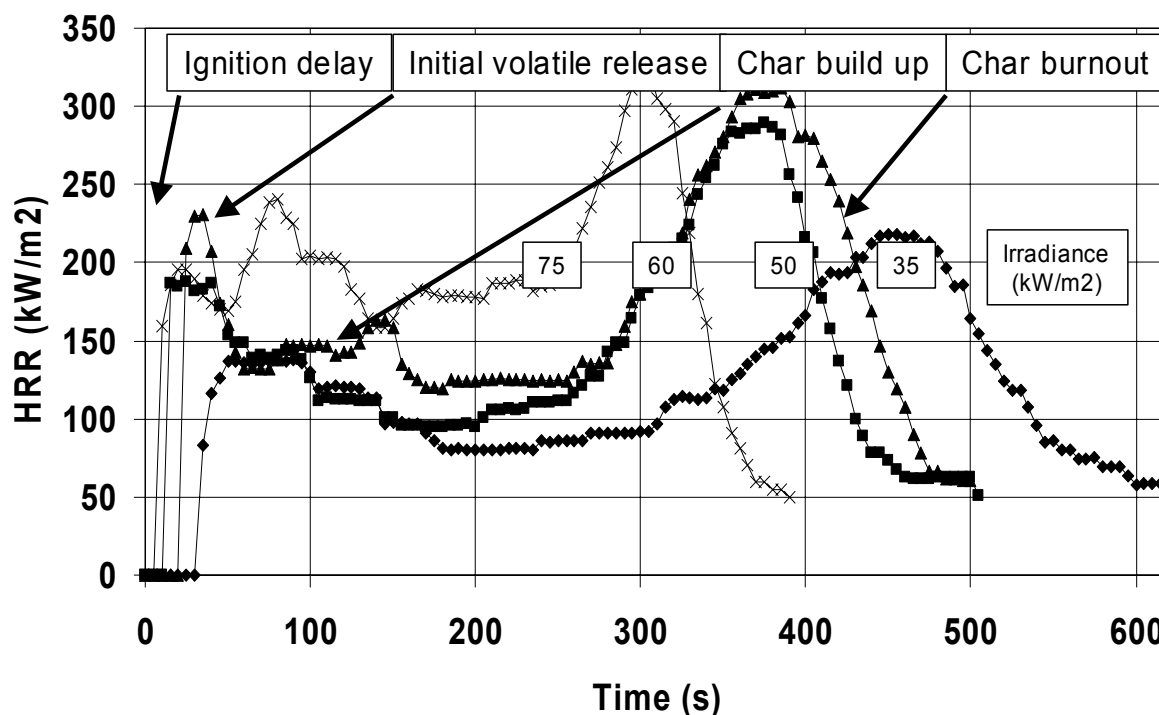


Figure 2 : Cone calorimeter data for plywood at three different incident heat fluxes. Heat release rate

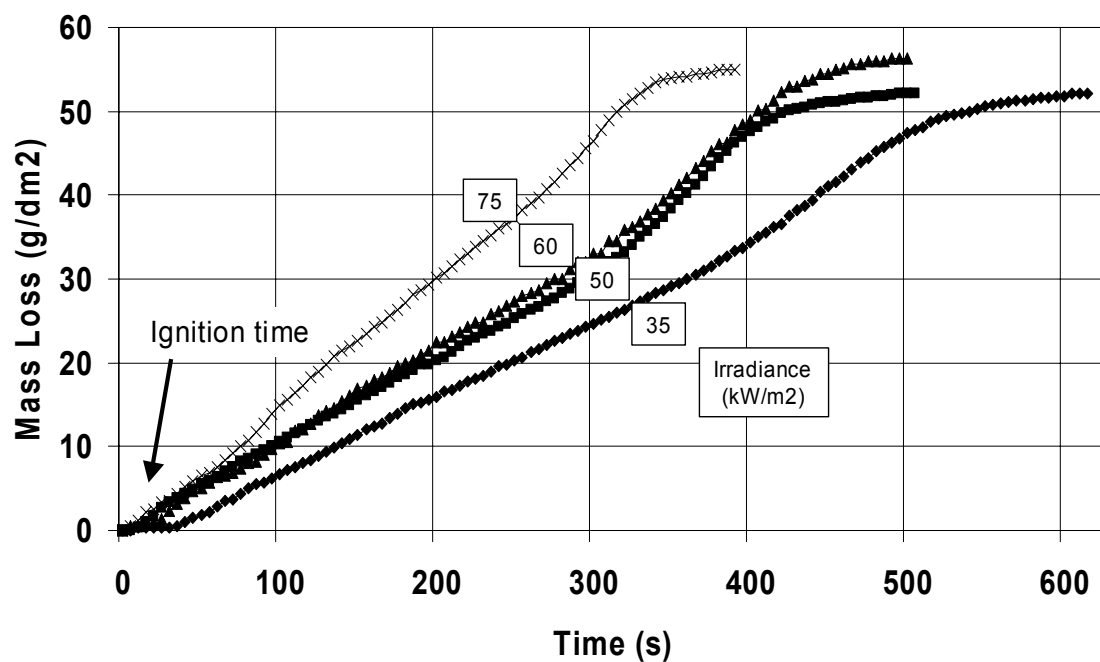


Figure 3 : Cone calorimeter data for plywood at three different incident heat fluxes. Cumulative mass loss

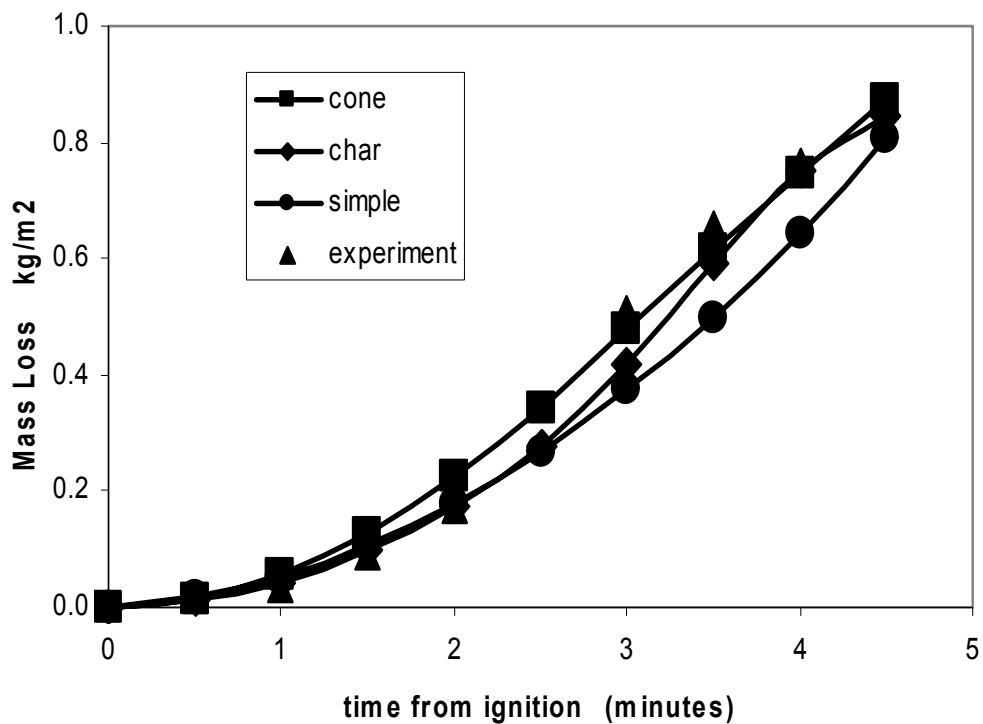


Figure 4 : Cumulative mass loss. Comparison of alternative models with experiment